Multi-Dimensional Numerical Simulation of Flow and Salinity Transport Processes in the Nile Estuary in the Context of Sea Level Rise

vorgelegt von

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Dedicated To

My beloved parents, my wife, my brother, my sisters and my nieces
Acknowledgment

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Contents

Contents ........................................................................................................................................ i
List of Figures .......................................................................................................................... v
List of Tables ................................................................................................................................ xiii
Nomenclature ............................................................................................................................... xv
Kurzfassung .................................................................................................................................... xix
Abstract ........................................................................................................................................ xxiii
1 Introduction ................................................................................................................................ 1
  1.1 General .................................................................................................................................. 1
  1.2 Motivation, goal and objectives ............................................................................................ 3
  1.3 Problem statement and research approach ............................................................................. 4
  1.4 State of the art ....................................................................................................................... 5
    1.4.1 The Nile River ................................................................................................................. 5
    1.4.2 The nature of the Egyptian water problems .................................................................... 8
    1.4.3 The expected impacts of climate change on the Egyptian coast .................................. 10
    1.4.4 Salt water intrusion phenomenon .................................................................................. 11
  1.5 Previous studies .................................................................................................................... 13
    1.5.1 Estuaries hydrodynamics and salinity transport ............................................................... 13
    1.5.2 Nile Estuary ................................................................................................................... 19
    1.5.3 Gravity currents .............................................................................................................. 20
    1.5.4 Position of this research in filling the gaps in the previous studies ............................... 22
  1.6 Structure of the thesis ........................................................................................................... 22
2 Model concepts .......................................................................................................................... 25
  2.1 Governing equations ............................................................................................................. 25
    2.1.1 Continuity and Navier-Stokes equations ...................................................................... 25
    2.1.2 Shallow water equations ............................................................................................... 27
## Contents

2.1.3 Saint-Venant equations ................................................................. 28
2.1.4 Turbulence .................................................................................... 30
2.1.5 Transport equation of tracers ....................................................... 34
2.1.6 Spatial variation of density in 2D ................................................ 35

2.2 Numerical modeling ......................................................................... 36
   2.2.1 Discretization methods ............................................................... 37
   2.2.2 Modeling aspects ......................................................................... 45

3 Modeling system .................................................................................. 51
   3.1 TELEMAC-MASCARET modeling system ....................................... 51
      3.1.1 Common characteristics of TELEMAC2D and TELEMAC3D .... 53
      3.1.2 TELEMAC2D modeling system ............................................... 54
      3.1.3 TELEMAC3D modeling system ............................................... 55
   3.2 Pre- and post-processing tools ......................................................... 56
      3.2.1 MATISSE ................................................................................ 57
      3.2.2 JANET .................................................................................... 57
      3.2.3 POSTEL3D ............................................................................. 58
      3.2.4 RUBENS ............................................................................... 58
      3.2.5 Blue Kenue ............................................................................ 58

4 Study area .............................................................................................. 59
   4.1 Location .......................................................................................... 59
   4.2 Geomorphology ............................................................................... 59
   4.3 Land use .......................................................................................... 61
   4.4 Climate, hydrology and irrigation .................................................... 61
   4.5 Bathymetry and coastal erosion ....................................................... 62

5 Two-dimensional surface water model ................................................. 65
   5.1 Model setup and parameters ............................................................ 65
   5.2 Hydrodynamics ................................................................................ 68
      5.2.1 Reference case .......................................................................... 68
      5.2.2 Changes in the flow conditions during the year ....................... 74
   5.3 Variations of bottom friction and turbulence model ....................... 75
      5.3.1 Bottom friction ......................................................................... 75
5.3.2 Turbulent viscosity ................................................................................ 78
5.4 Salinity transport ........................................................................................ 81
  5.4.1 Test cases ............................................................................................... 82
  5.4.2 Salinity transport in the Nile Estuary .................................................... 89
5.5 Sea level rise scenarios ................................................................................ 96
5.6 Water managements option and implications on the water budget of Egypt. ........................................................................................................... 99

6 Three-dimensional surface water model ....................................................... 101
  6.1 Model setup and parameters .................................................................. 101
  6.2 Hydrodynamics ......................................................................................... 104
  6.3 Salinity transport ...................................................................................... 111
    6.3.1 Verification study ............................................................................. 111
    6.3.2 Nile Estuary ...................................................................................... 135
  6.4 Sea level rise scenarios ............................................................................ 144
    6.4.1 Increase in Ls due to sea level rise .................................................. 144
    6.4.2 Mitigation measures to sea level rise .............................................. 147
  6.5 Comparison between the 2D and the 3D models ..................................... 148
    6.5.1 Hydrodynamics ............................................................................... 148
    6.5.2 Salinity transport ............................................................................ 149

7 Summary, conclusions and outlook ............................................................. 151
  7.1 Summary and conclusions ...................................................................... 151
  7.2 Outlook ..................................................................................................... 157

References ........................................................................................................ 159
List of Figures

Figure 1.1: Map for the Nile Delta shows the two branches of the Nile (source: http://maps.google.com) ............................................................................................................................................................................. 2
Figure 1.2: Schematic for the problem statement .............................................................. 5
Figure 1.3: Drainage area of the Nile (FAO, 2014) ........................................................... 7
Figure 1.4: Schematic for the main control structures on the Nile in Egypt (MWRI, 2005)........................................................................................................................................................................... 8
Figure 1.5: Impact of sea level rise on the Nile Delta and its coast (FitzGerald et al., 2008). ..................................................................................................................................................................................................... 11
Figure 1.6: Sketch for the saltwater intrusion into river system (Chanson, 2004) ...... 12
Figure 2.1: Schematic for the main procedures of CFD simulation system (after Hirsch (2007)) ................................................................................................................................................................................................ 37
Figure 2.2: Space discretization methods (after Hinkelmann, 2005) ............................ 43
Figure 2.3: Methods of control volume construction for the FVM (after Hinkelmann, 2005) ........................................................................................................................................................................ 44
Figure 2.4: Dimensions of models and their different types (after Jourieh, 2014)...... 48
Figure 3.1: TELEMAC modeling system (after Jourieh (2014)) ................................. 53
Figure 4.1: Map of the reach under study (http://maps.google.com) ............................ 60
Figure 4.2: Cross sections at different positions through the domain .......................... 63
Figure 4.3: Coastal line erosion at Rosetta Branch of the River Nile in the period from 1900 to 2006 (after Torab, 2006) .................................................................................................................................................................................................. 64
Figure 5.1: Bathymetry of the river and the grid at different positions through the domain .................................................................................................................................................................................................. 67
Figure 5.2: Time series for the water level at three positions in the domain (Mahgoub et al., 2012) .................................................................................................................................................................................................. 68
List of Figures

Figure 5.3: Water level in the whole domain.......................................................... 69
Figure 5.4: Time series for the flow velocity at three positions in the domain....... 70
Figure 5.5: Flow velocity in the domain (Mahgoub et al., 2012)......................... 71
Figure 5.6: Velocity vector showing eddies at two positions in the domain......... 72
Figure 5.7: Variations of the velocity due to changing the turbulence model ...... 73
Figure 5.8: Velocity vector showing eddies at one position in the domain using: (a) constant viscosity turbulence model, (b) k-ε turbulence model and (c) Elder turbulence model ......................................................................................................... 73
Figure 5.9: Flow velocity at the D.S. boundary due to changing sea level (Mahgoub et al., 2012)...................................................................................................................... 74
Figure 5.10: Flow velocity at the U.S. boundary due to changing sea level......... 75
Figure 5.11: Variations of water level near the U.S. boundary due to changing Manning coefficient (m^{1/3}/s) (Mahgoub et al., 2012)................................................................. 76
Figure 5.12: Variations of water level near the D.S. boundary due to changing Manning coefficient (m^{1/3}/s)........................................................................................................ 76
Figure 5.13: Variations of flow velocity near the U.S. boundary due to changing Manning coefficient (m^{1/3}/s)........................................................................................................ 77
Figure 5.14: Variations of flow velocity near the D.S. boundary due to changing Manning coefficient (m^{1/3}/s)........................................................................................................ 78
Figure 5.15: Variations of water level at the U.S. side due to changing turbulent viscosity (m^{2}/s)......................................................................................................................... 79
Figure 5.16: Variations of flow velocity at the D.S. side due to changing turbulence viscosity (m^{2}/s)......................................................................................................................... 79
Figure 5.17: Variations of flow velocity at the D.S. side due to changing turbulence model........................................................................................................................... 80
Figure 5.18: Variations of water level at the U.S. side due to changing turbulence model........................................................................................................................... 81
Figure 5.19: Schematic plan for the spatial variation of salinity in an estuary (Mahgoub and Hinkelmann, 2012)......................................................................................................................... 82
Figure 5.20: Grid of the rectangular channel (Mahgoub and Hinkelmann, 2012)..... 83
Figure 5.21: Initial conditions for salinity transport (Mahgoub and Hinkelmann, 2012) ................................................................. 84
Figure 5.22: Salinity transport for the rectangular channel for A) stagnant water with horizontal density variation only, B) stagnant water with diffusion only, C) stagnant water with horizontal density variation and diffusion and D) flowing water with horizontal density variation and diffusion (Mahgoub and Hinkelmann, 2012) ......... 85
Figure 5.23: Cross section of the trapezoidal channel (Mahgoub and Hinkelmann, 2012) ............................................................................................................................ 86
Figure 5.24: Grid of the trapezoidal channel (Mahgoub and Hinkelmann, 2012) ...... 86
Figure 5.25: Salinity transport for the trapezoidal channel for A) stagnant water with horizontal density variation only, B) stagnant water with diffusion only, C) stagnant water with horizontal density variation and diffusion and D) flowing water with horizontal density variation and diffusion (Mahgoub and Hinkelmann, 2012) ........... 87
Figure 5.26: Initial conditions for salt concentration ................................................... 90
Figure 5.27: Salt concentration after 40 days simulation time .................................... 91
Figure 5.28: Salinity concentration in the domain due to a sea storm (Mahgoub et al., 2012) ................................................................. 92
Figure 5.29: Salinity intrusion for different turbulent diffusivities: a) $10^{-1}$, b) $10^{-3}$ and c) $10^{-6}$ m$^2$/s ................................................................................................................... 93
Figure 5.30: Salt concentration after one day of simulation time for the Nile Estuary for: A) horizontal density variation only, B) turbulent diffusion only and C) horizontal density variation and turbulent diffusion (Mahgoub and Hinkelmann, 2012) .......... 95
Figure 5.31: Saltwater intrusion for the mean flow conditions in case of sea level increase by: a) 0.0 m (current status), b) 0.24 m, c) 0.69 m and d) 1.0 m .................. 97
Figure 5.32: Saltwater intrusion for sea storm conditions in case of sea level increase by: a) 0.0 m (current status), b) 0.24 m, c) 0.69 m and d) 1.0 m (Mahgoub et al., 2012) ......................................................................................................................... 98
Figure 5.33: Additional water amount that has to be discharged from Edfina barrage to prevent any further salinity intrusion for different sea level rise scenarios .......... 100
Figure 6.1: Domain and grid (Mahgoub et al., 2014b) .................................................... 102
Figure 6.2: 3D grid for the domain showing the different layers .......................... 103
List of Figures

Figure 6.3: Time series of the water level at the U.S. boundary.............................. 104
Figure 6.4: Flow velocity in the domain at the water surface (Mahgoub et al., 2014a) ................................................................................................................................... 105
Figure 6.5: Flow velocity in a cross section 3 km from the river mouth ............... 106
Figure 6.6: Velocity distribution over the vertical (in the middle of the section shown in Figure 6.5) ............................................................................................................. 106
Figure 6.7: Flow field in two positions in the domain.............................................. 107
Figure 6.8: Vector of the vertical component of the velocity for two cross sections in the domain ................................................................................................................. 108
Figure 6.9: Vector of the total velocity for two cross sections in the domain ......... 108
Figure 6.10: Flow velocity in a cross section 3 km from the river mouth for a 17 layer grid refined close to the bottom ................................................................................. 109
Figure 6.11: Velocity distribution over the vertical at the center of the section shown in Figure 6.10 with a grid refined close to the bottom ........................................... 110
Figure 6.12: Flow velocity in a cross section 3 km from the river mouth for a 11 layer grid refined close to the bottom ................................................................................. 110
Figure 6.13: Longitudinal section of the 2D lock-exchange experiment (Mahgoub et al., 2015) .................................................................................................................... 112
Figure 6.14: View of the tank used for the 2D lock exchange gravity currents. University Roma Tre, Department of Engineering, Hydraulics laboratory ............... 112
Figure 6.15: Relative error for test case C1 (Mahgoub et al., 2015) ....................... 114
Figure 6.16: Velocity distribution over the vertical in the middle of the gate after 0.5 second ........................................................................................................................ 115
Figure 6.17: Distribution of the vertical velocity component over the water column in the middle of the gate after 0.5 second .............................................................. 116
Figure 6.18: Comparison of numerical and the experimental results for dimensionless front position versus dimensionless time in test cases C1, C2 and C3 (Mahgoub et al., 2015) ................................................................. 117
Figure 6.19: Comparison of numerical and the experimental results for dimensionless front position versus dimensionless time in test cases C4, C5 and C6 (Mahgoub et al., 2015) ................................................................. 117
Figure 6.20: Comparison of numerical and the experimental results for dimensionless front position versus dimensionless time in test cases C7, C8 and C9 (Mahgoub et al., 2015) ................................................................. 118

Figure 6.21: Vertical profiles showing the evolution of the gravity currents in case C1 at: a) 2.5 s b) 7 s c) 12 s d) 17 s (Mahgoub et al., 2015) ................................................................. 118

Figure 6.22: Front velocity for test case C2 showing different phases of propagation (Mahgoub et al., 2015) ....................................................................................... 120

Figure 6.23: Distribution of the dynamic pressure over the water column for different times at the gate for experiment C1 ................................................................. 121

Figure 6.24: Vertical cross sections show the salinity at section 1 (at the gate) and section 2 (1.5 m from the gate) for experiment C1 .................................................... 122

Figure 6.25: Values of dimensionless front position for test case C1 and different \( x_0 \) values (Mahgoub et al., 2015) ........................................................................ 123

Figure 6.26: Top view in the 3D lock-exchange experiment (Mahgoub et al., 2015) 124

Figure 6.27: View of the tank used for the 3D lock exchange gravity currents, University Roma Tre, Department of Engineering, Hydraulics laboratory ................. 124

Figure 6.28: Comparison of numerical and the experimental results for dimensionless front position versus dimensionless time in test case D4 (Mahgoub et al., 2015) ..... 126

Figure 6.29: Comparison of numerical and experimental results for dimensionless front position versus the dimensionless time in test case D7 (Mahgoub et al., 2015) 126

Figure 6.30: Comparison of numerical and the experimental results for front position at different times in test case D5 near the bottom of the tank (Mahgoub et al., 2015) ............................................................................................................... 127

Figure 6.31: Comparison of experimental results, hydrostatic and the non-hydrostatic numerical simulations for dimensionless front position versus dimensionless time in test case D3 (Mahgoub et al., 2015) ................................................................. 128

Figure 6.32: Distribution of the dynamic pressure over the water column for case D1 in the middle of a cross section 0.1 m from the gate ............................................. 129

Figure 6.33: Distribution of the velocity over the water column for case D1 in the middle of a cross section 0.1 m from the gate after 2 s ............................................. 129
List of Figures

Figure 6.34: Distribution of the vertical component of the velocity over the water column for case D1 in the middle of a cross section 0.1 m from the gate after 2 s ... 130
Figure 6.35: Impact of bottom roughness (mm) on dimensionless front position for density $\rho_2 = 1015 \text{ kg/m}^3$ (Mahgoub et al., 2015) ................................................................. 131
Figure 6.36: Vertical profiles showing the evolution of the gravity currents in case D1 at: a) 2.0 s b) 4 s c) 6 s d) 8 s ................................................................. 132
Figure 6.37: Vertical cross sections at different locations in the tank and at different times for experiment D1 ................................................................. 133
Figure 6.38: The propagation of the dense fluid for different values for $b$ for case D1 ................................................................................................................. 134
Figure 6.39: Initial conditions of salinity concentration ........................................ 135
Figure 6.40: Propagation of saltwater in domain at: (a) surface and (b) bottom (Mahgoub et al., 2014b) ...................................................................................... 136
Figure 6.41: Vector of the vertical component of the velocity for two cross sections in the domain ............................................................................................ 137
Figure 6.42: Vector of the total velocity for two cross sections in the domain ....... 138
Figure 6.43: Change of salinity with time at points 1, 2, 3 and 4 (their positions are shown in Figure 6.39) at the surface (Mahgoub et al., 2014b) ......................... 139
Figure 6.44: Change of salinity with time at points 1, 2, 3 and 4 (their positions are shown in Figure 6.39) near the bottom (Mahgoub et al., 2014b) ....................... 139
Figure 6.45: The flow field at (a) the surface and (b) near the bottom (Mahgoub et al., 2014b) 140
Figure 6.46: Velocity distribution over the vertical in the middle of section ‘a’ shown in Figure 6.48...................................................................................... 141
Figure 6.47: Salinity concentration near bottom and bathymetry at one part of domain (Mahgoub et al., 2014b) ........................................................................ 142
Figure 6.48: Cross sections showing stratification of salt at following distances from intersection between Sea and Nile: (a) 0 km, (b) 1 km, (c) 2 km, (d) 3 km, (e) 4 km, (f) 8 km, (g) 12 km and (h) 16 km (Mahgoub et al., 2014b) .................................... 143
Figure 6.49: Propagation of saltwater in domain at bottom for sea level rise of: (a) 0.0 m (current status) (b) 0.24 m (c) 0.69 m (d) 1.0 m (Mahgoub et al., 2014a) .......... 146
Figure 6.50: Relationship between Ls and sea level rise (Mahgoub et al., 2014b)....147
List of Tables

Table 6.1: Parameters of 2D lock exchange experiments (Mahgoub et al., 2015)..... 113
Table 6.2: Characteristics of the evolution phases of the gravity currents in all test cases (Mahgoub et al., 2015).................................................................................................. 120
Table 6.3: Parameters of 3D lock exchange experiments (Mahgoub et al., 2015)..... 125
Nomenclature

Abbreviations

+msl above mean sea level
1D one-dimensional
2D two-dimensional
3D three-dimensional
BAW Bundesanstalt für Wasserbau
BCM billion cubic meters
BD Backward Differencing
BICGSTAB Biconjugate Gradient Stabilized Method
CAPMAS Central Agency for Public Mobilization and Statistics of Egypt
CD Central Differencing
CETMEF Centre d’Etudes Techniques Maritimes et Fluviales
CFD Computational Fluid Dynamics
COHERENS Coupled Hydrodynamical Ecological Model for Regional Shelf Seas
D.S. downstream
DG Discontinuous Galerkin method
DSWM Depth-integrated Shallow Water Model
ECOMSED Estuarine, Coastal and Ocean Modeling System with Sediments
EDF Electricité de France R&D
EFDC Environmental Fluid Dynamics Code
FD Forward Differencing
FDM Finite Difference Method
FEM Finite Element Method
Nomenclature

FVCOM  Finite-Volume Coastal Ocean Model
FVM    Finite Volume Method
GMRES  Generalized Minimum RESidual Method
IPCC   Intergovernmental Panel for Climate Change
LNHE   Laboratoire National d'Hydraulique, a department of Electricité de France
LRN    low-Reynolds number
MWRI   Ministry of Water Resources and Irrigation of Egypt
PCG    Preconditioned Conjugate Gradient Method
PDE    Partial Differential Equations
POM    Princeton Ocean Model
PSI    Positive Streamline Invariant
ROMS   Regional Ocean Modeling System
RWM    Random Wave Model
SUPG   Streamline Upwind Petrov-Galerkin Method
UNFCCC United Nations Framework Convention on Climate Change
U.S.   upstream
URANS  Unsteady Reynolds Averaged Navier-Stokes

Terms with Latin letters

\( \rho \)  water density \( \text{kg/m}^3 \)
\( \rho_0 \)  fresh water density \( \text{kg/m}^3 \)
\( \rho_{\text{ref}} \) reference density \( \text{kg/m}^3 \)
\( \vec{U} \)  velocity vector \( \text{m/s} \)
\( \rho \)  pressure \( \text{kg/m}^3 \)
\( \delta \)  identity tensor -
\( \mu \)  coefficient of dynamic viscosity \( \text{kg/(m\cdot s)} \)
\( \nu \)  coefficient of kinematic viscosity \( \text{m}^2/\text{s} \)
\( D \)  strain rate tensor \( 1/\text{s} \)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_s$</td>
<td>elevation of the free surface</td>
<td>m</td>
</tr>
<tr>
<td>$z$</td>
<td>elevation of the bottom</td>
<td>m</td>
</tr>
<tr>
<td>$p_{atm}$</td>
<td>atmospheric pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>$\nu$</td>
<td>diffusion</td>
<td>m$^2$/s</td>
</tr>
<tr>
<td>$F_x$</td>
<td>source or sink terms of momentum in x-direction</td>
<td>m$/^2$/s</td>
</tr>
<tr>
<td>$F_y$</td>
<td>source or sink terms of momentum in y-direction</td>
<td>m$/^2$/s</td>
</tr>
<tr>
<td>$F_z$</td>
<td>source or sink terms of momentum in z-direction</td>
<td>m$/^2$/s</td>
</tr>
<tr>
<td>$s_{ce}$</td>
<td>source or sink term of the flow</td>
<td>kg/(m$^3$.s)</td>
</tr>
<tr>
<td>$T$</td>
<td>concentration of the tracer</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$\nu_t$</td>
<td>turbulent viscosity</td>
<td>m$^2$/s</td>
</tr>
<tr>
<td>$\nu_T$</td>
<td>turbulent diffusivity</td>
<td>m$^2$/s</td>
</tr>
<tr>
<td>$F_{source}$</td>
<td>source term of tracer</td>
<td>kg/s</td>
</tr>
<tr>
<td>$\Delta \chi$</td>
<td>characteristic element length</td>
<td>m</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Crank-Nicholson factor</td>
<td>-</td>
</tr>
<tr>
<td>$c$</td>
<td>wave velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>$Cr$</td>
<td>courant number</td>
<td>-</td>
</tr>
<tr>
<td>$n$</td>
<td>Manning coefficient</td>
<td>m$^{1/3}$/s</td>
</tr>
<tr>
<td>$Ne$</td>
<td>Neumann number</td>
<td>-</td>
</tr>
<tr>
<td>$U$</td>
<td>velocity component in x-direction</td>
<td>m/s</td>
</tr>
<tr>
<td>$V$</td>
<td>velocity component in y-direction</td>
<td>m/s</td>
</tr>
<tr>
<td>$W$</td>
<td>velocity component in z-direction</td>
<td>m/s</td>
</tr>
<tr>
<td>$L_s$</td>
<td>intrusion length of the saline water inside the river</td>
<td>m</td>
</tr>
<tr>
<td>$R_e$</td>
<td>Reynolds number</td>
<td>-</td>
</tr>
<tr>
<td>$Fr_{do}$</td>
<td>Densimetric Froude number</td>
<td>-</td>
</tr>
<tr>
<td>$h_0$</td>
<td>water depth at the river mouth</td>
<td>m</td>
</tr>
<tr>
<td>$R_h$</td>
<td>hydraulic radius</td>
<td>m</td>
</tr>
<tr>
<td>$u_0$</td>
<td>velocity of river flow at the mouth</td>
<td>m/s</td>
</tr>
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### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \rho$</td>
<td>density difference between saltwater and fresh water</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$g$</td>
<td>gravitational acceleration</td>
<td>m/s$^2$</td>
</tr>
</tbody>
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Kurzfassung

Der Nil teilt sich bei El-Qanater (ca. 20 km nördlich von Kairo) in die Flüsse Rosetta (westlich) und Damietta (östlich), welche das Nildelta umschließen und so die Nilmündung formen. Über diese beiden Flüsse gelangt das Nilwasser in das Mittelmeer. Der Abfluss wird über mehrere wasserbauliche Strukturen gesteuert.


Der Ist-Zustand wurde auf der Grundlage der mittleren Strömungsbedingungen und des Meerwasserstands modelliert, um die Ausbreitung von Salzwasser im Nil zu untersuchen. Danach wurden Szenarien für den Anstieg des Meeresspiegels untersucht, um seinen Einfluss auf die Ausbreitung der Strömung zu bewerten.

Mit TELEMAC2D wurde zunächst ein zweidimensionales Modell aufgesetzt, obwohl der Salzgehalttransport eine dichtegesteuerte Strömung und daher in erster Linie ein dreidimensionales Phänomen ist. Die Fähigkeit von TELEMAC2D, dichteinduzierte horizontale Flüsse zu simulieren, wurde mit zwei Fallstudien (rechteckiger und trapezförmiger Querschnitt) verifiziert, und daraufhin werde das Modell verwendet, um die Nilmündung zu simulieren.
Kurzfassung


Sowohl für das 2D- als auch für das 3D-Modelle der Nilmündung wurden drei Szenarien für den Anstieg des Meeresspiegels analysiert, um die Auswirkungen zu untersuchen. Basierend auf den Ergebnissen der Modelle wurde festgestellt, dass sich das Salzwasser flussaufwärts bewegt und jede Erhöhung des Meeresspiegels eine weitere Intrusion der Salzwasserfront verursacht. Die Intrusionslänge erhöhte sich um 1,2 km, 5,1 km und 6,6 km bei einem Meeresspiegelanstieg von jeweils 0,24 m, 0,69 m und 1,0 m. Um die aktuelle Salzintrusion im Falle des Anstiegs des Meeresspiegels nicht zu erhöhen, sollte die Einleitung an der Edfina Staustufe erhöht werden. Das würde jedoch den Wasserhaushalt des Landes beeinflussen, da eine erhöhte Abgabe einen erheblichen Wasserverlust darstellt.

Vergleicht man die 2D- und die 3D-Modelle, sind die hydrodynamischen Ergebnisse in Bezug auf die Wasserstände und Abflüsse ähnlich; das Strömungsfeld ist jedoch
Abstract

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 interaction between the Nile and the Mediterranean Sea considered in this research includes water and salinity transport. Considered as a large scale case with a complex geometry, multi-dimensional models for the Nile Estuary were set up in this research, and the TELEMAC-MASCARET modeling system was used for this purpose. The main aim of the research was to simulate the current conditions of flow and salinity transport in the Nile Estuary to improve the process understanding and to investigate possible changes due to the anticipated sea level rise. The Nile Estuary is a tideless estuary, this type of estuaries are more complex in terms of salinity transport than tidy estuaries.

The current status was first modeled based on the mean conditions of flow and sea water level, in order to investigate the propagation of saltwater inside the Nile. Then scenarios for the sea level rise were assessed to evaluate the influence of sea level rise on the propagation of gravity currents.

A two-dimensional model was first set up using TELEMAC2D, although the salinity transport is density-driven flow and therefore it is mainly a three-dimensional phenomenon. The capability of TELEMAC2D to simulate flow driven by horizontal density differences was first checked using two case studies (rectangular and trapezoidal cross sections) and finally it was verified and hence it was used to simulate the Nile Estuary.
Abstract

As the density-driven flows (gravity currents) are the major phenomena that govern the transport of the saline water between the Nile and the sea, a 3D model to simulate these phenomena in two cases of lock-exchange experiments was first set up using TELEMAC3D in order to verify it. The results of the numerical model were compared with experimental results. The model showed high accuracy and it was concluded that the TELEMAC3D is capable of simulating such phenomena. It was also concluded that a non-hydrostatic simulation and the use of complex turbulence model achieve higher accuracy. Thereof, a 3D model for the Nile Estuary was set up to simulate the gravity currents and to assess the stratification of salinity in the Nile. The model simulated complex phenomena in a complex natural geometry.

It was concluded that the salt wedge is a stratified fluid in which the salinity decreases from the bottom towards the surface where a layer of less brackish water exists. The salt wedge was fluctuating, although steady boundary conditions were imposed, and it was not stagnant as it was expected, which could be caused by the weak balance between barotropic and baroclinic gradients in tideless estuaries as the case of the Nile Estuary.

For both the 2D and the 3D models of the Nile Estuary, three scenarios for the sea level rise were also analyzed to study its impact. Based on the results of the models, it was found that there was an intrusion for the saltwater inside the Nile, and any increase in the sea level will cause further intrusion. The intrusion length increased by 1.2 km, 5.1 km, and 6.6 km in case of sea level rise of 0.24 m, 0.69 m and 1.0 m, respectively. To keep the current status of balance, in terms of saltwater intrusion inside the Nile in case of sea level rise, the discharge of Edfina barrage has to be increased. However that would affect the water budget of the country as this water will be discharged into the sea being considered as losses.

Comparing the 2D and the 3D model, the hydrodynamic results were similar in terms of water levels and discharge, however the flow field was different as the secondary currents could be seen only in the 3D model. For the salinity transport, the intrusion length was much higher in the 3D model. The stratification of the salt wedge can only
be seen in the 3D model. So, the 2D model can be used for calculating water levels and average water velocity. For the salinity transport, the 3D model is more suitable, the 2D model can only be used as a rough estimation.
1 Introduction

This chapter is dedicated to present motivation of the research, background information, an overview of the state of the art and a review of the previous studies.

1.1 General

Considered as the main water source for Egypt, the Nile River has taken a great concern by the Egyptian government and the water professionals in the country, especially what is related to any possible impact on the Nile water. The Nile water started its journey from the equatorial lakes in the middle of Africa and ended with the Mediterranean Sea at two locations which are Rosetta and Damietta as the Nile divided at El-Qanater City to two branches (Rosetta branch and Damietta branch) enclosing the Nile Delta (Figure 1.1).

At the mouth of the Nile (where the Nile meets the sea) an interaction between the Nile water and the saltwater of the Mediterranean Sea takes place. This kind of complex interaction is important as it could have several impacts on the Nile and the surrounding agriculture lands. Moreover, this phenomenon is very important for the water policy of the country.

In addition, in the last few decades several observations and natural phenomena proved that the global climate changed in terms of temperature and rainfall (UNFCCC, 2007; IPCC, 2007), this change could have negative direct and indirect consequences on the whole earth. 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 and the fresh water at the mouths of the rivers, as the case of the Nile River (El Raey, 2010; Michel and Pandya, 2010). So, the sea level rise will also affect the interaction between the
1 Introduction

Saltwater of the Mediterranean Sea and the Nile water which make the problem more complex.

One of the successful techniques that can help better understanding such interaction is the modeling technique. By the use of the modeling technique more obvious picture about this interaction can be drawn so that suitable solutions for the problem can be found.

This research studies the interaction between the sea water and Nile water by using the modeling technique.

![Figure 1.1: Map for the Nile Delta shows the two branches of the Nile (source: http://maps.google.com)](image)

Figure 1.1: Map for the Nile Delta shows the two branches of the Nile (source: http://maps.google.com)
1.2 Motivation, goal and objectives

Due to its great importance to Egypt, the Nile River is usually in the focus of the water researchers and professionals. The protection of the Nile from any possible human or natural impact is therefore very important. The anticipated sea level rise could cause more saltwater intrusion from the Mediterranean Sea into the Nile which means several possible negative impacts, such as impacts on the water quality, impacts on the irrigation system in the surrounding area and impacts on the salinity of the agriculture lands around the Nile.

So, there is a need to get more in depth in the phenomenon of saltwater intrusion in the Nile in order to assess the current situation of saltwater intrusion and hence assessing how long more intrusion could take place, and also finding out the suitable water management option to combat any further saltwater intrusion.

Thereof, the main goal of this research is to improve the understanding of the behavior of the saltwater intrusion phenomenon in the Nile Estuary taking into account sea level rise and finding out a suitable solution for it. Therefore the specific objectives of the research are:

- to simulate the saltwater intrusion in the Nile Estuary at Rosetta branch of the Nile River,
- to assess the possible impacts of the sea level rise on the saltwater intrusion phenomenon in the Nile Estuary, and
- to find out suitable adaptation and mitigation measures for the phenomenon under study.

This research can help in achieving the following aims:

- assisting the decision makers in putting the appropriate plans for the water sector in Egypt, and
transferring the results to researchers and engineers in the field of water resources to guide them in carrying out similar studies in different places.

1.3 Problem statement and research approach

A mutual transport of water and salinity occurs between the Nile River and the Mediterranean Sea at the mouth of the Nile (Nile Estuary), in a way that the Nile discharges its fresh water into the sea while the sea water intrudes into the Nile in what is called a salt wedge which takes place normally in the lower part of the water column (Figure 1.6).

This mutual transport could be affected in case of any changes in the sea level or in the Nile flow, the sea level could rise due to the climate change which could also affect the flow of the Nile (positively or negatively), the flow of the Nile could also be affected due to the political aspects related to the Nile treaties and the share of the Nile water between the Nile basin countries.

Meanwhile, the changes in the flow of the Nile will decrease the recharge of the groundwater aquifer around the Nile which is recharged from the Nile water, in addition if the flow of the Nile decreases the dependency on the groundwater could increase, that will cause more groundwater abstraction which will affect the saltwater intrusion in the groundwater aquifer close to the sea. A schematic for the problem statement is shown in Figure 1.2.

The saltwater intrusion phenomenon is a complex phenomenon and the Nile Estuary is a complex system, therefore the interaction between the Nile and the Mediterranean Sea is also very complex and is affected much by the saltwater intrusion phenomenon.

The approach of the research depended on assessing the current situation of the saltwater intrusion inside the Nile Estuary by using of the numerical modeling technique. Then several scenarios for the sea level rise were analyzed using the same model to investigate the impact of the sea level rise on the saltwater intrusion in the Nile Estuary. The results of the current status and the sea level rise scenarios were then
compared and some management options were investigated, the aim of the management options was to maintain the current status.

Several test cases were also modeled as a way to verify the modeling system that were used in this research and as well for finding out the most suitable numerical parameters that can be used for the case of the Nile Estuary.

1.4 State of the art

1.4.1 The Nile River

The Nile River is the longest river in the world, its length is about 6,650 km (Melesse et al., 2014). It comprises two main tributaries; the main one is the Blue Nile which
originates from Lake Tana in Ethiopia and flows into southwest of Sudan, the Blue Nile contributes with about 86% of the Nile annual flow (Degefu, 2003). The second tributary is the White Nile which originates from the great lakes region in central of Africa, it generates about 14% of the Nile annual flow (Melesse et al., 2014). The White Nile featured by the swamps of the Sudd (in south Sudan) which cause too much evaporation losses, the outflow from the swamps is only half the inflow (MWRI, 2005). The two tributaries meet in Khartoum (the capital of Sudan) to flow north through Sudan and Egypt and ends in the Mediterranean Sea.

The drainage area is about 3.1 Million km² (FAO, 2014) (Figure 1.3). The Nile watershed is located in 11 countries which are Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. The 11 Nile basin countries have a combined population of 443 million in 2012 with a projected population of 726 million in 25 years (Melesse et al., 2014).

As it flows from south to the north, the Nile passes several hydroclimatic zones which are: (I) lake plateau territory (Burundi, Rwanda, Tanzania, Kenya, and Uganda), (II) Sudd freshwater swamp (southern Sudan), (III) Ethiopian highlands, (IV) Sudan plains (central Sudan), (V) northern Sudan and Egypt (from the Atbara and Nile Rivers confluence to Cairo), and (VI) Mediterranean zone (coastal region with no measurable rainfall) (Melesse et al., 2014).

The Nile extends more than 1200 km inside Egypt. Several control structures are constructed in Egypt to fully control the water of the Nile. The first and the most important structure in Egypt is Aswan High Dam in the south with its reservoir which is Nasser Lake (the biggest man-made reservoir in the world), then several barrages exist on the Nile for better distribution of the water for irrigation purposes. Before its end, 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 last two control
structures on the Nile in Egypt are Edfina barrage on Rosetta branch and Farascour barrage on Damietta branch (Figure 1.4).

Figure 1.3: Drainage area of the Nile (FAO, 2014)
1 Introduction

Figure 1.4: Schematic for the main control structures on the Nile in Egypt (MWRI, 2005)

1.4.2 The nature of the Egyptian water problems

Egypt is located in an arid belt; therefore it is fully dependent on the River Nile for its water resources (Loucks et al., 2005). The share of Egypt from the Nile according to the agreement with Sudan is 55.5 Billion Cubic Meters annually (BCM/year). Seeking
for water, about 97% of the population lives on 4% of the land in the small strip along the Nile and in the Delta (MWRI, 2005).

The population density is among the highest in the world and it continues to increase due to the population growth of about 2% per year (Loucks et al., 2005). In the last 25 years the population increased from 38 Million in 1997 to 66 Million in 2002 (MWRI, 2005) and about 94 Million in 2014 according to the Central Agency for Public Mobilization and Statistics (CAPMAS) of Egypt. This rapidly growing population and the related agricultural and industrial activities increased the demand on the water supply enormously.

To decrease the population density and for increasing food supply, the Egyptian government embarked several development projects for horizontal expansion such as Toshka project in the south and El-Salam project in Sinai in the east, the two projects are aimed to increase the agriculture area from 3.4 million ha in 1997 to 4.1 million ha in 2017 (Loucks et al., 2005).

However, the water resources are very limited which could affect the future development plan. So, Egypt is looking for possibilities to increase the supply by taking measures upstream in Sudan and Ethiopia. Examples are the construction of reservoirs on the Blue Nile in Ethiopia and the Jonglei Canal in Sudan that will partly drain the swamps in the Sudd and decrease the evaporation from them (Loucks et al., 2005). However, such cooperation with the Nile basin countries is currently problematic due to political aspects.

The water availability is not only of a great concern, but also the water quality. The increasing population and the related industrial activities caused severe deterioration of the water quality which means that the good quality water that could be used is reduced even further. Hence, Egypt is approaching an unbalance situation where the demands could exceed the supply. This situation will necessitate improved decision making for water resources planning and management.
1.4.3 The expected impacts of climate change on the Egyptian coast

The Egyptian coasts extend for about 3,500 km along the Mediterranean Sea and the Red Sea. The Nile delta coast has a length of about 300 km and there are highly populated cities located on it such as Alexandria, Port-Said, Rosetta, and Damietta, which are also important industrial zones and economical centers. The Nile delta coastal zone also includes a large portion of the most fertile low land of Egypt. The coastal zone suffers from population pressure problem (Agrawala et al., 2004).

As a low lying area with high local land subsidence, the Nile delta and its coastal front on the Mediterranean are considered vulnerable to the impacts of climate change. The impacts of climate change include shoreline erosion, stresses on fishers and most important is sea level rise (Agrawala et al., 2004).

The sea level rise could cause inundation for the low laying areas which could cause severe economic consequences, increase the saltwater intrusion into the coastal aquifer and the coastal estuaries of the Nile River (El Raey, 2010) and negatively impact the Egyptian northern lakes which constitute 25% of the total Mediterranean wet lands and produce about 60% of the fish products in Egypt (Agrawala et al., 2004). The possible impacts of sea level rise could affect several development sectors, including tourism, cultural and natural heritage, agricultural quality and productivity, freshwater availability, public health, and socioeconomic welfare (El Raey, 2010).

Considering two scenarios for sea level rise, Fitzgerald et al. (2008) showed that the affected population and the affected croplands will be about 3,800,000 capita and 1,800 km² respectively in case of sea level rise of 0.5 m, and 6,100,000 capita and 4,500 km² in case of sea level rise of 1.0 m (Figure 1.5).

Other consequences to climate change could be also an increase of soil salinity due to saltwater intrusion, an increase of extreme events such as flash floods and droughts with its related socio-economic consequences, and change of acidity and circulation patterns in coastal waters (El Raey, 2010).
1.4 State of the art

Figure 1.5: Impact of sea level rise on the Nile Delta and its coast (FitzGerald et al., 2008).

1.4.4 Salt water intrusion phenomenon

The saltwater intrusion into estuaries is usually in a form of salt wedge where the variation of density due to salinity difference forces the saltwater landward. In a
tideless sea, as the case of the Mediterranean Sea, the estuary is characterized by strong stratification and saltwater intrusion into the river system. The saltwater layer underlies the freshwater layer of the river as shown in Figure 1.6 (Chanson, 2004).

The flow due to density variations is called gravity currents (also called density currents or density-driven flows). Gravity currents are the major phenomena that govern the transport of saline water in estuaries especially in tidless estuaries such as the case of the Nile Estuary. Gravity currents are defined as complex phenomena occurring when a fluid with a given density is released into a fluid with different density (Hacker et al., 1996). The flow is driven by the variation of the buoyancy force caused due to density difference (Hacker et al., 1996).

Many examples of these phenomena exist in nature and in human activities; such as salt wedge propagation, turbidity currents (Adduce et al., 2012), disposal of cooling water from industrial applications (Ross et al., 2002) and discharging salt brine resulting from seawater desalinization (Hodges et al., 2011). In hydraulic engineering the main focus with respect to gravity currents are salinity, temperature and sediments. The gravity currents are of great importance when estuaries are modeled (Mahgoub and Hinkelmann, 2012).

Figure 1.6: Sketch for the saltwater intrusion into river system (Chanson, 2004)
Unlike the tideless estuaries, in tidy estuaries the tides have much more impact on the water and salinity exchange between seas or oceans and estuaries, and the density-induced flow is of less importance. Examples for tidy estuaries are the Elbe and Weser estuaries at the North Sea.

### 1.5 Previous studies

The numerical modeling has been widely used for simulating rivers’ and estuaries’ hydrodynamics and transport processes, however very few trials for the Nile Estuary were found. Hereafter is a review for the previous studies related to modeling of rivers’ estuaries in general, the Nile Estuary and gravity currents which are the main phenomena that govern the transport of saltwater between the Nile and the Mediterranean Sea.

#### 1.5.1 Estuaries hydrodynamics and salinity transport

The hydrodynamic of estuaries and the impacts of tides and river flow on it in addition to the salinity intrusion and the stratification phenomena were the main focus of the previous research in estuaries where tides are dominant. The previous studies used in general 2D or 3D or ocean models to simulate estuaries. Some researches tried to find out empirical formulas to calculate the salinity intrusion length. Integrated models were also applied by some researchers. The previous studies are presented hereafter.

1. **2D models**

Several researches used 2D models to simulate estuaries. Laterally averaged 2D models are used in some cases and in some case vertically averaged 2D models were adopted.

a. Laterally averaged 2D models

Laterally averaged 2D models were used to simulate the saltwater intrusion, salinity distribution and mixing processes in Columbia River Estuary in USA (Hamilton, 1990), Tanshui River estuary in Taiwan (Hsu et al., 1999), Swan River estuary in
Introduction

Australia (Kurup et al., 2000) and Arvand River estuary in Iran (Zahed et al., 2008). The four estuaries are of the tidy type.

They used different modeling systems, which are multi-channel estuary model, Hydrodynamic Eutrophication Model (HEM-V2D), TISAT and CE-QUAL-W2. Finite Difference Method and a hydrostatic pressure assumption were adopted by all of them. The mixing length theory was chosen by all of them to simulate the turbulence, Hamilton (1990) suggested a mixing length model based on turbulent length and bottom friction velocity. Hsu et al. (1999) implemented a mixing length model similar to the one developed by Pritchard (1960). Kurup et al. (2000) and Zahed et al. (2008) used Prandtl’s mixing length model.

According to Hamilton (1990) stratification and salinity propagation are very sensitive to turbulent diffusivity and viscosity, so he calibrated these parameters with several models, while Hsu et al. (1999) calibrated them by comparing salinity distributions of the model with those from the measured data. The latter also calibrated the friction coefficient by simulating the barotropic flow (tidal flow, river discharge, topographic currents and the interaction between them).

Hamilton (1990) and Zahed et al. (2008) emphasized the rapid change in the salinity intrusion in response to river flow changes. The latter obtained a simple equation to estimate the intrusion length as a function of upstream freshwater discharge. In addition, the former concluded that the vertical mixing was not affected due to the change in the tidal energy.

Vertically averaged 2D models

Vertically averaged 2D models were used by many researches to study saltwater intrusion into estuaries and the impact of river flow on the intrusion length. Examples for that are the use of Finite Element Method to model Gulf of Maine estuary in England (Proehl et al., 2004), Lima river estuary in Portugal (Pinho and Vieira, 2005), northern area of Bohai Sea in China (Zhu and Li, 2008), Scheldt estuary in Belgium (Brye et al., 2010) and Changjiang River estuary in China (Shi and Zhang, 2011), and
the use of Finite Difference Method to model Tanshui River estuarine system in Taiwan (Liu et al., 2004).

A hydrostatic pressure assumption was employed by all of them. Liu et al. (2004) used constant viscosity turbulence model while Zhu and Li (2008) adopted mixing length turbulence model. Proehl et al. (2004) used a Lagrangian particle method and sub-grid scale turbulence approach.

Zhu and Li (2008) and Brye et al. (2010) adopted coupling techniques. The former developed a coupled 2D waves and tidal currents model, the two components of the model were a 2D random wave model (RWM) including refraction-diffraction and a 2D depth-integrated shallow water model (DSWM). While, the latter developed a coupled 2D and 1D Finite Element model. The 2D model was used for the marine and estuarine parts and the 1D model was used for the river.

Impact of sea level rise on estuaries with respect to sediment transport or salinity transport was considered by Valentim et al. (2013) and Ahmadian et al. (2014). Tagus estuary and Ria de Aveiro lagoon in Portugal were simulated by Valentim et al. (2013) using MOHID 2D model to study residual circulation, tidal asymmetry and tidal dissipation, they considered the sea level rise also. Ahmadian et al. (2014) studied the impacts of sea level rise on the Severn Estuary and Bristol Channel, UK, in addition to the performance of the Severn Barrage. Several models were first used to predict the sea level rise then a 2D model was used to simulate the estuary.

2. 3D Models

3D models were also applied in several researches. The baroclinic circulation model ELCIRC, which is a Finite Volume Code applying the hydrostatic pressure approximation, was used by Chawla et al. (2004) and Gong et al. (2009) to study the mixing processes in Columbia River estuary in USA and the Chesapeake Bay area in U.S.A., respectively. Both focused on the mixing processes and the impact of tides.

CHEN et al. (2007) and Shi et al. (2010) employed COHERENS 3D model to simulate the East China Sea and tidal circulation within the North and South Passages
1 Introduction

of the Changjiang River estuary in China, respectively. The model applies the hydrostatic pressure approximation. For the hydrodynamic simulation CHEN et al. (2007) used the Total Variation Diminishing (TVD) scheme, while Lagrangian particle tracking method was adopted for the transport simulation. Smagorinsky model was used for modeling turbulence.

The 3D Environmental Fluid Dynamics Code (EFDC) model was adopted to simulate the hydrodynamics and salinity transport in Little Manatee River estuary in USA (Huang et al., 2008), York River estuary in USA (Gong et al., 2007), Pamlico River Estuary in USA (Xu et al., 2008) and Oujiang River Estuary in China (JIANG et al., 2009). Liu et al. (2008) integrated EFDC model with hydrological model to simulate St. Louis Bay estuary in USA. The EFDC is vertically hydrostatic and incorporates a second-order turbulence closure sub-model that provides eddy viscosity and diffusivity for the vertical mixing.

Flow and salinity transport processes in the Weser estuary in Germany were simulated by Malcherek (1995) using TELEMAC3D modeling system, the estuary is of a tidy type. WANG et al. (2006) developed a wave propagation model, the model was coupled with a 3D hydrodynamic model to simulate the Pearl River Estuary in Hong Kong. The model applied the Finite Element Method with hydrostatic pressure approximation. Chen (2012) employed a 3D unstructured Cartesian grid model, UnLESS3D, to simulate the Crystal River/Kings Bay system, Florida, United States. Based on the model an empirical formula was suggested relating the river discharge and the water levels with the groundwater level in a nearby well. Oujiang River Estuary in China was simulated by Xing et al. (2013) using a self-developed 3D semi-implicit Finite Volume model. They used horizontally unstructured grids and a boundary-fitted coordinate system in the vertical direction. A turbulence closure model was applied in this case.
Ocean models

Some researchers used ocean models to model estuaries, the widely used models in this context are Finite Volume coastal ocean model (FVCOM), Regional Ocean Modeling System (ROMS), Princeton Ocean Model (POM) and ECOM-si.

FVCOM, a 3D unstructured grid based Finite Volume model, was used to simulate Snohomish River estuary in USA (Yang and Khangaonkar, 2008), Skagit River estuary in USA (Yang and Khangaonkar, 2009), Pontchartrain Estuary in Mexico (Georgiou et al., 2009) and Changjiang Estuary in China (Ma et al., 2011), respectively. The main focus was studying tidal mixing and salt intrusion and the impact of river flow on the salinity intrusion. Yang and Khangaonkar (2009) concluded that the saltwater intrusion length is proportional to the river flow. FVCOM employs turbulent closure scheme for vertical mixing and the Smagorinsky scheme for horizontal mixing. In addition, the model assumes a hydrostatic pressure distribution.

Warner (2005) and MacCready et al. (2009) used ROMS model to simulate the Hudson River estuary and Columbia River estuary in USA, respectively. The former reported that stratification differed from the measured data, where the stratification in the model were over the whole water column, while the measurements indicated a distinct stratification and a surface mixed layer. They also concluded that the turbulence model did not affect the results much.

A modified version of the POM was used by Larson et al. (2005) to simulate Pearl River Estuary in China which is dominated by tides. The 3D numerical model ECOM-si, which originated from the Princeton Ocean Model, was employed by Wu et al. (2010) and Qiu and Zhu (2013) to simulate the Changjiang River estuary in China. The former studied the link between the subtidal circulation and salinity intrusion, while the latter studied the impact of seasonal runoff by the Three Gorges Reservoir on saltwater intrusion.

Simionato et al. (2004) used 3D Finite Difference Hamburg Shelf Ocean Model to set up 3 one-way nested models to simulate the tidal propagation from the Argentinean
1 Introduction

continental shelf to the Rio de la Plata estuary. Zheng et al. (2014) employed Estuarine, Coastal and Ocean Modeling System with Sediments (ECOMSED) to study the impact of river flow on the mechanism of the plume front in the Pearl River Estuary. The main forces that were considered by the model were winds, tides and river discharges. The results showed that the plume location is affected by the river flow.

3. Empirical formulas to calculate the intrusion length of saltwater

Finding out empirical formulas to calculate the intrusion length of saltwater was also one of the aspects that was studied by several authors. Burgh (1968) developed an empirical relation to predict the impact of deepening of rivers on the saltwater intrusion into estuaries, it was concluded that a small change in the depth caused high change in the intrusion length. Markofsky (1980) and Chanson (2004) developed two different 1D formulas to calculated the intrusion length into estuaries based on the flow characteristics and the density difference. Shaha and Cho (2009) compared four empirical models for the Sumjin River estuary to find out the most suitable one for calculating and predicting the saltwater intrusion length. The results showed that the model is very dependent on the type of estuary.

Zhang et al. (2010) studied the relationship between the river discharge and the salinity intrusion length analytically and established two empirical equations for the discharge-salt intrusion length relationship for the Modaomen estuary. Parsa and Etemad-Shahidi (2011) suggested an empirical formula to predict the salinity intrusion into alluvial estuaries, the formula is based on studying the main parameters that could affect the salinity intrusion, these parameter are the geometric, hydrologic and hydrodynamic characteristics. A previously verified model, CE-QUALW2, was used to investigate the effects of the governing parameters on the salinity intrusion.

4. Integrated Models

Setting up an integrated model for simulating not just the surface water but also the groundwater and their interaction with the seawater in estuaries was carried out by
1.5 Previous studies

Delhez and Carabin (2001) who used three-fold model for the Scheldt and Belgian Coastal Zone where descriptions of the groundwater, river and marine domains are provided by coupling appropriate numerical models of these different sub-systems. The coupling of the three models was done using the client-server architecture where a central application is used to receive and send all the information from and to the three models.

5. Tideless estuaries

One of the very few studies that was related to salinity transport in tideless estuaries were done by Jasinska (1993) who studied the motion of salt water in the Baltic Sea along a Polish estuary by taking measurements for water level, velocity and salinity at different sites, he also used a 3D semi-implicit Finite Difference model. The results emphasized the unsteady nature of the motion of salt water in tideless estuaries. It is important to mention that simulating salinity transport (density-currents) in complex bathymetries is very difficult.

Hinkelmann (2005) studied the flow and salinity transport in Darß-Zingster Boddenkette estuary in Germany. He constructed a 2D model for the study area using TELEMAC2D modeling system. A hydrostatic pressure assumption and constant viscosity turbulence model were adopted by him.

1.5.2 Nile Estuary

Few works have been found where numerical 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 1D 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 and Aziz M. (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 to compare several formulas used in this context.

1.5.3 Gravity currents

Gravity currents have drawn the attention of researchers since long time. Several models have been proposed and used to study gravity currents. Kàrmàn (1940) proposed a perfect-fluid model for deep gravity flows propagating steadily. Benjamin (1968) used the perfect-fluid theory and some of its simple extensions (such as theory of hydraulic jumps) to investigate the properties of steady gravity currents. Nandi and Date (2009) used single fluid formalism to simulate flows with an interface between two incompressible and immiscible fluids. La Rocca and Bateman (2010) and La Rocca et al. (2012b) proposed a two-layer shallow-water model. La Rocca et al. (2012a) developed a Lattice Boltzmann model for two immiscible shallow water-layers of different density.

These phenomena have been studied numerically or experimentally or both. Experimentally, Alavian (1986) investigated the behavior of density currents on an inclined surface. He concluded that flow becomes super-critical and periodic interfacial instabilities appear as the incline increases, these instabilities were found to be the main mechanism for entrainment. Cenedese and Adduce (2008; 2010) focused on the mixing of gravity currents and its parameterization, a new parameterization was suggested depending on Froude number and Reynolds number and considering the sub-critical flow. Nogueira et al. (2013) studied the impact of bed roughness on the evolution of gravity currents and they analyzed the characteristic variables for the different evolution phases using lock-exchange experiments. It was found that bed roughness caused a reduction in the front velocity of the gravity currents.

Numerically, Klemp et al. (1994) studied the factors that regulate the propagation of gravity currents through the evaluation of theoretical models and 2D numerical model simulations. According to his results, the surface friction reduces the propagation speed. Bombardelli and Garcia (2002) assessed the potential development of density
1.5 Previous studies

currents in the Chicago River using a 3D hydrodynamic model. Mahgoub and Hinkelmann (2012) used a 2D model to assess and quantify the impact of density-driven flow for two theoretical cases of a rectangular and trapezoidal channel and for a real case of the Nile Estuary.

Several researches also investigated gravity currents through numerical simulations and compared it with results from experimental setup. La Rocca et al. (2008) studied the dynamics of 3D gravity currents by means of laboratory experiments and numerical simulations based on the shallow-water theory with the single-layer approximation. They used a Finite Volume code with Riemann solver for the simulation, the proposed model showed good accuracy. Firoozabadi et al. (2009) studied density currents with a uniform velocity and concentration in an experimental setup and compared it to numerical simulations with low-Reynolds number k-ε model. Adduce et al. (2012) investigated gravity currents with laboratory experiments and a two-layer shallow water model with a modified Turner’s formula to account for the entrainment between the two fluids.

The above reviewed literature used hydrostatic approximation; however there are conditions where the non-hydrostatic pressure component has to be considered, such as flows over abruptly changing bathymetry, intensive vertical circulation, flows around obstacles and cases of very strong density gradients (Jankowski, 1999). Therefore, there are some applications where non-hydrostatic simulation was used. Paik et al. (2009) used 3D unsteady Reynolds averaged Navier-Stokes (URANS) equations closed with a buoyancy corrected low-Reynolds number (LRN) k-ε model to simulate discontinuous gravity currents in a rectangular channel using the Finite Volume Method. Kanarska and Maderich (2003) presented a 3D non-hydrostatic model for simulating unsteady free-surface density stratified flows. Yam et al. (2011) evaluated an algebraic slip model for simulating turbidity currents. Mahgoub et al. (2015) simulated gravity currents using a non-hydrostatic 3D modeling system (TELEMAC3D), the numerical results were compared to two sets of laboratory scale 2D and 3D lock-exchange experiments, the results showed that the TELEMAC3D modeling system is capable of simulating gravity currents in regular geometry.
1 Introduction

1.5.4 Position of this research in filling the gaps in the previous studies

All the reviewed literature focused mainly on estuaries where tides are dominant while only one study for tideless estuary was found. 2D, 3D or ocean models were used to simulate the hydrodynamics or salinity transport or both of many estuaries around the world; however no studies carried out on saltwater intrusion for the Nile Estuary were found. No high resolution 2D and 3D flow simulation in the Nile Estuary was found. No studies have been found where non-hydrostatic simulation was used for estuaries.

As this research focuses on the Nile Estuary which is a tideless estuary and non-hydrostatic simulation was also used, so this research is adding a new contribution in terms of the type of estuary, the case study and the modeling technique used.

1.6 Structure of the thesis

This thesis consists of 7 chapters which are organized in the following manner:

Chapter 1 (current chapter): presents a brief introduction about the research, the goal and objectives, the problem statement, the necessary background information related to the research and a review for the previous studies related to the topic of this research.

Chapter 2: provides the main governing equations used in the research for the 2D and the 3D models (Navier-Stokes equations, shallow water equations and transport equations), in addition the main concepts related to numerical modeling are also discussed, this includes the discretization methods (in time and space) and modeling aspects.

Chapter 3: describes the modeling system used in the research which is the TELEMAC-MASCRET modeling system. A presentation of the main modules of the modeling system is discussed with a special focus on TELEMAC2D and TELEMAC3D as they are the ones used in the research. The pre- and post-processing...
tools used in the research are presented also in this chapter, namely MATISSE, JANET, POSTEL3D, RUBENS and BlueKenue.

Chapter 4: presents the study area (the last reach of Rosetta branch of the Nile River), it includes location, geomorphology, land use, hydrology and irrigation, bathymetry and flow conditions, climate and coast line.

Chapter 5: shows the results of the 2D model for the Nile Estuary. The setup of the model is first presented including the grid generation, the boundary conditions, the initial conditions and the model parameters. Then the results of the hydrodynamics and parameters’ study are presented. For the salinity transport, the results of two test cases are first discussed, then the results of the Nile Estuary are presented. The impact of sea level rise through several scenarios, using the same 2D model, is discussed in this chapter too. The chapter also includes management options to face any expected impact of the sea level rise.

Chapter 6: shows the results of the 3D model for the Nile Estuary. The model setup is first presented including the grid generation, the boundary conditions, the initial conditions and the model parameters. The hydrodynamics results for the Nile Estuary are first discussed. Test cases (lock-exchange experiments) for simulating the gravity currents (which occur also in the Nile Estuary) are presented, and then the results of the salinity transport for the Nile Estuary are presented. The impact of the sea level rise on the salinity transport in the Nile Estuary, using the same 3D model, is discussed. Mitigation measures to tackle the impact of the sea level rise are presented. The chapter also includes brief comparison between the results of the 2D model and the 3D model with respect to salinity transport.

Chapter 7: presents the main conclusions of the research and an outlook for further research.
2 Model concepts

This chapter is dedicated to present the governing equations related to the research and the numerical methods to solve these equations.

2.1 Governing equations

Considered as the cornerstone of fluid mechanics, the main equations that govern the motion of fluids are the continuity and Navier-Stockes equations which are derived from laws of conservation of mass and linear momentum. Shallow water equations are derived from Navier-Stokes equations to describe the flow in open channels.

2.1.1 Continuity and Navier-Stokes equations

The two basic conservation equations are mass conservation equation or continuity equation which expresses the conservation of the fluid mass and the momentum equation which is derived from the fundamental relations of dynamics (Hervouet, 2007).

A fluid of density $\rho$ is considered and $\vec{U}$ is the velocity vector, whose components are $U$, $V$ and $W$. The conservative form of the continuity equation and Navier-Stokes equations is given in the following:

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \text{div} (\rho \vec{U}) = 0 \quad (2.1)$$
Conservation of momentum:

\[
\frac{\partial (\rho \vec{U})}{\partial t} + \nabla (\rho \vec{U} \otimes \vec{U}) = \text{div}(\sigma) + \rho \vec{g} + \rho \vec{F}
\]  

(2.2)

Substituting with the mass conservation equation into the momentum equation, the non-conservative form of the momentum equation can be written as:

\[
\frac{\partial \vec{U}}{\partial t} + \vec{U} \nabla \vec{U} = \frac{1}{\rho} \text{div} \sigma + \vec{g} + \vec{F}
\]  

(2.3)

The conservative and the non-conservative forms (equations 3.2 and 3.3) are not identical in the case of compressible fluids (Hervouet, 2007). For Newtonian fluids (incompressible fluids), the stress tensor is expressed as:

\[
\sigma = -p \delta + 2\mu \overline{D}
\]

Where \( p \) is the pressure, \( \delta \) is the identity tensor, \( \mu \) is the coefficient of dynamic viscosity (equals \( \rho \nu \), where \( \nu \) is the coefficient of kinematic viscosity) and \( \overline{D} \) is the strain rate tensor and it is equal to \( \frac{1}{2}(\nabla \vec{U} + \nabla \vec{U}^\top) \).

The equations can be written in the non-conservative form in Cartesian coordinates assuming constant density and no source or sink term as follows:

Conservation of mass:

\[
\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0
\]  

(2.4)

Conservation of momentum:

\[
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \Delta U + F_x
\]  

(2.5)
2.1 Governing equations

\[
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \Delta U + F_y
\]  

(2.6)

\[
\frac{\partial W}{\partial t} + U \frac{\partial W}{\partial x} + V \frac{\partial W}{\partial y} + W \frac{\partial W}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - g + \nu \Delta W + F_z
\]  

(2.7)

The pressure \( p \) in equations 2.5, 2.6 and 2.7 is the sum of the hydrostatic and the dynamic pressure. \( F_x, F_y \) and \( F_z \) are momentum sink or source terms (e.g. Coriolis force).

2.1.2 Shallow water equations

Shallow water equations govern the free surface flows in shallow water. They are derived from Navier-Stokes equations considering some simplification hypotheses which are valid for a wide range of applications in surface water flow. The main hypotheses are as follows (Hinkelmann, 2005):

1. The wavelength should be much greater than the water depth (20-25 times bigger)

2. Hydrostatic pressure: This means that the acceleration arising from pressure counterbalances the gravity. That can be mathematically expressed as:

\[ p(x, y, z, t) = \rho g (Z_s - Z_b) + p_{atm} \]

Where \( Z_s \) is the elevation of the free surface, \( Z_b \) is the elevation of the bottom and \( p_{atm} \) is the atmospheric pressure.

3. Negligible vertical acceleration: this is to be in accordance with the hypothesis of the hydrostatic pressure.

4. Small bottom gradient

Taking the abovementioned hypotheses into account, the equations can be written as follows (non-conservative form and without source or sink term):
2 Model concepts

Conservation of mass:

\[ \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0 \]  (2.8)

Conservation of momentum

\[ \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} = - \frac{1}{\rho} \frac{\partial p}{\partial x} + v_h \frac{\partial^2 U}{\partial x^2} + v_h \frac{\partial^2 U}{\partial y^2} + v_v \frac{\partial^2 U}{\partial z^2} + F_x \]  (2.9)

\[ \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} = - \frac{1}{\rho} \frac{\partial p}{\partial y} + v_h \frac{\partial^2 V}{\partial x^2} + v_h \frac{\partial^2 V}{\partial y^2} + v_v \frac{\partial^2 V}{\partial z^2} + F_y \]  (2.10)

\[ 0 = - \frac{1}{\rho} \frac{\partial p}{\partial z} - g \quad \Rightarrow \quad p = \rho_0 g (Z_s - Z_b) + \rho_0 g \int_{Z_b}^{Z_t} \Delta \rho / \rho_0 \, dz \]  (2.11)

Where \( v_h \) and \( v_v \) are the horizontal and the vertical turbulent viscosity, respectively, \( \rho_0 \) is a reference density and \( \Delta \rho \) is the density difference.

2.1.3 Saint-Venant equations

Averaging the velocity over the depth in equation 2.8, 2.9 and 2.10 results the 2D form of the equations which are called the Saint-Venant equations. This is done by introducing the components of the velocity vector as follows:

\[ u = \frac{1}{h} \int_{Z_b}^{Z_t} Udz \quad \text{and} \quad v = \frac{1}{h} \int_{Z_b}^{Z_t} Vdz \]

The conservative form of the 2D Saint-Venant equations with source or sink term \((Sce)\) is as follows:

Continuity equation:

\[ \frac{\partial h}{\partial t} + \text{div} (h \vec{u}) = Sce \]  (2.12)
2.1 Governing equations

Momentum equation:

\[ \frac{\partial (hu)}{\partial t} + \frac{\partial}{\partial x} (huu) + \frac{\partial}{\partial y} (hu \nu) = -gh \frac{\partial Z_s}{\partial x} + hF_x + \text{div}(h \nu \text{grad } u) \quad (2.13) \]

\[ \frac{\partial (hv)}{\partial t} + \frac{\partial}{\partial x} (hu \nu) + \frac{\partial}{\partial y} (h \nu \nu) = -gh \frac{\partial Z_s}{\partial y} + hF_y + \text{div}(h \nu \text{grad } \nu) \quad (2.14) \]

The non-conservative form of the 2D Saint-Venant equations can be obtained by substituting the continuity equation into the momentum equation, therefore equations with source or sink term can be written as follows:

Continuity equation:

\[ \frac{\partial h}{\partial t} + u \text{grad } h + h \text{div } u = Sce \quad (2.15) \]

Momentum equations:

\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \nu \frac{\partial u}{\partial y} = -g \frac{\partial Z_s}{\partial x} + F_x + \frac{1}{h} \text{div}(h \nu_h \text{grad } u) \quad (2.16) \]

\[ \frac{\partial \nu}{\partial t} + u \frac{\partial \nu}{\partial x} + \nu \frac{\partial \nu}{\partial y} = -g \frac{\partial Z_s}{\partial y} + F_y + \frac{1}{h} \text{div}(h \nu_h \text{grad } \nu) \quad (2.17) \]

In the previous equations two additional terms could appear which are \((u_{sce} - u) \frac{Sce}{h}\) and \((\nu_{sce} - \nu) \frac{Sce}{h}\), where \(u_{sce}\) and \(\nu_{sce}\) are velocities at the source, however both terms can be considered as part of \(F_x\) and \(F_y\), therefore they are imbedded in \(F_x\) and \(F_y\). One of the most important sink or sink terms of momentum is the bed friction. Several formulas exist to calculate the bottom friction, for instance Manning formula which is as follows (Hervouet, 2007):
2 Model concepts

\[ F_x = \frac{u}{\cos(\alpha)} \frac{gn^2}{h^{4/3}} \sqrt{u^2 + v^2} \]  

(2.18)

\[ F_y = \frac{v}{\cos(\alpha)} \frac{gn^2}{h^{4/3}} \sqrt{u^2 + v^2} \]  

(2.19)

Where \( \alpha \) is the angle of bottom slope and \( n \) is Manning coefficient.

It is important to mention that the conservative and non-conservative forms are not equivalent in case of discontinuities (Hervouet, 2007).

2.1.4 Turbulence

Turbulence modeling can be carried out by the use of several models. These models can be categorized into three categories which are: statistical turbulence models, Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS) (Hinkelmann, 2005). The main parameter in modeling turbulence is the viscosity (\( \nu \)) which is the summation of the molecular viscosity (\( \nu_{mol} \)) and the turbulence viscosity (\( \nu_t \)), i.e. 

\[ \nu = \nu_{mol} + \nu_t. \]

However, \( \nu_t \gg \nu_{mol} \), therefore \( \nu_{mol} \) is usually assumed to be equal to zero and hence \( \nu = \nu_t \).

1. Statistical models

The models in this category are based on Reynolds equations or on a temporal averaging and lead to eddy viscosity principle (Hinkelmann, 2005). The following are examples to this category.

a. Constant viscosity

A constant value for eddy viscosity for the whole computational domain is used in this case (Hinkelmann, 2005). This model can be suitable when the flow is governed by the pressure and by advection (Hervouet, 2007).
b. Elder model

It is an algebraic model that can be used only with Saint-Venant equations, and it is better than the constant viscosity model. It takes into account the dispersion and calculates two different coefficients one along the flow \( K_l \) and one transverse to the flow \( K_t \). The two coefficients are dependent on the shear velocity (Hervouet, 2007) where:

\[
K_l = 6 u^* h \tag{2.20}
\]

\[
K_t = 0.6 u^* h \tag{2.21}
\]

Where \( u^* \) is the shear velocity and \( h \) is the water depth.

c. Mixing length models

These are algebraic eddy viscosity models in which the eddy viscosity is related to a characteristic length scale which is the mixing length \( (L_m) \). They allow spatial variation of turbulence (Hinkelmann, 2005). For shallow water flow, often constant values are used for the horizontal direction \( (\nu_{ht}) \) and a mixing length model for the vertical direction \( (\nu_{vt}) \) (Note: the subscript \( t \) in \( \nu_{ht} \) and \( \nu_{vt} \) refers to turbulence and the subscripts \( h \) and \( v \) refer to horizontal and vertical directions).

Prandtl mixing length model along the vertical calculates the vertical viscosities for velocity and tracer as follows (Hervouet, 2007):

\[
\nu_{vt} = f(R_i) L_m^2 \left[ \left( \frac{\partial U}{\partial z} \right)^2 + \left( \frac{\partial V}{\partial z} \right)^2 \right] \tag{2.22}
\]

\[
\nu_{vT} = f_T(R_i) L_m^2 \left[ \left( \frac{\partial U}{\partial z} \right)^2 + \left( \frac{\partial V}{\partial z} \right)^2 \right] \tag{2.23}
\]
2 Model concepts

Where

\[ R_i = - \frac{g}{\rho_0} \frac{\partial \rho}{\partial z} \left( \frac{\partial U}{\partial z} \right)^2 + \left( \frac{\partial V}{\partial z} \right)^2 \]  (2.24)

\[ L_m = \begin{cases} \frac{k z}{h} & \text{if } z \leq 0.2h \\ 0.2kh & \text{if } z > 0.2h \end{cases} \]  (2.25)

\( L_m \) is the mixing length parameter, \( R_i \) is the Richardson number, \( k \) is von Karman constant \((k = 0.41)\), and \( f \) and \( f_T \) are the dumping functions for velocity and tracer.

d. \( k - \varepsilon \) model

This model solves two additional transport equations, one for the turbulent kinetic energy \((k)\) and one for the turbulent kinetic dissipation \((\varepsilon)\). It is suitable for simulating transport of turbulent structures. For 3D simulation, \( k - \varepsilon \) equations are as follows (Hervouet, 2007):

\[ \frac{\partial k}{\partial t} + U_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \frac{\nu_i}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + P - G - \varepsilon \]  (2.26)

\[ \frac{\partial \varepsilon}{\partial t} + U_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \frac{\nu_i}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i} \right) + C_{\nu} \frac{\varepsilon}{k} \left[ P + (1 - C_{3\varepsilon})G \right] - C_{2\varepsilon} \frac{\varepsilon^2}{k} \]  (2.27)

Where \( P \) is the term for production of turbulent energy (Hervouet, 2007):

\[ P = \nu_i \left( \frac{\partial U_j}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{\partial U_i}{\partial x_j} \]  (2.28)

\( G \) is the source term due to gravity forces in the case of temperature gradient (temperature effect was ignored in this research):
2.1 Governing equations

\[ G = \beta \frac{V_i}{P_{rt}} g \frac{\partial T}{\partial z} \]  

(2.29)

Where \( \beta = \frac{1}{\rho} \frac{\partial \rho}{\partial t} \) and \( P_{rt} \) is Prandtl number. The turbulent viscosity and diffusivity can be calculated as:

\[ V_t = C_\mu \frac{k^2}{\varepsilon} \]  

(2.30)

\[ V_{tT} = C_{\muT} \frac{k^2}{\varepsilon} \]  

(2.31)

The relation between \( V_t \) and \( V_{tT} \) is usually expressed in Schmidt number (\( S_c \)) as follows:

\[ S_c = \frac{V_t}{V_{tT}} \]  

(2.32)

Schmidt number is usually assumed to be equal to 1.

2. Large Eddy Simulations (LES)

This method is based on the assumption that the large eddies larger than the grid size are directly solved by the mesh. A turbulence model is required for the eddies smaller than the grid size (Hinkelmann, 2005). LES is suitable for anisotropic turbulent structures. The standard model is Smagorinski model which is based on the mixing length model. The formulation of Smagorinski model is as follows (Hervouet, 2007):

\[ V_t = C_s^2 \Delta^2 \sqrt{2D_{ij}D_{ij}} \]  

(2.33)

Where \( C_s \) is a dimensionless coefficient (often \( C_s \approx 0.1 \)), \( \Delta \) is the grid size and \( D_{ij} \) is the strain rate tensor which is expressed as (Hervouet, 2007):
2. Model concepts

\[ D_{ij} = \frac{1}{2} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \]  \hspace{1cm} (2.34)

3. Direct Numerical Simulations (DNS)

In this method the mesh is refined up to the size of the smallest eddies. Therefore, the computational effort is extremely high and this method is limited to small Reynolds number and academic test cases (Hinkelmann, 2005).

2.1.5 Transport equation of tracers

Tracer represents a physical quantity contained in the water such as a contaminant, salinity, sediment or temperature. The tracer could interact with the flow hydrodynamics, in this case it is called active tracer, and an example of it is the salinity. If there is no interaction between the tracer and the flow hydrodynamics the tracer is then called passive tracer (Hervouet, 2007).

The main transport mechanisms in the surface water are: advection where the tracer is carried by the current and diffusion which depends mainly on the gradient of the concentration (Hinkelmann, 2005).

If \( T \) is the concentration of the tracer, and \( \nu_T \) is the diffusion coefficient (molecular, \( \nu_{molT} \), and turbulent, \( \nu_{tT} \)) and \( F_{source} \) is source term of the tracer, the conservative form of the transport equation can be written as follows (Hervouet, 2007):

\[ \frac{\partial (\rho T)}{\partial t} + \text{div} (\rho T \overrightarrow{U} - \nu_T \text{grad} (\rho T)) = F_{source} \]  \hspace{1cm} (2.35)

By using the mass conservation equation and substituting it in equation 2.18, the non-conservative form of the transport equation can be written as follows:

\[ \frac{\partial}{\partial t} T + \overrightarrow{U} \text{grad} T - \text{div} (\nu_T \text{grad} T) = Q \]  \hspace{1cm} (2.36)

Where, \( Q \) is the source or sink term.
The density can be calculated from the following equation of state:

$$\rho(S, \theta) = \rho_0 \left[ 1 - (7(\theta - \theta_{ref})^2 - 750S)10^{-6} \right]$$

(2.37)

$S$ is the salinity, $\theta$ is the temperature, $\theta_{ref}$ is the reference temperature of 4°C and $\rho_0$ is the reference density at zero salinity (equals to 999.72 kg/m$^3$).

### 2.1.6 Spatial variation of density in 2D

The 2D vertically averaged Saint-Venant equations (section 2.1.3) cannot represent the stratification resulting from the vertical variations of the density as a function of salinity or temperature (Hervouet, 2007).

However, and although it is rarely accounted for, it is possible to consider the horizontal variations in density by the method presented by Hervouet (2007). These variations cause two effects which are the dilatation of water and differential effects of gravity (Hervouet, 2007).

The dilatation of water is a secondary effect which can be ignored. The differential effects of gravity due to variations in salinity can become very important especially in estuaries, therefore they should be considered. Hervouet (2007) used Boussinesq’s hypothesis which takes the variations in salinity only in terms of gravity into account. The buoyancy terms in the Saint-Venant equation (the first term in the right hand side in equations 2.16 and 2.17), will become:

$$-\frac{1}{\rho_0} \text{grad} \left[ \rho g (Z_s - Z_b) \right]$$

Integrating this term between the bottom ($Z_b$) and the surface ($Z_s$) while considering the spatial variations of the density, that will produce two terms which are (Hervouet, 2007):
2 Model concepts

a. Barotropic pressure gradient:

\[- \frac{\rho}{\rho_0} \frac{gh}{\rho} \text{grad} \ Z_s\]

b. Baroclinic pressure gradient:

\[- \frac{g}{\rho_0} \frac{h^2}{2} \text{grad} \ \rho\]

The two terms replace the first term in the right hand side in equations 2.16 and 2.17.

2.2 Numerical modeling

Numerical modeling is the simulation of the reality with certain simplifications based on mathematical equations. Within the context of hydraulic engineering the process can be called as computational fluid dynamics (CFD). The process of computation can be classified according to Hirsch (2007) into the following steps (Figure 2.1)

1. Definition of the mathematical model: it includes defining the level of approximation to the reality which will be simulated

2. Discretization: it has two main components which are discretization of the space and discretization of the equations

3. Numerical scheme analysis: including the stability and the accuracy

4. Solution of the numerical scheme

5. Graphical representation of the results

Step 1 can be considered as the conceptual model, step 2 is the pre-processing phase, steps 3 and 4 are the processing phase and step 5 is the post-processing phase (Hinkelmann, 2005).
2.2 Numerical modeling

Figure 2.1: Schematic for the main procedures of CFD simulation system (after Hirsch (2007))

2.2.1 Discretization methods

The equations mentioned in the previous section 2.1 are mainly non-linear partial differential equations which have rarely an analytical solution, so discretization methods are needed to transform them to algebraic equations to be solved
2 Model concepts

(Hinkelmann, 2005). According to Hinkelmann (2005) the following requirements have to be achieved in the discretization methods:

- **Consistency:**
  Discretization error (the difference between the analytical solution and the numerical solution) should tend to zero.

- **Stability:**
  Oscillations should vanish in the course of the simulation; several techniques exist to achieve stability; however some of these techniques could lead to numerical diffusion. More information about stabilization techniques can be found in Hinkelmann (2005).

- **Convergence:**
  The numerical solution should converge towards the analytical solution (total error tends to zero).

- **Monotonicity**
  The value of each node should be between the values of its neighbors, i.e. no overshooting or undershooting should occur.

- **Conservation**
  The conservation of physical quantities (mass, momentum and energy) should be ensured. The conservation can be locally achieved (for each element) in some methods (e.g. Finite Volume Method) or globally (for the whole domain) in some methods (e.g. Finite Element Method).

2.2.1.1 Time discretization

The total simulation time is subdivided into number of time steps $\Delta t^n (n$ is the number of time steps), the time step could be constant or variable. If $e$ is a scalar or vector entity and $A$ is an operator which represents the spatial derivatives and other terms,
the time discretization can be carried out based on one of the following categories (Hinkelmann, 2005):

1. One-step methods:

In these methods, the solution function on the new time level \( n+1 \) is determined in one step depending on the current time step \( n \). Within this category one can define also explicit methods or implicit methods. In the explicit methods (Forward Euler Method), the unknowns on the time level \( n+1 \) depends only on the known values of the current time level \( n \) (Hinkelmann, 2005):

\[
\frac{e^{n+1} - e^n}{\Delta t^n} = A e^n
\]  

(2.38)

The explicit method has a limit to the time step size for stability reasons and its order of consistency is \( O(\Delta t) \). The stability criteria that have to be fulfilled by this method are the Courant-Friedrichs-Lewy or CFL condition (Courant number \( Cr \) must be less than one) and the Neumann criterion (Neumann \( Ne \) number must be less than 0.5). The Neumann criterion is generally not relevant in shallow water equations (Hinkelmann, 2005).

\[
Cr = \frac{(c + \nu)}{\Delta x / \Delta t} \leq 1
\]  

(2.39)

\[
Ne = \frac{\nu_t \Delta t}{\Delta x^2} \leq 0.5
\]  

(2.40)

\[
Ne = \frac{\nu_t \Delta t}{\Delta x^2} \leq 0.5
\]  

(2.41)

\( \nu \) is the flow velocity, \( \Delta x \) is the characteristic element length, \( \nu_t \) is turbulent viscosity, \( \nu_t \) is the turbulent diffusivity and \( c \) is the wave velocity, \( c = \sqrt{gh} \).

In the fully implicit method (Backward Euler Method), the unknowns in the new time level \( n+1 \) depend on each other leading to a system of equations and higher
2 Model concepts

computational effort, the order of consistency is \(O(\Delta t)\) and there are no limitation for the time step size (Hinkelmann, 2005):

\[
\frac{e^{n+1} - e^n}{\Delta t^n} = Ae^{n+1}
\]

(2.42)

\(e\) can also be computed between the current time level \(n\) and the new time level \(n+1\), this method is known as the Crank-Nicholson Method:

\[
\frac{e^{n+1} - e^n}{\Delta t^n} = \theta Ae^{n+1} + (1 - \theta) Ae^n
\]

(2.43)

This method is also implicit and \(\theta\) is Crank-Nicholson factor and can be between 0 and 1, however for stability reasons its preferred to be between 0.55 and 0.66 (Hinkelmann, 2005).

2. Multi-step methods:

In these methods, the solution function on the new time level \(n+1\) is determined in more than one step and depends on more than one time level. Example for these methods is the Operator-Splitting Method which is also implemented in the TELEMAC modeling system:

\[
\frac{\partial e}{\partial t} = A_1 e + A_2 e
\]

(2.44)

\[
\frac{e^{ni} - e^n}{\Delta t^n} = A_1 e
\]

(2.45)

\[
\frac{e^{n+1} - e^{ni}}{\Delta t^n} = A_2 e
\]

(2.46)

\(e^{ni}\) is an intermediate result, the level of consistency for Operator-Splitting Methods is \(O(\Delta t)\) (Hinkelmann, 2005). In the Operator Splitting Method, the terms of the differential equations are split up into hyperbolic and parabolic ones. Then a suitable
method can be used for each (Hinkelmann, 2005). For instance, the advective terms can be solved by the Method of Characteristics, and the diffusive and right hand terms can be solved by FEM.

2.2.1.2 Space discretization methods

In the following a description for the main space discretization methods is given.

1. Finite Difference Methods (FDM)

The FDM is one of the oldest methods to solve partial differential equations (PDE) (Hinkelmann, 2005). Mainly, it replaces the region over which the independent variables in the PDE are defined by a finite grid (also called a mesh) of points (Causon and Mingham, 2010), the grid can consist of rectangular or quadrilateral cells (Figure 2.2) (Hinkelmann, 2005). The values of the unknowns are approximated in the nodes which are located at the centers of the cells or at the intersection points of cell boundaries (Hinkelmann, 2005).

The main concept of the FDM is that the derivatives in differential equations are written in form of discrete quantities which results in simultaneous algebraic equations (Chung, 2008). The equations can be put in an explicit or implicit way taking into consideration the initial and boundary conditions (Hinkelmann, 2005). The partial derivatives in the PDE are approximated from neighboring values by using Taylor’s theorem (Causon and Mingham, 2010; Hinkelmann, 2005).

Three different ways can be used to obtain the first derivative of a function \(e\), namely: forward differencing (FD), backward differencing (BD) and central differencing (CD), they are formulated as follows:

\[
FD : \quad \frac{\partial e_{i,j}}{\partial x} = \frac{e_{i+1,j} - e_{i,j}}{\Delta x} + O(\Delta x) \quad (2.47)
\]

\[
BD : \quad \frac{\partial e_{i,j}}{\partial x} = \frac{e_{i,j} - e_{i-1,j}}{\Delta x} + O(\Delta x) \quad (2.48)
\]
Model concepts

\[ CD : \frac{\partial e_{i+1,j}}{\partial x} = \frac{e_{i+1,j} - e_{i-1,j}}{2\Delta x} + O(\Delta x^2) \]  \hspace{1cm} (2.49)

The second derivative is determined as follows:

\[ \frac{\partial^2 e_{i,j}}{\partial x^2} = \frac{e_{i+1,j} - 2e_{i,j} + e_{i-1,j}}{\Delta x^2} + O(\Delta x^2) \]  \hspace{1cm} (2.50)

FD and BD are of first order accuracy and CD and the second derivatives are of second order (Hinkelmann, 2005). According to Jourieh (2014) following are the main characteristics of FDM are:

a) Easy to be formulated and to be translated into a computer program, and suitable to show principal numerical effects

b) Suitable for simple geometries (structured-rectangular mesh) but difficult to be used for complex geometries or inner structures

c) Does not necessarily ensure mass or momentum conservation

d) Harmonic averaging is possible

e) Existence of problems with boundary conditions at interfaces with jumps in coefficients in 2D and 3D

Due to its disadvantages it is not widely used currently in space discretization however it is used with other methods for time discretization (Jourieh, 2014).

2. Finite Element Methods (FEM)

The FEM is the most general and efficient tool to solve general PDE numerically (Šolin, 2006), therefore it is used widely in environment water for several decades (Hinkelmann, 2005). It is based on subdividing the computational domain into finite elements (Figure 2.2); triangles or quadrilaterals in 2D and tetrahedra, prisms or bricks in 3D (Šolin, 2006).
2.2 Numerical modeling

The unknowns are defined at the nodes or at the center of the elements or the center of the edges (Hinkelmann, 2005). The solution is approximated through a set of polynomial shape functions (interpolation functions) by which the continuous domain is transformed into a discrete domain (Šolin, 2006).

The general concept is to replace an unknown function, which belongs to an infinite dimensional space, by an approximation defined on a finite dimensional space (Jourieh, 2014). Using the interpolation functions to approximate the solution over each element provides continuity of the solution within the element boundaries (Hinkelmann, 2005).

The main characteristics of FEM are (Jourieh, 2014):

a) Complex in terms of mathematical derivation

b) Suitable to represent complex boundaries and inner structures

c) Ensures the conservation of mass and momentum globally

d) Allows arithmetic averaging only and doesn’t allow harmonic averaging

Figure 2.2: Space discretization methods (after Hinkelmann, 2005)
2 Model concepts

3. Finite Volume Methods (FVM)

The FVM is suitable for the numerical simulation of many types of conservation laws (elliptic, parabolic or hyperbolic); it has been widely used in several engineering fields and in fluid mechanics (Eymard et al., 2000). It is often applied to structured grids; in case of rectangular grids the method is also called Integral-Finite-Difference Method (IFDM), since more than a decade it has been also used for unstructured grids (Hinkelmann, 2005).

The space is divided into control volumes, the shape of the control volume is arbitrary however often the same grid as in the FEM (Figure 2.2) can be used (Jourieh, 2014). The control volume can be constructed in three ways which are cell-centered (Figure 2.3 left), node-centered based on the verticals on the midpoints of the edges (Figure 2.3 middle) and node-centered based on the polygons of elements centers and edges centers (Figure 2.3 right) (Hinkelmann, 2005).

![Figure 2.3: Methods of control volume construction for the FVM (after Hinkelmann, 2005)](image)

The main idea of the FVM is integrating the differential equations in their conservative form over all control volumes (Hinkelmann, 2005). Therefore, the FVM ensures local conservation (Eymard et al., 2000).

In the following the main characteristics of FVM are given (Jourieh, 2014):
a) Complex mathematical derivation (more complex than FDM but less complex than FEM)

b) Suitable for complex boundaries and complex inner structures

c) Ensures the conservation of mass and momentum locally and globally

d) Possibility of harmonic averaging

e) Very suitable for the approximation of sharp fronts

### 2.2.2 Modeling aspects

#### 2.2.2.1 Model selection

The selection of the suitable numerical model is an important step in the modeling process and it affects the final results greatly. The model should be capable of meeting all or most of the study objectives (Ji, 2008). Several criteria have to be considered to select the appropriate model such as: objectives of the study, time and resources needed, data availability, technical expertise, model availability and familiarity, documentation quality of the model and technical support for the model (Ji, 2008).

Simplicity of the model is also a very important criterion in the model selection, the model should be as simple as possible, however the selection of a too simple model may affect the accuracy, on the other hand a very complex model may increase the cost and misdirect the resources (Ji, 2008).

To select an appropriate model, some key questions should be answered (Ji, 2008):

a) What are the key processes that should be modeled (hydrodynamic processes or transport processes)?

b) Are there water quality concerns and what are these concerns?

c) What are the spatial and temporal scales suitable for modeling the key processes?
2 Model concepts

d) How will the model be utilized in supporting decision-making?

2.2.2.2 Classification of numerical models

According to Ji (2008), numerical models can be classified based on the following criteria:

a) Numerical method: FDM, FEM, FVM, etc.

b) Grid type: Cartesian grid, curvilinear grid, unstructured grid, etc.

c) Time-differencing scheme: explicit, implicit, semi-implicit, etc.

d) Spatial-differencing scheme: upwind, central difference, flux-corrected transport, etc.

In addition, models can be classified according to the number of dimensions to 1D, 2D and 3D models (Figure 2.4):

One-dimensional models (1D): 1D is the simplest model type; it considers only one dimension from the system (mostly the dimension in the flow direction and ignoring the vertical and lateral variations), it computes the water depth and an average velocity at each node in the grid. 1D models are simple and fast, however they doesn’t describe details of horizontal or vertical velocity (Jourieh, 2014).

Two-dimensional models (2D): 2D models simulate two dimensions from the system (mostly the two components of the horizontal direction). They give more details about the physical processes. They can take into consideration the horizontal variability of the flow. Triangular or quadrilateral elements can be used; triangular elements are better in case of complex boundaries or inner structures (Jourieh, 2014).

Three-dimensional (3D) and 2.5 dimensional (2.5D) models: In these models the three dimensions of the system are modeled, if the grid in the vertical direction is structured (several replications from the 2D mesh over the vertical) this is called 2.5D model, and when unstructured grid over the vertical is used that can be called fully 3D model.
Both types are usually referred as 3D models and the term 2.5D is rarely used (Jourieh, 2014).

The physical processes and the configuration of the computational domain affect the choice of the model dimensions, for instance in case of a very narrow river a 1D model could be sufficient while in estuaries as there are vertical stratification and horizontally variable flow a 3D model is essential.

### 2.2.2.3 Spatial and temporal resolution of the model

Spatial and temporal resolutions are important characteristics and affect the construction of the model. They are related to each other; changing the spatial resolution could require changing the temporal resolution to achieve stability, accuracy and efficiency (Ji, 2008). The choice of spatial resolution depends mainly on the extent to which spatial gradients occur and the extent to which these variations should be considered (Ji, 2008).

The main two rules that govern the selection of spatial and temporal resolutions according to Ji (2008) are:

a) Fine resolution decreases the numerical error, but too fine resolution can increase the study costs and in some cases without increasing the accuracy.

b) Coarse resolution may decrease the costs, but too coarse resolution may decrease the accuracy.

Some aspects should be considered when choosing the temporal resolution such as: the temporal resolution should ensure the stability criteria (e.g. for explicit methods $Cr \leq 1$, for implicit methods $Cr \geq 1$ but not too high), the simulation should be long enough to eliminate the impact of the errors in the initial conditions, the size of the study area and the physical processes of interest (Ji, 2008).
2 Model concepts

Verification, calibration and validation are three steps to test the model, the order of carrying out these three steps differs in the literature in addition the term validation sometimes is used instead of verification and the other way around, however the most common definitions for these terms are as follows:

**Verification:** It is to prove the correctness of the numerical results and this is carried out by comparing the results with analytical solution, however analytical solutions are only available for simple cases (Hinkelmann, 2005). Plausibility tests can also be used
for verifying the model, an example for that is checking the mass conservation (Jourieh, 2014). Model verification is carried out by the model developer.

**Calibration:** In the calibration, the model parameters are adjusted in such a way that the model results agree as good as possible with experimental results or field data. The main parameters that have to be calibrated in surface water flow are the bottom friction coefficient and, to a certain extent, turbulent viscosity, for the transport process in surface water the turbulent diffusivity has to be calibrated. The calibration is often done manually based on the experience of the modeler but some automatic procedures also exist (Hinkelmann, 2005).

**Validation:** The model is validated by using it in simulating independent data set (data that are not used in the calibration). Validation can be done by experimental data or by field data, however field data are desirable because experimental data reflect only a single phenomenon and in controlled conditions. However, the availability of field data is often a big obstacle (Hinkelmann, 2005).

2.2.2.5 **Sensitivity analysis**

Sensitivity analysis is used to examine the changes in the model results due to changes in the model parameters and to check the most influential parameters (Ji, 2008). This analysis is very important in case of the lack of field data for validating the model (Hinkelmann, 2005). Sensitivity analysis is carried out by changing one parameter at a time and compute the change of the results (Ji, 2008). It helps in assessing the relationship between the uncertainty in the parameter value and the model results (Ji, 2008). The most important parameters that require sensitivity analysis in surface water are bottom friction and, to a certain extent, turbulent viscosity and turbulent diffusivity.
3 Modeling system

A description of the modeling system used in the research in addition to the pre- and post-processing tools is briefly presented in this chapter.

3.1 TELEMAC-MASCARET modeling system

The TELEMAC-MASCARET system is a modeling tool that is used in the field of free-surface flows in both seas and rivers, it can be applied either to large extent areas (on a sea scale) or to smaller domains (coasts and estuaries) (LNHE, 2013). The main applications are related to the marine environment, such as investigations of currents being induced either by tides or density gradients with or without the influence of wind or air pressure, the impact of sewer effluents, the study of thermal plumes and sedimentary transport. It can be also used to study the thermal plumes in rivers and the hydrodynamic behavior or natural or man-made lakes (LNHE, 2007, 2013).

The system was developed initially by the Laboratoire National d'Hydraulique, a department of Electricité de France's Research and Development Division. TELEMAC-MASCARET is currently managed by a consortium consists of the following organizations: Artelia (formerly Sogreah, France), Bundesanstalt für Wasserbau (BAW, Germany), Centre d’Etudes Techniques Maritimes et Fluviales (CETMEF, France), Daresbury Laboratory (United Kingdom), Electricité de France R&D (EDF, France), and HR Wallingford (United Kingdom) (LNHE, 2014). The TELEMAC-MASCARET system has a complete processing chain to calculate the motion of water, tracer and sediment in the fluvial, coastal, estuarine, lacustrine and groundwater domains (Hervouet, 2000). TELEMAC-MASCARET modeling system is an open source since 2010.
3 Modeling system

TELEMAC-MASCARET modeling system consists of several modules which use algorithms based mainly on FEM. The main modules of the system are (LNHE, 2014):

- ARTEMIS: wave agitation in harbors
- MASCARET: 1D flows
- TELEMAC2D: 2D flows - Saint-Venant equations (including transport of a diluted tracer)
- TELEMAC3D: 3D flows – shallow water equations (including transport of active or passive tracers)
- TOMAWAC: wave propagation in the coastal zone
- SISYPHE: 2D sediment transport
- SEDI-3D: 3D suspended sediment transport
- DREDGESIM: simulation of dredging operations
- ESTEL2D and ESTEL3D: 2D and 3D underground saturated and not-saturated flow simulation.

In addition, it is also linked to Delft3D to simulate water quality.
In this research only the TELEMAC2D and TELEMAC3D (Figure 3.1) were used and hereafter is more description for both of them.

### 3.1.1 Common characteristics of TELEMAC2D and TELEMAC3D

TELEMAC2D and TELEMAC3D can take the following processes into account (LNHE, 2007):

- bottom friction
- influence of the Coriolis force
- sources and sinks for fluid momentum within the flow domain
- influence of weather elements: wind and air pressure
3 Modeling system

- influence of temperature and/or salinity on density
- dry areas in the computational domain: tidal flats
- consideration of the thermal exchanges with the atmosphere
- Simple or complex turbulence models taking the effects of the Archimedean force (buoyancy) into account. The available turbulence models are: constant viscosity, Elder, mixing length, $k-\varepsilon$, $k-\omega$ models and Large Eddy Simulation (LES) using Smagorinsky model for small eddies
- current drift and diffusion of a tracer with generation or disappearance terms

TELEMAC2D and TELEMAC3D allow the choice among a variety of discretization and stabilization techniques and fast solvers. The stabilization techniques are: operator splitting method, Method of Characteristics (trajectories); centered semi-implicit scheme with Streamline Upwind Petrov-Galerkin (SUPG) scheme; conservative scheme with SUPG; PSI scheme and N scheme (Jourieh, 2014). They can use the same or different time step for the flow and transport, in addition sub-iterations can be carried out to treat the non-linearities.

The available solvers are: PCG (Preconditioned Conjugate Gradient, symmetric matrices), BICGSTAB (Stabilized Biconjugate Gradient, non-symmetric matrices), GMRES (Generalised Minimum RESidual, non-symmetric matrices) (Jourieh, 2014).

TELEMAC2D and TELEMAC3D have been applied for numerous studies in fluvial and maritime hydraulics (Hervouet, 2007; Hinkelmann, 2005; Jourieh, 2014; Jourieh et al., 2009; Mahgoub and Hinkelmann, 2012; Mahgoub et al., 2015; Mahgoub et al., 2012; Mahgoub and Hinkelmann, 2012; Mahgoub et al., 2015).

3.1.2 TELEMAC2D modeling system

TELEMAC2D uses mainly FEM (recently FVM was added also to the code of the model) for solving the non-conservative form of 2D Saint-Venant equations (equations 2.15 - 2.17) and transport equation (equation 2.36) (LNHE, 2007).
3.1 TELEMAC-MASCARET modeling system

For solving the PDEs, the algorithm can use one step method (e.g. SUPG, PSI scheme and N scheme) or it can use fractional step method (2 steps). In the first step the advection terms are calculated using the Method of Characteristics. In the second step the propagation, the diffusion and the source terms are calculated using the FEM.

At each node of the grid, TELEMAC2D calculates the water depth and the velocity averaged over the vertical, in addition to the tracer concentration if any (LNHE, 2007).

TELEMAC2D can be used for several applications. In the maritime environment, it is implemented in simulating the port structures, the effects of dikes or dredging and the impact of waste discharged from a coastal outfall. In river applications it can be adopted in studies related to the impact of construction works (bridges, weirs, groynes), dam breaks, flooding or the transport of decaying or non-decaying tracers (LNHE, 2007).

3.1.3 TELEMAC3D modeling system

TELEMAC3D solves Navier-stokes equations and continuity equation in their non-conservative form (equations 2.4 – 2.7), with or without the hydrostatic pressure assumption, and the non-conservative form of the transport equation of intrinsic quantities (e.g. contaminants, salinity and temperature) (equation 2.36).

The basic algorithm is based on the fractional step method where the solution of the PDEs is divided into three computational steps (three fractional steps). In the first step, the advected velocity components are computed by only solving the advection terms in the momentum equations. In the second step, the new velocity components, from the advected velocities, are calculated in addition to the diffusion terms and the source terms in the momentum equations. In the third step the water depth from the vertical integration of the continuity equation and the momentum equations is computed only including the pressure-continuity terms (Hervouet, 2007).

In case of non-hydrostatic simulation the equations can be first handled as a hydrostatic pressure distribution, and then a fourth step based on the satisfaction of the continuity equation (2.4) is performed in order to calculate the dynamic pressure.
3 Modeling system

which is added to the hydrostatic pressure as a correction term in the non-hydrostatic case (Hervouet, 2007). It is important to mention that TELEMAC3D basic algorithm uses the sigma transformation to overcome the problem of the variation of the domain with time (due to the variation of the free surface), this may cause artificial density currents due to numerical errors (Decoene and Gerbeau, 2009).

The main results at each point are the velocity in all three directions, the water depth and the concentrations of transported quantities (Janin et al., 1992), and the dynamic pressure in case of non-hydrostatic pressure. TELEMAC3D provides a weak coupling between flow and transport.

TELEMAC3D is suitable for simulating flow and transport in applications with variations in the vertical direction, such as density-induced flow, currents induced by tides and influence of the wind (LNHE, 2013). TELEMAC3D can be applied in many fields, especially those related to rivers, seas, estuaries, and lakes.

3.2 Pre- and post-processing tools

Pre- and post-processing includes the generation of the grid, setting the boundary conditions and visualization of the results. TELEMAC2D uses mainly triangular grids however quadrilateral elements can be used also (Hinkelmann, 2005). Structured grids or unstructured grids can be used with TELEMAC2D; however for complex domains unstructured grids are better. The grid can be refined locally when needed (e.g. in case of very steep bottom slope or very narrow width).

TELEMAC3D constructs the 3D grid from a 2D unstructured horizontal grid generated from a suitable grid generator by replicating the horizontal grid over the vertical according to the required grid resolution. It uses a structured layered grid in the vertical direction following the terrain.

Hereafter is a brief presentation of the pre- and post-processing tools that were used in this research.
3.2 Pre- and post-processing tools

3.2.1 MATISSE

MATISSE is part of the TELEMAC-MASCARET modeling system. It is used as a pre-processor to generate 2D triangular grids. MATISSE includes the bathymetry of the domain and its outlines. In addition, it includes the boundary conditions of the domain. It uses an automatic operation to generate the grid, however the user can adapt the grid manually. The grid generation based on linear interpolation between the nodes (Abderrezak, 2009).

MATISSE provides an easy tool to generate the mesh and to visualize it; however it has only very limited options for adapting the grid. The main outputs of MATISSE are a geometry file which contains the coordinates and the elevation of each node and a boundary conditions file which contains the type of boundary condition for each node in the grid.

3.2.2 JANET

JANET is a tool for creating and editing grids for different numerical models, special support are given to: Marina, TELEMAC, UnTRIM and Swan modeling systems (Smile Consult, 2005). It has a user-friendly interface written with Java programing language (Jourieh, 2014). JANET supports unstructured FEM grid and structured FDM grids (Smile Consult, 2014). Janet is a commercial software.

The main features of JANET are (Lippert and Sellerhoff, 2005):

- It supports triangular, quadrilateral and hybrid grids.
- The method of “constraint edges” can be used to define the geometric constraints.
- It provides many grid generation techniques (e.g. barycentric refinement, advancing front refinement).
- It contains several optimization methods for unstructured grids (e.g. Laplacian smoothing, orthogonality optimization for UOG).
3 Modeling system

3.2.3 POSTEL3D

POSTEL3D is considered as an intermediate module in the TELEMAC-MASCARET modeling system. By the mean of POSTEL3D, 2D vertical or horizontal cross sections can be extracted from the 3D result file of TELEMAC3D. The resulting cross sections can be visualized by several post-processors such as RUBENS (LNHE, 2013).

3.2.4 RUBENS

RUBENS was the default post-processor of TELEMAC-MASCARET modeling system. It visualizes the results and allows viewing it in several ways such as contour plots, time histories and cross sections (Jourieh, 2014). RUBENS gives the possibility of carrying out some calculations on the results such as calculating a new variable from the variables calculated by TELEMAC (LNHE, 2014) (e.g. calculating the velocity direction from the magnitude of the velocity in the x- and y-directions).

3.2.5 Blue Kenue

Blue Kenue is a pre- and a post-processor which can be used to generate FEM meshes along with the geometry file and the boundary conditions file; in addition it is used as a visualization tool for the results.

It is based on EnSim technology which provides a tool to prepare and analyze the data of numerical models in the field of hydraulics. It was developed by Laboratoire National d'Hydraulique of Electricité de France initially as a post-processor for the TELEMAC family. Recently, the pre-processing options was added to it and it can import and export data from other grid generators such as ADCIRC, SMS, INRS Eau HydroSim and the TriGrid (CHC, 2010). Blue Kenue is a freeware.
4 Study area

Although some test cases were analyzed, the research focused mainly on the last part of Rosetta branch of the Nile River. So, in this chapter a description of the study area is presented and the description of the test cases will be described in the related parts in the following chapters.

4.1 Location

As mentioned in section 1.4.1, the Nile in Egypt is divided before its end into Rosetta branch and Damietta branch where the discharge of the two branches is controlled through several water structures, the last two control structures are Edfina barrage and Farascour barrage on Rosetta branch and Damietta branch respectively.

The reach under study is the last reach of Rosetta branch of the Nile River, starting from Edfina barrage and ends with the Mediterranean Sea (the north-west part of the Nile Delta). The reach is located between 31.32° and 31.45° north and 30.34° and 30.53° east. It is the discharge point of the Rosetta branch of the Nile River on the Mediterranean Sea (Figure 4.1).

4.2 Geomorphology

The Nile Delta was formed mainly from the sediments carried by the Nile flood in the last 6000-8000 years before the construction of the High Aswan Dam. These sediment deposits consist of high fertile clay layers (Sneh and Weissbrod, 1973) and its thickness ranges from 5 m along the fringes with the desert to 20 m in the Delta center (Sharaky et al., 2007).
4 Study area

The Nile was divided into seven branches in the Delta and it had six by around the 12th century, the tributaries silted up and only Rosetta and Damietta branches remained (Torres, 2012). According to Stanley and Warne (1998) cited by Torres (2012), the deposits in the Nile Delta are mainly Nile silts, sands, sandy clay, clay and gravel.

As it is located in the northern eastern part of the Nile Delta, Rosetta is a low lying area with elevations ranging from -1 m to 3 m above sea level. The soil in the area is mostly formed as a result to the alluvial sediments from the River Nile and the Marine alluvial that is ranged from coarse textured soil to very heavy textured soil. In addition to small areas of sand dunes, which are declining because of the use of sand dunes in some low land areas to be suitable for agriculture, and in some cases it’s used as a construction material.

Figure 4.1: Map of the reach under study (http://maps.google.com)
4.3 Land use

The location of the area near the Mediterranean Sea affected the salinity of the soil. The soil salinity ranged between normal saline soils to very high saline soils except the area near the Nile River which is clayey soil with very low salinity.

The high content of salts in the soil affected its productivity greatly, so large areas in Rosetta can be considered as very weak productivity lands. The high productivity lands can be found in the areas close to the Nile River.

The dominant land use in Rosetta is agriculture use representing about 90% of the total area.

4.4 Climate, hydrology and irrigation

Throughout Egypt, days are commonly warm or hot, and nights are cool. Egypt has only two seasons: a mild winter from November to April and a hot summer from May to October. The only differences between the seasons are variations in daytime temperatures and changes in prevailing winds. Generally, the northern coast has lower temperature than the other parts of Egypt, in addition to bigger amounts of rainfall. The rain falls in the winter season only mainly from December to March.

According to Köppen-Trewartha classification, the Nile Delta and Egypt in general are classified as dry desert where the annual evaporation rate exceeds the precipitation. Average temperature is about 18°C and the specific temperature is above 30°C in summer. Average annual precipitation is less than 200 mm/year at the coast and less than 100 mm/year in the Nile Delta. The potential evapotranspiration ranges between 600-1100 mm/year (Torres, 2012).

The River Nile is the main source of water for Rosetta, as it is the case in the whole country, through the Rosetta branch. The dependency on the Nile water in the area is not only due to the sustainability of this resource, but also due to the high salinity of the groundwater because of the saltwater intrusion phenomenon. The salinity of the
groundwater is ranging from 5,000 ppm to more than 20,000 ppm. The only exception is the wells that are near the River Nile.

The average discharge during the year is 83.6 m$^3$/s and the average water level at the downstream (D.S.) is 0.37 m above 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.

Irrigation canals are distributing the Nile water to the agriculture lands in the different locations. The allocation of the water is done by discharge control through several control structures. The secondary canals are under a water rotation system. All the canals ended up with drains to prevent flooding of agriculture lands and for emergency situations (Torres, 2012). Flood irrigation is the main type of irrigation in the Nile Delta, a considerable part of the irrigation water ended up in the drainage system where the water is reused (there are some official uses and non-official uses).

### 4.5 Bathymetry and coastal erosion

In such a big domain (about 30 km length), variations in the depths and widths are expected (Figure 4.2). The water depth ranges from 2.30 m to about 26.5 m with a mean value of about 10 m. The width of the domain ranges from 200 m to 950 m with a mean value of 500 m.

The bathymetry of the reach under study was created from two data sources. The first source was contour maps which were digitized with the help of ArcGis. Although the maps are from the 1970s but only minor changes on the bathymetry could be expected, because the low flow velocity and the low sediment load. The second source was measured cross sections which were measured by the National Water Research Center in Cairo, the sections were every about 2000 m.
4.5 Bathymetry and coastal erosion

The Delta coast erosion was first observed in 1898, but it accelerated after the construction of the Aswan High Dam, the dam changed the hydraulic regime of the Nile downstream and it decreased the sediments in the Nile water, this caused imbalance between the sea waves and the Nile sedimentation which caused accelerated erosion in the Nile Delta coast (Torab, 2006).

The erosion of the coast at Nile Estuary in Rosetta started in year 1900 after the construction of the Aswan Low Dam. About 879 and 1282 meters from the western and eastern sides of the mouth respectively were lost between 1900 and 1964; the average rate is about 13.7 and 20.0 m/year for the western and eastern side respectively. Then the erosion increased after the construction of Aswan High Dam.

Figure 4.2: Cross sections at different positions through the domain
where the erosion rate increased to be 95.3 and 124.8 m/year for the western and eastern sides of the mouth (Torab, 2006). The changes are shown in Figure 4.3.

The construction of sea walls along the coast and around the mouth of Rosetta branch helped in stopping any further erosion of the coastal line.

Figure 4.3: Coastal line erosion at Rosetta Branch of the River Nile in the period from 1900 to 2006 (after Torab, 2006)
5 Two-dimensional surface water model

As a first step in this research, the last reach of Rosetta branch of the Nile River was modeled in 2D using TELEMAC2D modeling system (section 3.1.2). Hereafter is a description for the simulation process and the results of this model. In addition, the results of some test cases carried out to verify the model are also presented. The results of sections 5.2, 5.3.1, 5.4.2, 5.5 and 5.6 are published in Mahgoub et al. (2012), and the results of section 5.4.1 are published in Mahgoub and Hinkelmann (2012).

5.1 Model setup and parameters

The pre-processing stage is very important to include the bathymetry of the river and for setting the boundary conditions types (closed boundary or open boundary). The MATISSE grid generator was used for the pre-processing stage (see section 3.2.1).

Because of its complex geometry and bathymetry, a triangular grid was generated for the reach under study (Figure 4.1). The discretization length of the elements was 40 m in most of the domain. The grid was refined in several parts in the domain, where the bottom level has a steep slope and the parts where the river has a small width, for such parts a finer grid with 20 m discretization length was generated. The ratio between the coarse and the fine grid elements was chosen to be small (2:1) to ensure smooth transition in the grid and for having a feasible number of elements. The total number of nodes was 19,448 and the total number of elements was 36,669 (Figure 5.1).

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 were considered the only two open boundaries in the domain and all the other boundaries, mainly the banks, are closed. This was also introduced by the use
5 Two-dimensional surface water model

of MATISSE; an imposed water level at the D.S. boundary and imposed discharge at
the U.S. boundary were given.

The flow of the river and the water levels of the sea are fluctuating during the year as
mentioned in section 4.5. However, according to the data, an average flow value is
dominant in most periods of the year (83.6 m$^3$/s), so this value was used in the
simulations. For the mean flow conditions an average value for the sea level of 0.37 m
+msl was used. The fluctuations in the sea level and its impact on the flow regime
were simulated by using the minimum and maximum values of sea level in the
calculations of the boundary conditions. In addition the impact of sea level rise was
also investigated. The sea level rise will be discussed in section 5.5.

As mentioned in section 1.4.1, the Nile in Egypt is fully controlled with several
control structures starting from Aswan High Dam which protects the country from
floods. Therefore, no flood events are expected D.S. Aswan High Dam, and this is
valid also for the reach under study. The increase in the flow and hence the water level
can rarely occur, it happens when a very high flood which exceeds the capacity of
Nasser Lake takes place. In this case more flow from Aswan High Dam is released to
be discharged to the sea.

A Manning friction coefficient of 0.022 m$^{1/3}$/s (Mahmoud et al., 2006) and a simple
turbulence model with constant value ($\nu = 0.01$ m$^2$/s) were chosen (section 2.1.4).
Streamline Upstream Petrov-Galrkin method (SUPG) was used as the stabilization
method for the FEM, the centered semi-implicit scheme was chosen for time
discretization, and the solver applied was the Generalized Minimum RESidual method
(GMRES) which is suitable for the non-symmetric matrices (section 3.1.1)
(Hinkelmann, 2005).

The simulations were carried out with a time step of 5 seconds. The Courant number
ranged from 0.5 to 4.1. As the method used is semi-implicit in the case, there are no
limitations for the Courant number to achieve stability, however it is preferred that the
largest Courant number is not too high.
Figure 5.1: Bathymetry of the river and the grid at different positions through the domain
5.2  Hydrodynamics

5.2.1  Reference case

A total simulation time of three days was carried out assuming an initial condition of zero velocity, initial water level of 0.37 m +msl and considering the mean flow conditions (section 5.1). This simulation was carried out to reach a steady state condition which was later chosen as initial condition for all the other calculations and scenarios. The steady state condition was achieved after about two and a half days as shown in Figure 5.2 which shows the water level versus time in several positions in the domain.

![Figure 5.2: Time series for the water level at three positions in the domain (Mahgoub et al., 2012)](image)

At the D.S. boundary, there were almost no fluctuations except minor fluctuations in the beginning of the simulation because the water level was imposed at this boundary. The fluctuations in the water level increased in the direction of the U.S. boundary, but it diminished with time till reaching almost no fluctuations condition or in other words
a steady state condition. The fluctuations took place at the beginning of the simulation because the initial condition assumed a zero velocity in the whole domain which differs much from the real velocity, so the model fluctuated and it required time to reach the real velocity. In addition, adding a flow suddenly (at time zero) at the boundary causes such fluctuations, so a gradual discharge can decrease the fluctuations, however it will not affect the final results.

The water level did not change much through the domain; it ranged from 0.37 m +msl at the D.S. side to 0.373 m +msl at the U.S. side (Figure 5.3) which means that the free surface slope was very small close to zero.

Figure 5.3: Water level in the whole domain.
The same behavior concerning the fluctuations was also noticed with respect to the velocity, however in this case no fluctuations were found at the U.S. boundary as the flow, and hence the velocity, is imposed there (Figure 5.4). It can be seen also in Figure 5.4 that the model started the calculations from zero velocity as an initial condition.

The range in the flow velocity variations was higher due to the change in the flow cross section along the reach; however the magnitude of the velocity was very small. The maximum velocity was at the D.S. boundary with a value of about 7.8 cm/s and the velocity decreased to reach zero near the banks of the river (Figure 5.5). This slow flow is due to the fact that the discharge allowed to pass through the domain is very small (as it is considered as loss from the water budget of the country because it is being discharged into the sea for navigational and environmental purposes) while the flow cross section is big.
5.2 Hydrodynamics

The meandering of the river in this reach caused some eddies usually after each curvature (Figure 5.6); however the flow velocity of these eddies was generally very small (about 2 cm/s). These eddies in addition to the velocity vector shown in Figure 5.6 are the reason for unsuitability of 1D model in this case study.

The eddies are expected in such cases, however it is important also to mention that the presence of sharp curves in the model, which is not the case in the reality, could enhance the phenomena of eddies formation.

Figure 5.5: Flow velocity in the domain (Mahgoub et al., 2012)
The velocity of the eddies did change when using other turbulence models and their behavior changed also. In Figure 5.7, the variations in the flow velocity when using Elder and k-ε turbulence models were compared with the constant viscosity model. The average velocity was 0.018, 0.019 and 0.020 m/s for constant turbulent viscosity, k-ε and Elder model, respectively. Elder model showed less fluctuations and higher average velocity, but the increase in the velocity was considerably low.

Concerning the behavior of the eddies, the Elder model showed a very close behavior to the one of the constant viscosity model. In the case of k-ε model the configuration of the eddies was different, three zones of eddies were formed instead of one zone as in the other two models (Figure 5.8). Thereof, k-ε model should be used for better simulation of the eddies.
5.2 Hydrodynamics

Figure 5.7: Variations of the velocity due to changing the turbulence model

Figure 5.8: Velocity vector showing eddies at one position in the domain using: (a) constant viscosity turbulence model, (b) k-ε turbulence model and (c) Elder turbulence model
5.2.2 Changes in the flow conditions during the year

The fluctuations in the discharge and the sea level during the year affect 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 Figures 5.9 and 5.10; higher velocities were recorded for lower water levels. The fluctuations in the velocity values until reaching a steady state were much smaller at the U.S. boundary compared to the D.S. boundary, as the discharge value was given to the model at the U.S. side.

Figure 5.9: Flow velocity at the D.S. boundary due to changing sea level (Mahgoub et al., 2012)

The simulations in the three cases investigated here used the results of the steady state simulation of the previous section as initial conditions, therefore in Figures 5.9 and 5.10 no fluctuations in the case of sea level of 0.37 m +msl occurred, because it is the same as the initial conditions (previous steady state). The fluctuations in the other two cases are due to the initial conditions and the boundary conditions. In the case of the D.S. boundary (Figure 5.9), the real velocity differs from the initial velocity given to the model, and therefore some fluctuations occurred at the beginning until reaching the final velocity. In the case of the U.S. boundary (Figure 5.10), an imposed value for the
flow and hence the velocity was given (boundary condition), so the model was forced to use this value, therefore the fluctuations were higher than in the U.S. boundary.

Figure 5.10: Flow velocity at the U.S. boundary due to changing sea level.

5.3 Variations of bottom friction and turbulence model

The sensitivity of the model to changes in the friction coefficient and the turbulent viscosity was examined using the reference case. Hereafter the results of the variations are presented.

5.3.1 Bottom friction

Using the same model, two Manning coefficients \( n \) of 0.01 and 0.03 m\(^{1/3}\)/s were compared to the reference case with \( n = 0.022 \) m\(^{1/3}\)/s (section 2.1.3). According to the model results, the effect of changing the 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 reference case, that means a change of 0.5% (with respect to the mean water level) which is insignificant impact. This effect decreases when moving from the U.S. to the
D.S. boundary (Figures 5.11 and 5.12) because the water level is controlled at the D.S. boundary. The very slow flow velocities in the domain are one reason to the small sensitivity of the friction coefficient.

Figure 5.11: Variations of water level near the U.S. boundary due to changing Manning coefficient (m$^{1/3}$/s) (Mahgoub et al., 2012)

Figure 5.12: Variations of water level near the D.S. boundary due to changing Manning coefficient (m$^{1/3}$/s)
The change in the flow velocity was reversely related to the change of the friction coefficient; higher flow velocities occurred for a lower Manning coefficient, the change at the D.S boundary was +0.003 and -0.001 m/s for Manning coefficients of 0.01 and 0.03, respectively, corresponding to 3.8 % and -1.3 % change in the flow velocity. This change differs throughout the domain but with the same trend (Figures 5.13 and 5.14). The relative change in the velocities due to changing the bottom friction was small, but the absolute change was, indeed, very small.

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, the same behavior was also noticed with respect to the change in the water level.

The impact on the flow velocity was higher than on the water level, but in both cases the impact was very small. Overall, the model was found to be not sensitive to the changes in friction coefficient.

Figure 5.13: Variations of flow velocity near the U.S. boundary due to changing Manning coefficient (m^{1/3}/s)
5.3.2 Turbulent viscosity

5.3.2.1 Constant turbulent viscosity

The sensitivity of the results for changing the turbulent viscosity was investigated by comparing the reference case ($\nu = 0.01 \text{ m}^2/\text{s}$) to $\nu = 0.001$ and $0.1 \text{ m}^2/\text{s}$ and with fixing all the other physical and numerical parameters.

The sensitivity of the water level to the change in constant turbulence viscosity was found to be very small (Figure 5.15), an increase in the water level of about 1.5% for the case of turbulence viscosity of $0.1 \text{ m}^2/\text{s}$ was recorded if compared to the mean conditions, while the turbulence viscosities of $0.001$ and $0.01 \text{ m}^2/\text{s}$ gave very similar results. The increase in the water level was due to the increased resistance caused by the increase of the constant turbulent viscosity. At the D.S. side the water level for the three turbulent viscosity values was the same, because the water level was imposed at the D.S. side.
5.3 Variations of bottom friction and turbulence model

Figure 5.15: Variations of water level at the U.S. side due to changing turbulent viscosity (m²/s)

The same trend was also recorded for the flow velocities, where the sensitivity was found to be very small too (Figure 5.16). At the U.S. side the flow velocity for the three turbulence viscosity values was the same, because the discharge was imposed at the U.S. side. So, it can be concluded that the model was not sensitive to the changes in constant turbulent viscosity.

Figure 5.16: Variations of flow velocity at the D.S. side due to changing turbulence viscosity (m²/s)
5.3.2.2 Different turbulence models

Two different turbulence models were compared with the constant viscosity model used in the previous calculations ($\nu = 0.01 \text{ m}^2/\text{s}$); the two models are the Elder and the k-\varepsilon model (sections 2.1.4 and 3.1.1). The two models were tested for the conditions of the reference case. Both, the Elder and the k-\varepsilon model showed a small increase in the flow velocity when compared to the case of the constant viscosity model; the change was about 0.5% (Figure 5.17). The results for the Elder and the k-\varepsilon model were very similar in the values, but Elder model showed less fluctuations than k-\varepsilon model, and both of them showed much less fluctuations than the constant viscosity model especially in the beginning of the simulation.

The change in the water level was even smaller; it was about 0.05% (Figure 5.18). So, as the impact of using a complex turbulence model instead of using a simple one, in terms of water levels and velocities, was very small, it was decided to use the simple constant turbulent viscosity model in this case, as it saves the time and resources and it did not affect the accuracy much.

![Figure 5.17: Variations of flow velocity at the D.S. side due to changing turbulence model](image)

Figure 5.17: Variations of flow velocity at the D.S. side due to changing turbulence model
5.4 Salinity transport

The saltwater intrusion into tideless estuaries is characterized by strong stratification (Chanson, 2004). The stratification effect cannot be modeled in a 2D model, because the concentration is averaged over the depth. Nevertheless, the effect of spatial density variation (in the horizontal direction) as a function of salinity concentration can be considered in a 2D model leading to a barotropic and baroclinic pressure gradient (Figure 5.19). TELEMAC2D uses the method explained in section 2.1.6 to simulate the horizontal variation of density.
5.4.1 Test cases

Before applying it to the Nile Estuary case, the ability of the TELEMAC2D modeling system to model and quantify the effect of horizontal density variation was first investigated using two theoretical cases of a rectangular channel and a trapezoidal channel. For the two theoretical cases, four scenarios were modeled which are:

1) Stagnant water with horizontal density variation only and ignoring diffusion
2) Stagnant water with diffusion only and ignoring horizontal density variation
3) Stagnant water with both diffusion and horizontal density variation
4) Flowing water with both diffusion and horizontal density variation

The aim of the previous scenarios was to check how the horizontal variation of density can affect the results and to compare its impact with the one of diffusion. In addition, the shape impact was also analyzed.

5.4.1.1 Rectangular channel

The channel dimensions are 5 m, 200 m and 1000 m for the depth, the width and the length respectively, and with zero bottom slope. A triangular grid of 10 m
discretization length was generated by MATISSE; the grid was refined in the middle part of the channel where a 4 m discretization length was used due to the choice of the initial conditions (see Figure 5.21). The total number of nodes was 3,303 and the total number of elements was 6,344 (Figure 5.20).

The channel has two open boundaries which are an U.S. boundary where the flow was given (zero in case of stagnant water and 80 m$^3$/s in case of flowing water) and zero salinity, and a D.S. boundary where a water level of 5 m and a salinity concentration of 35 mg/l were imposed. The discharge and salinity values chosen in case of flowing water were very similar to the conditions of the Nile Estuary. The same Manning friction coefficient as for the Nile case of 0.022 m$^{1/3}$/s and a constant turbulent viscosity ($\nu = 0.01$ m$^2$/s) were employed here. The time step of the simulation was 5 seconds.

Figure 5.20: Grid of the rectangular channel (Mahgoub and Hinkelmann, 2012)

The Positive Streamline Invariant (PSI) distributive scheme was chosen after testing the other available schemes (SUPG and Method of Characteristics) which caused either stability problems or gave high negative salinity. Thereof, PSI scheme is very suitable to salinity transport simulations. The solver used in this case was GMRES. A hydrodynamic simulation was first done for the case of flowing water until reaching a steady state condition, but for the other cases it was not necessary because the water was stagnant.
The initial condition for salinity was that half of the channel (starting from the D.S. boundary) was saline water and the other half was fresh water as shown in Figure 5.21. The diffusion (molecular and turbulent) was assumed to be constant with a value of 0.001 m²/s.

![Figure 5.21: Initial conditions for salinity transport (Mahgoub and Hinkelmann, 2012)](image)

The simulation of the rectangular channel showed smaller impact for the diffusion than of density variation as shown in Figures 5.22A and 5.22B for 100 days of simulation time. For longer simulation time the impact of density variation will be bigger as it still shows slow changes while for the case of diffusion no further change was noticed after 10 days of simulation.

As the impact in case of turbulent diffusion only was quite small, combining both diffusion and density variation showed very similar results as the case of density variation only (Figure 5.22C).

When introducing a flow from the U.S. boundary (80 m³/s), the saline water moved towards the D.S. boundary very quickly (Figure 5.22D shows the result after about 80 minutes only) due to the momentum produced from the flow velocity which was higher than the one due to the spatial variation of density. No doubt that changing the discharge will affect the movement speed of the saline water.
Figure 5.22: Salinity transport for the rectangular channel for A) stagnant water with horizontal density variation only, B) stagnant water with diffusion only, C) stagnant water with horizontal density variation and diffusion and D) flowing water with horizontal density variation and diffusion (Mahgoub and Hinkelmann, 2012)

5.4.1.2 Trapezoidal channel

The channel has a total length of 1000 m; the cross section is shown in Figure 5.23. The grid configurations, the boundary conditions, the physical and the numerical parameters are the same as in the case of the rectangular channel. The MATISSE grid
Two-dimensional surface water model

generator was used in this case also to generate the grid. The total number of nodes was 3,325 and the total number of elements was 6,388 (Figure 5.24). The initial conditions as shown in Figure 5.21 are applied in this case also.

Figure 5.23: Cross section of the trapezoidal channel (Mahgoub and Hinkelmann, 2012)

The changes were faster in this case than in the case of the rectangular channel. After 10 days of simulation, an obvious difference can be noticed between the four modeled scenarios. In the case of horizontal density variation only, most of the channel was turned to be saline water, which means that the impact of the salinity difference forced the fresh water to leave the system (Figure 5.25A).

Figure 5.24: Grid of the trapezoidal channel (Mahgoub and Hinkelmann, 2012)

The changes were faster in this case than in the case of the rectangular channel. After 10 days of simulation, an obvious difference can be noticed between the four modeled scenarios. In the case of horizontal density variation only, most of the channel was turned to be saline water, which means that the impact of the salinity difference forced the fresh water to leave the system (Figure 5.25A).
Changes in the salinity concentration with respect to the depth variation were also noticed, where higher concentrations were in the deeper parts, this is consistent with the results of Hansen and Ratray (1965), where they concluded that lateral variations of the depth cause a lateral variation of the turbulence and bottom friction which results in a tilt of the gravitational flow responsible for the density-driven flow in 2D model. In addition, the horizontal pressure force due to horizontal density gradient is
Two-dimensional surface water model

proportional to the depth; therefore the tendency of the heavier salty water to replace the lighter fresh water landward is stronger when increasing the depth (Li et al., 1998).

The impact of the turbulent diffusion was much smaller than the impact of density variation; it was limited in a small part in the middle of the channel (Figure 5.25B). The influence of turbulent diffusion was quite similar in both the trapezoidal channel and the rectangular channel (Figures 5.22B and 5.25B) which is not the case for the impact of the density variation.

When combining diffusion and density variation together (Figure 5.25C), only a slight difference compared to the case of the density variation only can be seen; instead of the uniform variation with respect to the horizontal axes, the variation of salinity was only in the lower lateral boundary.

Like the case of the rectangular channel mentioned earlier, introducing a slow flow to the system (80 m³/s) caused that the saltwater moved quickly towards the D.S. boundary (Figure 5.25D). However the shape of the saltwater wedge is completely different compared to the case of the rectangular channel. That also emphasizes the strong impact of the shape on the salinity transport.

5.4.1.3 Comments on the test cases

The simulation of the test cases revealed that the impact of density variation was higher than the turbulent diffusion. The value used for turbulent diffusion was a high value (0.001 m²/s), so the impact of diffusion could be smaller if smaller value for turbulent diffusion was used. The shape considerably influenced the results, as a much faster change was noticed in the trapezoidal channel (approximately the whole domain turned to be saltwater in 10 days simulation time), while the change was quite slow in the rectangular channel. However, the impact of the shape was recorded only for the case of horizontal variation of density and it was not observed for the case of diffusion, thereof the diffusion is independent of the shape. The effect of the water depth was also noticed; higher salt concentration occurred with higher water depth (as described in the case of trapezoidal channel).
According to the plausible results of the test cases, the TELEMAC2D modeling system was applied to simulate horizontal density-driven flow in the Nile in the following. In addition, the test cases emphasized the importance of including the spatial variation of density when simulating tideless estuaries as in the case of the Nile River. However, 2D simulations cannot account for the stratification, they can consider only the spatial density variations due to barotropic and baroclinic gradients; so the following simulations for the Nile can be considered as a first estimation, and 3D simulations are required for more realistic results.

### 5.4.2 Salinity transport in the Nile Estuary

#### 5.4.2.1 Mean conditions

The mean conditions of flow and head were considered in this case. The calculations were started from the steady state reached in the hydrodynamic simulation and using the same model configuration as in section 5.4.1.1. As the used method (PSI) is an explicit scheme, the Courant number should be smaller than one to ensure stability, in the calculations domain Cr ranged from 0.5 to 4.1, however TELEMAC2D makes sub-iterations to decrease Cr to be less than one. The initial condition for salinity concentration was calculated based on the following equation (Markofsky, 1980):

\[
L_s = \frac{2h_0}{0.5R_e^{0.25}} \left(\frac{1}{2Fr_{do}^2} - 2 + 3Fr_{do}^{2/3} - \frac{6}{5}Fr_{do}^{4/3}\right)
\]  

(5.1)

Where, \(L_s\) is the intrusion length of the saline water inside the river, \(R_e\) is the Reynolds number which is expressed as \(4R_hu_0/\nu\), \(Fr_{do}\) is densimetric Froude number which is expressed as \(u_0/\sqrt{(g\Delta\rho h_0/\rho)}\), \(h_0\) is the water depth at the river mouth, \(R_h\) is the hydraulic radius, \(u_0\) is the velocity of river flow at the mouth, \(\rho\) is the fresh water density, \(\Delta\rho\) is the density difference between saltwater and fresh water and \(g\) is the gravitational acceleration. Equation 5.1 was used to calculate the total length of the saltwater intrusion inside the river considering the D.S. boundary with a salinity concentration of 38.5 kg/m³, the intrusion length was found to be 15329
m, then a linear change of the concentration was assumed providing that the salinity at the U.S. boundary is zero, so the initial condition of salt concentration was set to be as shown in Figure 5.26.

Figure 5.26: Initial conditions for salt concentration

After 40 days of simulation using the mean conditions for water level and flow, the saltwater was limited to the last 400 m of the domain near the D.S. boundary, this due to the impact of the flow velocity (although a small flow velocity) which balances the
impact of the density difference and limit it to a small part in the river as shown in Figure 5.27. So, the higher the flow velocity, the less is the intrusion length.

The results differ much from the initial conditions, which could be because the 1D nature of the equation used for calculating the initial condition in addition to the 3D nature of the phenomenon and the fact that the concentration is averaged over the water depth in such 2D model. So, a 3D model is a necessity to account for the stratification and allowing an inflow (in the lower part of the boundary) and an outflow (in the upper part of the boundary).

Figure 5.27: Salt concentration after 40 days simulation time
5.4.2.2 Case of sea storm

Using the same model configuration described in the previous section, a case of a sea storm was simulated to quantify the intrusion length and the impact of advection in comparison to the impact of density variation on the salinity intrusion. A sea storm was assumed in such a way that the water level in the sea (D.S.) increased by 50 cm within 10 hours. The initial salinity was set to zero in the whole domain (initial conditions are believed not to affect the final results, it can only affect the simulation time). A Dirchlet boundary condition for the salinity with 38.5 kg/m$^3$ was chosen at the sea side, and the average discharge of 83.6 m$^3$/s at the U.S. boundary was used. The results of this case are shown in Figure 5.28.

Figure 5.28: Salinity concentration in the domain due to a sea storm (Mahgoub et al., 2012)
In this case, the saltwater intruded a distance of about 4.8 km into the river (Figure 5.28). However, this distance is bigger than in the reference case due to the advection impact caused by the sea storm. The salt concentration decreased towards the U.S. 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.

Comparing this case with the previous one, it can be concluded that advection has much higher impact than the density variation with respect to salinity intrusion in estuaries. This should be taking into consideration in simulating estuaries where tides are dominant which is not the case of the Nile Estuary.

5.4.2.3 Parameter study: turbulent diffusivity

The sensitivity of the model to the turbulent diffusivity was analyzed by running the model with three different turbulent diffusivity values which are: $10^{-1}$, $10^{-3}$ and $10^{-6}$ m$^2$/s with using a constant value for the turbulence viscosity (0.01 m$^2$/s). The other conditions of section 5.4.2.1 were applied in this case also.

![Figure 5.29: Salinity intrusion for different turbulent diffusivities: a) $10^{-1}$, b) $10^{-3}$ and c) $10^{-6}$ m$^2$/s](image)
5 Two-dimensional surface water model

For five days of simulation, no significant influence for turbulent diffusivity was noticed as shown in Figure 5.29, the intrusion length was very similar in the three cases with minor changes mainly in the transverse direction. The sensitivity of the model to the turbulent diffusivity was very small. That could be because of the small impact of diffusion on the propagation of saltwater; this is discussed in the following section.

5.4.2.4 Comparing the influence of diffusion to density-driven flow

It was also important to check whether the diffusion or the density-driven flow has a larger impact on the propagation of the saltwater inside the Nile. Therefore, the first three scenarios which were mentioned in section 5.4.1 were tested for the Nile Estuary also but with flowing water with the mean flow conditions in the Nile.

Comparing the results after one day of simulation time for the case of horizontal density variation only to the case of turbulent diffusion only (Figures 5.30A and 5.30B) showed that the intrusion length was rapidly decreased in both cases (if compared to the initial conditions), however it was less in the case of the turbulent diffusion only. So, the impact of density variation was relatively higher than the turbulent diffusion as it causes more momentum, therefore it had higher tendency to resist the momentum of the flow.

For the case of both turbulent diffusion and horizontal variation of density together (Figure 5.30C) the results seem to be similar to the one of horizontal variation of density only (Figure 5.30A). These results for the Nile Estuary are consistent with the result found in the two theoretical cases described earlier in section 5.4.1 (higher impact of horizontal variation of density than the one of turbulent diffusion).

The impact of the bathymetry (variations in the bottom level and hence the water depth) are seen here also, as the lateral variation in the salinity corresponds to the variation in the bathymetry which shows the same behavior that was described in the test cases (section 5.4.1).
Figure 5.30: Salt concentration after one day of simulation time for the Nile Estuary for: A) horizontal density variation only, B) turbulent diffusion only and C) horizontal density variation and turbulent diffusion (Mahgoub and Hinkelmann, 2012)
5.5 Sea level rise scenarios

As a direct consequence to climate change, the sea level rise will affect the salinity transport between the Nile and the Mediterranean Sea, such impact is dependent on the value of the sea level rise. El-Fishawi and Badr (1995) indicated that the local estimates of sea level rise along the Nile Delta ranged between 0.24 m and 0.69 m. According to IPCC (2007), the global sea level rise is ranging from 0.18 m to 0.59 m by 2100, but the IPCC does not include the effect of land subsidence. Therefore, three scenarios for sea level rise were chosen to be analyzed in this research, which are: an increase of sea level by (a) 0.24 m (minimum value from El-Fishawi and Badr (1995)), (b) 0.69 m (maximum value from El-Fishawi and Badr (1995)) and (c) 1.0 m (as an extreme value). The three scenarios were simulated one time for the mean flow conditions and one time for the same storm event described in the section 5.4.2.2 and under the average discharge in the river.

In both cases (mean flow conditions and sea storm event), an obvious increase in the intrusion length was noticed for a sea level rise of 1.0 m if compared to the current conditions and less increase for the case of sea level rise of 0.69 m. But for only 0.24 m sea level rise the change with respect to the current status was very small for the average condition (Figure 5.31) and higher for the case of the storm event (Figure 5.32).

Comparing the three scenarios to the current status revealed that the saltwater intrusion will increase to be about 500 m, 900 m, and 4200 m for the mean conditions (Figure 5.31) and 7.1 km, 10.1 km and 12.7 km for the case of storm event (Figure 5.32) in case of sea level rise by 0.24 m, 0.69 m and 1.0 m respectively. So, further saltwater intrusion occurred. The saltwater intrusion is then directly proportional to the sea level. The further saltwater intrusion will affect the irrigation activities in the surrounding area and it will increase the salinity of the agricultural lands in the vicinity of the Nile River.
Figure 5.31: Saltwater intrusion for the mean flow conditions in case of sea level increase by: a) 0.0 m (current status), b) 0.24 m, c) 0.69 m and d) 1.0 m
Figure 5.32: Saltwater intrusion for sea storm conditions in case of sea level increase by: a) 0.0 m (current status), b) 0.24 m, c) 0.69 m and d) 1.0 m (Mahgoub et al., 2012)
5.6 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 in response to sea level rise to push the saltwater towards the sea. To calculate the new discharge, several simulations for each sea level rise scenario were carried out with different discharge rates until reaching the discharge that achieve the same intrusion length calculated in section 5.4.2.1 which is the current situation.

According to the model results, for the mean conditions, the river discharge should be about 100 m$^3$/s, 140 m$^3$/s and 230 m$^3$/s to balance the increase of the sea level by 0.24 m, 0.69 m and 1.0 m respectively.

That means that an additional annual water amount has to be discharged to the sea, the additional water amount was calculated to be 0.5, 1.6, 4.6 Billion Cubic Meters (BCM) per year (Figure 5.33). If we consider a total share for Egypt from the Nile water of about 55.5 BCM/year currently, the additional amount of water will be 1%, 2.9% and 8.3% of the total water budget of the country for sea level rise of 0.24 m, 0.69 m and 1.0 m respectively. 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 loss.

However, some compromises can be made 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 the case of a reduction of the Nile flow as a result of the climate change as more intrusion in such a case is expected.

Generally, a 2D model can help to investigate the different scenarios, however a 3D model should be used as shown in chapter 6.
Figure 5.33: Additional water amount that has to be discharged from Edfina barrage to prevent any further salinity intrusion for different sea level rise scenarios
6 Three-dimensional surface water model

A 3D model for the Nile Estuary was also set up using TELEMAC3D; the model are presented hereafter including the hydrodynamics and salinity transport in addition to test cases used to verify the model. The results of section 6.2 are published in Mahgoub et al. (2014a), the results of section 6.3.1 are published in Mahgoub et al. (2015), the results of sections 6.3.2 and 6.4 are published in Mahgoub et al. (2014b).

6.1 Model setup and parameters

The grid was generated using MATISSE grid generator. The same specifications of the 2D grid described in section 5.1 was used here also, the only difference is that in this case a part from the sea was added to the domain. The generated 2D grid was then replicated over the vertical by TELEMAC3D to produce the 3D grid used in the simulations. The number of horizontal levels was 11, the horizontal levels are evenly distributed over the vertical and the heights of the levels vary depending on the water depth. The number of nodes in each level was 23,016 and the number of elements was 43,597. Figure 6.1 shows the domain and the 2D grid and Figure 6.2 shows the 3D grid, obviously the domain has a complex geometry and bathymetry.

The domain has two open boundaries: the first is at the U.S. where the discharge was given, and the second is at the D.S. where the water level and the salinity were given. First, the D.S. boundary was directly set at the mouth of the Nile. It was found out that the boundary was very sensitive due to varying inflow and outflow conditions over time and over the vertical also requiring dynamic switches of boundary condition types from Dirichlet to Neumann (and vice versa) which is automatically done in TELEMAC3D. To make the results less dependent on this sensitive boundary, the computational domain was extended to the sea. When the boundary in the sea is open
everywhere, again varying inflow and outflow as described before occurred. To reduce this phenomenon to a smaller area, only a part of the sea boundary with the width of the Nile mouth was set open (see Figure 6.1) and the rest was set closed.

Figure 6.1: Domain and grid (Mahgoub et al., 2014b)
6.1 Model setup and parameters

Figure 6.2: 3D grid for the domain showing the different layers

The initial conditions were a zero velocity and a water level of 0.37 m + msl. Manning friction coefficient of 0.022 (Mahmoud et al., 2006) was adopted (see section 2.1.3). Prandtl’s mixing length model and the k-ε model to define the vertical and the horizontal turbulent viscosity and diffusivity, respectively, were chosen.

A time step of five seconds was used. The Courant number was in the range from 0.5 to 4.1 in the whole computational domain. The numerical method used is explicit (distributive scheme) which needs a Courant number of a value less than ‘1’ for stability reasons, however Courant numbers higher than ‘1’ are automatically adjusted in TELEMAC3D through sub-iterations (LNHE, 2007). GMRES was chosen as the solver (see section 3.1.1)
6 Three-dimensional surface water model

6.2 Hydrodynamics

The mean conditions (flow at U.S. boundary is 83.6 m$^3$/s and sea level is 0.37 m +msl) were analyzed in the 3D case to be used later as initial conditions for the salinity transport. In this case hydrostatic pressure assumption was used, while in the salinity transport (section 6.3) a non-hydrostatic approach was used. The steady state was reached after about two and half days of simulation (Figure 6.3). The changes in the free surface through the domain were very small (the free surface at the U.S. boundary was 0.003 m+ msl higher than the D.S. boundary), and the slope of the free surface was close to zero (the same result found in the 2D simulations).

![Figure 6.3: Time series of the water level at the U.S. boundary](image)

A relatively low flow velocity was found, the maximum value was 0.09 m/s near the river mouth (Figure 6.4). The variations of the flow velocity throughout the domain were higher than those of the water level due to the variations of the flow area.
According to the results, the maximum velocity calculated from the 3D model was found to be higher than the 2D case (0.078 m/s) due to the fact that in 2D an average value over the depth was calculated; in both cases the flow velocity was very small.

The flow velocity varied also laterally, the highest velocity was in the middle of the domain and it decreased to reach zero at the banks (Figure 6.5). The same behavior should be also over the vertical where the velocity near the bottom should be close to zero and increase in parabolic shape till the surface, the later behavior was not clear in the model (Figure 6.6), the reason could be due to the low resolution in the vertical direction which could not capture the influence area of the bottom roughness (see the discussion at the end of this sub-chapter).

Figure 6.4: Flow velocity in the domain at the water surface (Mahgoub et al., 2014a)
As described in the results of the 2D model (section 5.2.1), some eddies were formed due to the meandering of the river. This behavior was noticed here also as shown in Figure 6.7. The same magnitude of the velocity within this eddies that was found in the results of the 2D model (maximum value of 0.02 m/s) was recorded in this case also.

Figure 6.5: Flow velocity in a cross section 3 km from the river mouth

Figure 6.6: Velocity distribution over the vertical (in the middle of the section shown in Figure 6.5)
The values of the vertical component of the velocity were considerably small if compared to the total velocity value; they did not exceed 0.003 m/s. Therefore, the direction of the flow field was not affected much with the direction of the vertical component of the velocity. Figure 6.8 shows the directions of the vertical component of the velocity, the directions affected with the bathymetry of each cross section. Plotting the directions for the total velocity (Figure 6.9) showed that the magnitude was much higher than the one of the vertical component of the velocity and the direction was perpendicular to the cross section and did not follow the bathymetry as the case of the vertical component of the velocity.

The vertical component of the velocity was in the range of 2 – 6 % from the total velocity. Of course it is better to consider it, however obviously ignoring it will not affect the results much. So, a 2D model could be a good approximation for the hydrodynamic simulation in the Nile Estuary.
6 Three-dimensional surface water model

Figure 6.8: Vector of the vertical component of the velocity for two cross sections in the domain

Figure 6.9: Vector of the total velocity for two cross sections in the domain
Refining the vertical mesh near the bottom can improve the behavior shown in Figure 6.6. A refined mesh consisting of 17 levels were tested to check this behavior; the mesh had 7 levels in the lowest 1% of the water column (close to the bottom). The results of this case are shown in Figure 6.10. Obviously, the small velocities (values of zero or close to zero) are found only in a very thin layer close to the bottom. The same behavior was found with 11 layers only but with one of the layer at 1% of the water column near the bottom as shown in Figure 6.12.

The velocity distribution in the middle of the same section showed that a maximum velocity was close to the bottom. This behavior is not very common; it could be due to the uneven distribution of the grid over the vertical (Figure 6.11). So, it was decided to use a grid with 11 layers evenly distributed for all the simulations to avoid the abovementioned behavior and not to affect the simulations in case of salinity transport because it propagates over the complete water column not only near the bottom.

Figure 6.10: Flow velocity in a cross section 3 km from the river mouth for a 17 layer grid refined close to the bottom
Figure 6.11: Velocity distribution over the vertical at the center of the section shown in Figure 6.10 with a grid refined close to the bottom

Figure 6.12: Flow velocity in a cross section 3 km from the river mouth for a 11 layer grid refined close to the bottom
6.3 Salinity transport

6.3.1 Verification study

Gravity currents are the major phenomena that govern the transport of saline water between the Mediterranean Sea and the Nile River. Therefore, gravity currents were first simulated using test cases to verify the ability of TELEMAC3D to model these phenomena in order to use it in the case of the Nile Estuary. The gravity currents were simulated using two sets of lock-exchange experiments that were carried out in the laboratories of Roma University and published in La Rocca et al. (2008). The first set of experiments is considered as a quasi 2D case whereas the second one is considered as a 3D case. The experimental results were compared to the numerical ones to assess the accuracy of the model, hereafter is a description for the experiments and the results.

6.3.1.1 2D lock-exchange experiments

A. Constant mass of dense fluid

As shown in La Rocca et al. (2008), the configuration of these experiments is a rectangular tank with 3.0 m length and 0.20 m width. Two fluids with different densities are separated by a gate inside the tank. The denser fluid (saline water), of density $\rho_2$, is located in the left hand side of the tank at a fixed distance $x_0 = 0.20$ m, the right hand side is filled with fresh water with a density of $\rho_1 = 1000$ kg/m$^3$ (Figure 6.13). The bottom is smooth and horizontal. The walls are smooth too. As there are no variations along the width and the lateral direction is small, this configuration is considered as a 2D lock-exchange experiment. The experimental setup is shown in Figure 6.14.
The nine combinations of variable density $\rho_2$ and variable water depth ($H_1$) reported in La Rocca et al. (2008) were simulated (Table 6.1). For the simulation, a triangular horizontal grid was generated with the ‘JANET’ mesh generator (see section 3.2.2) (Smile Consult, 2005). The discretization length in the horizontal direction was 2 cm (in both $x$- and $y$-directions). In the vertical direction, the number of horizontal levels was 30 for water depth of 0.3m, 20 levels for water depth of 0.2 m and 20 levels for the water depth of 0.1 m (higher resolution in the vertical direction was important for accurate results in the smallest water depth of 0.1 m), the number of nodes was about 1,600 and the number of elements was about 3,000 in each horizontal level. The
chosen mesh was found to be convergent, where less resolution affected the results (caused numerical diffusion and high error) and higher resolution did not achieve better results. A closed boundary has been used for all the walls of the tank. As the walls and the bottom are smooth in the simulated experiments, zero friction was set along them.

Table 6.1: Parameters of 2D lock exchange experiments (Mahgoub et al., 2015)

<table>
<thead>
<tr>
<th>Test</th>
<th>$x_0$</th>
<th>$\rho_2$ (kg/m$^3$)</th>
<th>$H_1$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.20</td>
<td>1035</td>
<td>0.30</td>
</tr>
<tr>
<td>C2</td>
<td>0.20</td>
<td>1035</td>
<td>0.20</td>
</tr>
<tr>
<td>C3</td>
<td>0.20</td>
<td>1035</td>
<td>0.10</td>
</tr>
<tr>
<td>C4</td>
<td>0.20</td>
<td>1065</td>
<td>0.30</td>
</tr>
<tr>
<td>C5</td>
<td>0.20</td>
<td>1065</td>
<td>0.20</td>
</tr>
<tr>
<td>C6</td>
<td>0.20</td>
<td>1065</td>
<td>0.10</td>
</tr>
<tr>
<td>C7</td>
<td>0.20</td>
<td>1095</td>
<td>0.30</td>
</tr>
<tr>
<td>C8</td>
<td>0.20</td>
<td>1095</td>
<td>0.20</td>
</tr>
<tr>
<td>C9</td>
<td>0.20</td>
<td>1095</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The results were scaled using the following dimensionless parameters (La Rocca et al., 2008):

$$T^* = \frac{t}{x_0 / \sqrt{g' H_1}} , \quad x_f^* = \frac{x_f}{H_1}$$

t is the time, $x_f$ is the front position of the gravity currents, $T^*$ is the dimensionless time, $x_f^*$ is the dimensionless front position and $g'$ is the reduced gravity, defined as:

$$g' = g (1 - \rho_2 / \rho_1)$$

Constant viscosity, Prandtl’s mixing length and the k-\(\varepsilon\) turbulence models were considered (see section 2.1.4). The influence of the turbulence model, in terms of the front position and hence propagation velocity, was higher at the beginning of the flow. Constant viscosity model showed slower propagation velocity which was 3 % less
than the other two models. Afterwards all the turbulence models had almost the same results. Although, changing the turbulence model did not affect the results much, the more accurate turbulence models were used. Thereof, Prandtl’s mixing length model and the k-ε model were used to define the vertical and the horizontal eddy viscosity respectively. It is important to mention that simulating the experiments with the hydrostatic pressure assumption showed higher error (Figure 6.15) which means that the non-hydrostatic simulation was a necessary choice and more suitable for the analyzed cases.

![Relative Error Graph](image)

Figure 6.15: Relative error for test case C1 (Mahgoub et al., 2015)

The relative error in Figure 6.6 was calculated as follows:

\[
\text{relative error} \% = \left| \frac{(x_{f_{\text{model}}} - x_{f_{\text{exp}}})}{x_{f_{\text{exp}}}} \right| \times 100
\]

Where \( x_{f_{\text{exp}}} \) is the front position in the experiment and \( x_{f_{\text{model}}} \) is the front position in the model.
6.3 Salinity transport

At the start of the numerical simulation (releasing the gate in the experiments) a light front (fresh water) started to develop towards the left of the tank, whereas a heavy front (saline water) moved towards the right of the tank below it. Therefore, the velocity distribution over the vertical was in the shape shown in Figure 6.16, where a negative velocity formed in the upper layers and a positive velocity formed in the lower layers.

![Velocity distribution over the vertical in the middle of the gate after 0.5 second](image)

Figure 6.16: Velocity distribution over the vertical in the middle of the gate after 0.5 second

A considerably high vertical velocity component was also noticed, especially at the beginning of the simulation (just after the release of the gate). This emphasizes the necessity of using non-hydrostatic pressure approach. The values of the vertical velocity component were mainly negative (towards the bottom of the tank) and with a sine wave-like shape (Figure 6.17), the only exception was a positive value close to the bottom, that supports the idea of the formation of secondary currents which may enhance the mixing between the two fluids. The magnitude of the velocity (total...
magnitude or vertical component only) decreased with time as the front of the salt wedge moves.

![Distribution of the vertical velocity component over the water column in the middle of the gate after 0.5 second](image)

Figure 6.17: Distribution of the vertical velocity component over the water column in the middle of the gate after 0.5 second

A very good agreement between the numerical and the experimental results was achieved, as the plots in Figures 6.18, 6.19 and 6.20 show. There the dimensionless front position is plotted over the dimensionless time. The model can simulate the considered 2D lock-exchange experiments with a very small error. The relative difference between the experimental and numerical front position was indeed ±2.5%, then revealing a very close agreement between the experimental and numerical value of the front propagation velocity. Although the model simulated the behavior of gravity currents quite precisely, but the shape of gravity currents (Figure 6.21) is not so well captured by the model and it looks different compared to other literature (such as Adduce et al. (2012)).
6.3 Salinity transport

Figure 6.18: Comparison of numerical and the experimental results for dimensionless front position versus dimensionless time in test cases C1, C2 and C3 (Mahgoub et al., 2015)

Figure 6.19: Comparison of numerical and the experimental results for dimensionless front position versus dimensionless time in test cases C4, C5 and C6 (Mahgoub et al., 2015)
Figure 6.20: Comparison of numerical and the experimental results for dimensionless front position versus dimensionless time in test cases C7, C8 and C9 (Mahgoub et al., 2015)

Figure 6.21: Vertical profiles showing the evolution of the gravity currents in case C1 at: a) 2.5 s b) 7 s c) 12 s d) 17 s (Mahgoub et al., 2015)
According to La Rocca et al. (2012b), the evolution of the 2D gravity currents is characterized by three phases: the slumping phase, the self-similar phase and the viscous phase, the first two phases for test case C2 are seen in Figure 6.22.

The first phase starts when the gate, separating the two fluids and placed at $x = x_0$, is released, as a result a rarefaction wave moves backward and the gravity currents move forward. The rarefaction wave hits the end wall of the tank, at $x = 0$, and is reflected so that a bore starts to propagate forward with a speed bigger than that of the front of the gravity currents. When the bore reaches the front, the second phase starts. Throughout the first phase, the position of the front ($x_f$) depends linearly on the time ($t$) (La Rocca et al., 2012b). For test case C2, $x_f \sim 0.12 t$, except at the very beginning of the simulation where the velocity was considerably higher.

The second phase starts when the front of the gravity currents has travelled a distance equal to about 10 $x_0$ (Rottman and Simpson, 1983), in this phase the height and the velocity of the front decreases, and $x_f$ depends on $t^{2/3}$ (La Rocca et al., 2012b). For test case C2, the second phase starts at about 9.5 $x_0$, and $x_f \sim 0.31 t^{2/3}$.

In the last phase the height and the velocity of the front decrease at a faster pace. This phase starts when the front travels a distance $x_v$ which can be calculated according to the following equation (Rottman and Simpson, 1983):

$$x_v = \left( \frac{x_0 H_1}{v^2} g \frac{\rho_2}{\rho_1} - 1 \right)^{1/7}$$

(6.1)

In the analyzed test case C2, this phase should start when the front travels a distance of about 4.47 m, which is bigger than the dimensions of the experiment, so it cannot be seen here. Table 6.2 lists the characteristics of each phase for all test cases. The results in Table 6.2 are consistent with the above-mentioned theory and with the discussed results of test case C2.
Figure 6.22: Front velocity for test case C2 showing different phases of propagation (Mahgoub et al., 2015)

Table 6.2: Characteristics of the evolution phases of the gravity currents in all test cases (Mahgoub et al., 2015)

<table>
<thead>
<tr>
<th>Test</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(the slumping phase)</td>
<td>(the self-similar phase)</td>
<td>(the viscous phase)</td>
</tr>
<tr>
<td></td>
<td>$x_f$ (m)</td>
<td>starting at</td>
<td>$x_f$ (m)</td>
</tr>
<tr>
<td>C1</td>
<td>0.15 t</td>
<td>10.2 $x_0$</td>
<td>0.37 $t^{2/3}$</td>
</tr>
<tr>
<td>C2</td>
<td>0.12 t</td>
<td>9.5 $x_0$</td>
<td>0.31 $t^{2/3}$</td>
</tr>
<tr>
<td>C3</td>
<td>0.085 t</td>
<td>9.8 $x_0$</td>
<td>0.23 $t^{2/3}$</td>
</tr>
<tr>
<td>C4</td>
<td>0.20 t</td>
<td>10.0 $x_0$</td>
<td>0.43 $t^{2/3}$</td>
</tr>
<tr>
<td>C5</td>
<td>0.155 t</td>
<td>9.7 $x_0$</td>
<td>0.39 $t^{2/3}$</td>
</tr>
<tr>
<td>C6</td>
<td>0.115 t</td>
<td>10.4 $x_0$</td>
<td>0.29 $t^{2/3}$</td>
</tr>
<tr>
<td>C7</td>
<td>0.23 t</td>
<td>10.2 $x_0$</td>
<td>0.49 $t^{2/3}$</td>
</tr>
<tr>
<td>C8</td>
<td>0.195 t</td>
<td>10.5 $x_0$</td>
<td>0.43 $t^{2/3}$</td>
</tr>
<tr>
<td>C9</td>
<td>0.14 t</td>
<td>10 $x_0$</td>
<td>0.34 $t^{2/3}$</td>
</tr>
</tbody>
</table>

The development of the dynamic pressure varied with time. Just after the release of the gate a negative pressure (in the negative x-direction) developed near the top, the
negative value increases until reaching its maximum near the middle of the water column, then it decreases again until reaching the bottom with a value close to zero. The maximum negative value decreases with time until the dynamic pressure became zero for the whole water column (Figure 6.23). The time it took to reach a zero dynamic pressure differed according to the position of the point along the tank.

Figure 6.23: Distribution of the dynamic pressure over the water column for different times at the gate for experiment C1

A clear stratification of the salinity over the vertical was also noticed (Figure 6.24). The salinity concentration varied with time due to the propagation of the salinity throughout the domain. Figure 6.24 shows vertical profiles for the salinity at two different sections. The saltwater appeared in section 2 only after 12 seconds, that depended on the front velocity. The variations in the transverse direction were very small as can be seen in Figure 6.24.
B. Variable mass of the dense fluid

As the model was well verified, the impact of changing $x_0$ on the evolution of the gravity currents was analyzed numerically. Four different values of $x_0$ (0.1, 0.3, 0.4 and 0.5 m) were considered. The four values were compared to the value previously checked (0.2 m) for experiments C1, C4 and C7 (only results of C1 are shown because the three test cases have the same trend). Different values of $x_0$ lead to different quantities of the denser liquid and then different values of initial potential energy. Therefore, the propagation velocity of the heavier fluid achieved the largest value for $x_0 = 0.50$ m and the slowest for $x_0 = 0.10$ m (Figure 6.25). The change in the value of the dimensionless front position was directly related to the change of the value of $x_0$, the change was an increase of about 45% for every 0.1 m increase in the value of $x_0$. It is important to note that the analysis was stopped when the gravity currents reached the right wall of the tank. In Figure 6.25 the results are shown at the same
dimensionless time for reasons of a good comparison. No experimental data were available for these simulations.

Figure 6.25: Values of dimensionless front position for test case C1 and different $x_0$ values (Mahgoub et al., 2015)

6.3.1.2 3D lock-exchange experiments

A. Constant gate width

In these experiments two fluids with different densities were placed in two equal square tanks, each has a length of 1.0 m and they were separated by a gate with a width $b = 0.20$ m. The denser fluid (saline water with density $= \rho_2$) was located in the left side of the tank and the right side was filled with fresh water with a density of $\rho_1 = 1000$ kg/m³. The water depth in the two tanks was 0.15 cm (Figure 6.26) (La Rocca et al., 2008). The experimental setup is shown in Figure 6.27.
Figure 6.26: Top view in the 3D lock-exchange experiment (Mahgoub et al., 2015)

Figure 6.27: View of the tank used for the 3D lock exchange gravity currents, University Roma Tre, Department of Engineering, Hydraulics laboratory

The impact of the density difference and the tank roughness were assessed by testing several combinations of the density $\rho_2$ and the roughness diameter ($\varepsilon$) as listed in Table 6.3 (La Rocca et al., 2008). The bottom friction was expressed in TELEMAC3D in terms of Nikuradse law, while the walls were considered smooth.
6.3 Salinity transport

Table 6.3: Parameters of 3D lock exchange experiments (Mahgoub et al., 2015)

<table>
<thead>
<tr>
<th>Test</th>
<th>b</th>
<th>$\rho_2$ (kg/m³)</th>
<th>$\varepsilon$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>0.20</td>
<td>1015</td>
<td>0.0</td>
</tr>
<tr>
<td>D2</td>
<td>0.20</td>
<td>1015</td>
<td>1.0</td>
</tr>
<tr>
<td>D3</td>
<td>0.20</td>
<td>1015</td>
<td>1.6</td>
</tr>
<tr>
<td>D4</td>
<td>0.20</td>
<td>1015</td>
<td>3.0</td>
</tr>
<tr>
<td>D5</td>
<td>0.20</td>
<td>1025</td>
<td>0.0</td>
</tr>
<tr>
<td>D6</td>
<td>0.20</td>
<td>1025</td>
<td>1.0</td>
</tr>
<tr>
<td>D7</td>
<td>0.20</td>
<td>1025</td>
<td>1.6</td>
</tr>
<tr>
<td>D8</td>
<td>0.20</td>
<td>1025</td>
<td>3.0</td>
</tr>
</tbody>
</table>

A triangular horizontal grid was also used in this case. The mesh was generated with the MATISSE mesh generator (see section 3.2.1). In the horizontal direction a discretization length of 2 cm was used for the entire domain except around the gate where the mesh was refined to have a discretization length equal to the gate thickness (0.4 cm). In the vertical direction 15 horizontal levels were chosen (one level at each 1 cm), for each horizontal level the number of elements was about 20,000 and the number of nodes was about 10,000. The mesh resolution was customized through several trials with different mesh sizes. Due to the complexity of the flow, the $k-\varepsilon$ model was used to define the vertical and the horizontal eddy viscosity respectively.

The results of the numerical simulation agreed fairly with the experimental ones. The trend in all of the test cases was the same: initially the numerical front propagated slightly faster than the experimental front, then the numerical front velocity decreased at a larger rate than that of the experimental front velocity. Figures 6.28 and 6.29 show samples of the results (not all the results are shown because the other test cases have the same trend). The front position was difficult to be identified in the numerical results, a threshold of a value of 0.1 ppm for the salinity concentration near to the bottom was used to distinguish between the fresh and the saline water and hence to identify the front position. In Figures 6.28 and 6.29, the front position along the $x$-direction in the middle of the tank is plotted.
Figure 6.30 shows a top view on the gravity current’s front (only the right half of the tank is shown). Both numerical and experimental results are plotted at different instants of times. It can be seen that the lateral propagation of the numerical model was usually bigger than the experimental results, while the longitudinal propagation of the numerical model was smaller than that of the experiment except at the very beginning of the simulation.

Figure 6.28: Comparison of numerical and the experimental results for dimensionless front position versus dimensionless time in test case D4 (Mahgoub et al., 2015)

Figure 6.29: Comparison of numerical and experimental results for dimensionless front position versus the dimensionless time in test case D7 (Mahgoub et al., 2015)
6.3 Salinity transport

Generally the differences between the numerical and experimental results were relatively small. This difference could be a result of the initial conditions, where the numerical initial conditions do not represent the lifting of the gate, which occurs in a finite interval of time. Therefore, the model was somewhat faster.

In the 3D lock-exchange case, the hydrostatic approximation showed much larger deviation when compared with the results of the non-hydrostatic approach shown here. For example in test case D3, the relative error at the end of simulation increased from 5.44% in the non-hydrostatic approach to be 20.36% in the hydrostatic approach (Figure 6.31), therefore the use of the non-hydrostatic approach was necessary.
The values of the dynamic pressure were very small (a maximum of 1 pa for case D1) if compared to the values of the static pressure (a maximum of 1493 pa for case D1). The behavior of the dynamic pressure was similar to the one described in the case of the 2D lock-exchange experiments (section 6.3.1.1) but with smaller values (because of the smaller density and the smaller water depth). A negative dynamic pressure was formed in the top of the water column (with its maximum almost in one-third of the water column). The negative dynamic pressure decreased with time until reaching almost zero (Figure 6.32).
6.3 Salinity transport

Figure 6.32: Distribution of the dynamic pressure over the water column for case D1 in the middle of a cross section 0.1 m from the gate

The distribution of the total velocity (Figure 6.33) had also similar behavior as mentioned in the 2D lock-exchange experiments (section 6.3.1.1). Relatively high values for the vertical component of the velocity, if compared to the total value of the velocity, were noticed (Figure 6.34).

Figure 6.33: Distribution of the velocity over the water column for case D1 in the middle of a cross section 0.1 m from the gate after 2 s
The bottom roughness affected the front velocity and then the front position (Figure 6.35), however its influence was not very high. This is due to the small simulation time and the small dimensions of the experiment, indeed the roughness’ effects need time to reveal themselves. In addition the considered values of $\varepsilon$ (the same values used by La Rocca et al. (2008)) are quite small. Evident differences among the results obtained with $\varepsilon$ equal to 1.0, 1.6 and 3.0 mm were only noticed at late stages of the simulations ($T^* > 2.0$ to 2.5), while an visible effect of the roughness was highlighted between the numerical results obtained with $\varepsilon=0$ and $\varepsilon \neq 0$ since $T^* > 1.0$. The same trend was also noticed for the other test cases therefore they are not shown here.
The profiles of the gravity currents are showed in Figure 6.36 (a threshold of salinity of 1 g/l to differentiate between saltwater and fresh water was assumed in this case). The front of the salt wedge was to some extent in a vertical position till 6 seconds, then a steep gradient was formed as can be seen in Figure 6.36d. The profiles of the gravity currents found by the model were quite similar to the numerical results of La Rocca et al. (2008), however it was not similar to the experimental results found also by La Rocca et al. (2008).
Figure 6.36: Vertical profiles showing the evolution of the gravity currents in case D1 at: a) 2.0 s b) 4 s c) 6 s d) 8 s

Unlike the 2D experiments (section 6.3.1.1), obvious variations in the salinity in the transverse direction were noticed in the 3D lock-exchange experiments (Figure 6.37). The salinity took a parabolic shape in the transverse direction, where the extension in the transverse direction increased with the time. The height of the salt wedge from the bottom of the tank decreased with time. Some of the sections shown in Figure 6.37 showed only fresh water at certain times, this was related to the front velocity of the gravity currents, in other words the saline water did not reach such sections at these times.
Figure 6.37: Vertical cross sections at different locations in the tank and at different times for experiment D1

B. Variable gate width

The gate width affected the form of the propagation mainly in the transverse direction (Figure 6.38); the bigger the gate width, the wider the propagation in the transverse direction. However the effect on the front position (x-direction) was rather small and with a changing trend. At smaller simulation time a smaller value of the gate width leads to a faster propagation in the x-direction, this continued with a continuous decrease in the difference of the front positions until 6 s, then (at 8 s) the trend was
switched where faster propagation was accompanied with a bigger value of the gate width, for longer simulation times the latter trend (at 8 s) could continue. No experimental data were available here to be compared with the numerical results.

![Figure 6.38: The propagation of the dense fluid for different values for b for case D1](image)

**Figure 6.38:** The propagation of the dense fluid for different values for b for case D1

### 6.3.1.3 Conclusions on the verification cases

The non-hydrostatic approach was essential for the cases under study, in addition to the necessity of using suitable turbulence models (Prandtl’s mixing length model and the $k-\varepsilon$ model were used to define the vertical and the horizontal eddy viscosity respectively). Overall, the non-hydrostatic 3D simulation using TELEMAC3D proved to achieve satisfactory results in simulating the complex phenomenon of gravity currents in regular geometry, so it was concluded that it can be used also to simulate the Nile Estuary which has a complex bathymetry.
6.3 Salinity transport

6.3.2 Nile Estuary

After a steady state was reached, the results of the hydrodynamics (section 6.2) were used as an initial conditions for simulating the saltwater propagation; in this case the initial conditions for the salt concentration were calculated according to the equation from Markofsky (1980) (equation 5.1) and assuming constant salinity over the vertical, the same as done in the 2D model (Figure 6.39) which is described in section 5.4.2.1. The same physical and numerical parameters used in the in the hydrodynamics simulation (section 6.2) were used here also. The boundary conditions described in section 6.1 was employed here, the salinity was imposed at the D.S. boundary.

Figure 6.39: Initial conditions of salinity concentration
6.3.2.1 Current status

After 27 days of simulation, a quasi-steady state condition was reached where the length of the salt wedge (Ls) was fluctuating between 11.3 km to 12 km (a range of 700 m) at the surface (Figure 6.40a) and at the bottom the salt wedge was about 16 km with minor fluctuations of few meters (Figure 6.40b).

The difference in Ls between the surface and the bottom is ranging between 4.0 and 4.7 km (over an average water column of 10 m), so the front of the salt wedge (the interface between fresh water and saline water) has a very small slope (0.21 % - 0.25 %).

Figure 6.40: Propagation of saltwater in domain at: (a) surface and (b) bottom (Mahgoub et al., 2014b)
The propagation of the salinity changed the velocity regime. Higher velocity values were recorded in this case. The increase in the velocity was due to the presence of two fluids moving separately over each other. So, higher water volume (when we add the saline water to the fresh water) in the same water area, which caused higher velocity values (the maximum value was 0.5 m/s).

The vertical component of the velocity increased an order of magnitude if compared with the hydrodynamics results, the maximum value was 0.03 m/s in the case (without salinity transport the maximum value was 0.003 m/s). Its direction followed the bathymetry as shown in Figure 6.41. However, the value of the vertical component of the velocity was much smaller than the horizontal component in the flow direction, therefore its direction did not affect the flow field much (Figure 6.42).

Due to the presence of the saline water, two directions for the flow can be distinguished (Figure 6.42), one in the bottom from the right to the left (saline water) and one in the top from the left to the right (fresh water).
6. Three-dimensional surface water model

6.3.2.2 Fluctuations of salinity

The fluctuations in the $L_s$, as the boundary conditions were constant, were not expected. The fluctuations were in a form of a cycle of an onward and a backward movement of the salt wedge (inflow and outflow of saline water), the cycles were not regular, however the change in the $L_s$ had a maximum value that was not exceeded (700 m). So, the case can be considered as a quasi-steady state. This behavior can be seen in Figures 6.43 and 6.44, where there are some cycle-like variations of increase and decrease of salinity then stabilize for a while and repeating the cycle again. The fluctuations were higher at the river mouth and they decreased in the direction of the U.S. boundary until they almost diminished at the end of the salt wedge. The fluctuations extended for longer distance near the bottom as the salt wedge near the bottom was longer than it is at the surface. An obvious difference in the salinity between the surface and the bottom can also be seen in Figures 6.43 and 6.44, for example at the Nile mouth the salinity is about 38.5 mg/l near the bottom and about 15 mg/l at the surface.

Figure 6.42: Vector of the total velocity for two cross sections in the domain
Figure 6.43: Change of salinity with time at points 1, 2, 3 and 4 (their positions are shown in Figure 6.39) at the surface (Mahgoub et al., 2014b)

Figure 6.44: Change of salinity with time at points 1, 2, 3 and 4 (their positions are shown in Figure 6.39) near the bottom (Mahgoub et al., 2014b)
Similar results were found by Jasinska (1993) in the Baltic sea along a Polish estuary, his study was mainly a field study however he used numerical modeling as well. According to him the salinity transport occurs due to the barotropic and baroclinic gradients of the pressure which act simultaneously, hence two way-exchange is expected (inflow and outflow). In tideless estuaries and during calm weather the balance between the barotropic and baroclinic gradients is very weak; therefore a changeable direction of the flow occurs (Jasinska, 1993). It is believed that the steady-state like fluctuations are caused by the density-driven flow in complex bathymetry, as they do not occur when the bottom depth is constant and the profile is rectangular.

As shown in Figure 6.45, an outflow occurred at the surface (and also in the layers near to the surface but it is not shown in the figure) and an inflow occurred near the bottom, in other words a saltwater flow was entering the Nile and a brackish water flow was leaving the domain (forced by the fresh water flow coming from the U.S. boundary), however the magnitude of the inflow and the outflow fluctuated with time which affected the fluctuations in the salinity described earlier. It was also noticed that some eddies formed at the D.S. boundary at the surface (Figure 6.45a) because of the density-driven flow in a complex bathymetry.

Figure 6.45: The flow field at (a) the surface and (b) near the bottom (Mahgoub et al., 2014b)
The same behavior shown in Figure 6.45 can be also demonstrated in Figure 6.46 which shows the velocity distribution over the vertical, obviously a positive velocity (outflow towards the sea) was formed in the top part of the water column, and negative velocity (inflow from the sea) formed in the lower part of the water column.

![Velocity distribution over the vertical](image)

Figure 6.46: Velocity distribution over the vertical in the middle of section ‘a’ shown in Figure 6.48

### 6.3.2.3 Longitudinal and lateral variations of salinity

The salt concentration and hence the density differed significantly throughout the salt wedge in the longitudinal direction as well as the vertical direction. The change in the density value was affected by the buoyancy which affected the mixing between the fresh and saline water (Nogueira et al., 2013). The density decreased as we went from the bottom towards the surface and as we go from the D.S. towards the U.S., so the lowest density was at the end of the salt wedge.

Changes in the density in the lateral direction were also noticed. Such changes were accompanied with the changes in the bathymetry; higher concentrations were at higher water depths for the same transverse section as shown in Figure 6.47. This is due to
the fact that the pressure force due to the density gradient is proportional to the depth; therefore the tendency of the heavier salty water to replace the lighter fresh water is stronger when increasing the depth (Li et al., 1998). The same behaviour was noticed in the 2D model.

![Figure 6.47: Salinity concentration near bottom and bathymetry at one part of domain (Mahgoub et al., 2014b)](image)

6.3.2.4 Vertical stratification

The stratification due to density difference was very clear at the intersection between the sea and the Nile (Figure 6.48), due to the decrease in the density the stratification impact decreased until it almost disappeared at the front of the salt wedge. The dilution of the density occurred as the saline water moves towards the river. The dilution was very fast where the amount of the water with the highest density decreased from almost 70% of the cross section at the intersection between the sea and the Nile (Figure 6.48a) to be about 5% just after 1 km (Figure 6.48b) then it disappeared totally after 2 km (Figure 6.48c).
Figure 6.48: Cross sections showing stratification of salt at following distances from intersection between Sea and Nile: (a) 0 km, (b) 1 km, (c) 2 km, (d) 3 km, (e) 4 km, (f) 8 km, (g) 12 km and (h) 16 km (Mahgoub et al., 2014b)
According to Julien (2002) the height of the salt wedge at a river mouth can be calculated according to the following equation:

\[
\frac{h_{s1}}{h_0} = 1 - \left( \frac{V}{V_A} \right)^{2/3}
\]

(6.2)

Where \( h_{s1} \) and \( V \) are the height of the salt wedge and the velocity at the river mouth respectively and 

\[
V_A = \sqrt{\frac{\Delta \rho}{\rho} g h_0}
\]

For the conditions in the Nile Estuary, the value of \( h_{s1} \) equals \( 0.82 * h_0 \). That would mean that a fresh water layer of about 18% of the water column exists near the surface. A similar value was also found by the model for the top layer at the river mouth (Figure 6.48a); however the model results showed no layer with pure fresh water at the river mouth but rather a mixed stratified-fluid (brackish water). It is assumed that this is due to the influence of circulations due to complex bottom variations in addition to turbulence and mixing which apparently was not considered by Julien (2002), these effects could cause higher vertical advection.

### 6.4 Sea level rise scenarios

The same sea level rise scenarios mentioned in section 5.5 were modeled here also using the same 3D model used for the current status with the same configuration to facilitate the comparison between the different scenarios and the current status.

#### 6.4.1 Increase in \( L_s \) due to sea level rise

The three aforementioned scenarios were modeled for a period of 27 days (the same period that was used for the current status for better comparison). An increase in \( L_s \) of 1.2 km, 5.1 km and 6.6 km in case of sea level rise of 0.24 m, 0.69 m and 1.0 m respectively were noticed (Figure 6.49). The more the sea level rises the more intrusion of the saltwater inside the Nile occurs. The sea level rise caused mainly
increased the advection of the saline water, which led to more salt water propagation in the Nile.

The increase of the salt water propagation was quite small in case of sea level rise of 0.24 m if compared with the other two scenarios which showed relatively close propagation values (5.1 and 6.6 km) although the rise of sea level in the second scenario (sea level rise of 0.69 m) is almost two third of the third scenario (sea level rise of 1.0 m). It was also noticed that the differences in the propagation length were less for the higher concentration values near the bottom, that means that the sea level rise did not affect much the very dense layers which apparently needed more momentum to be moved.

Using a simple linear regression, a relation between $L_s$ and the value of sea level rise was formed (Figure 6.50), with a regression coefficient ($R^2$) of 97.5% the relationship is as follows:

$$L_s = 67.856 \times \text{(sea level rise value)} \quad (6.3)$$
Figure 6.49: Propagation of saltwater in domain at bottom for sea level rise of: (a) 0.0 m (current status) (b) 0.24 m (c) 0.69 m (d) 1.0 m (Mahgoub et al., 2014a)
6.4.2 Mitigation measures to sea level rise

More saltwater intrusion inside the Nile means negative impacts on the soil and the irrigation activities in the surroundings agriculture lands. So, there is a need for mitigation options. A direct mitigation option could be increasing the river flow or discharging more water from Edfina Barrage to maintain the current status of balance. However, this option seems to be very costly in terms of wasting a lot of fresh water in the sea which means a direct negative impact on the water budget of the country.

Estimations for the Nile flow that could maintain the current status of balance were made using the same model for the same analyzed sea level rise scenarios. The results showed that the flow had to be increased from 83.6 m$^3$/s to be about 120, 200 and 260 m$^3$/s in case of sea level rise of 0.24 m, 0.69 m and 1.0 m respectively. So the flow will be increased by 1.15, 3.67 and 5.56 billion cubic meters annually (BCM/year) in case of sea level rise of 0.24 m, 0.69 m and 1.0 m respectively. According to the Nile basin treaties the share of Egypt is about 55.5 BCM/year, that means that the increase
in the discharge to mitigate the effect of sea level rise is about 2.1%, 6.6% and 10.0% of the country’s water budget in case of sea level rise of 0.24 m, 0.69 m and 1.0 m respectively, which is a huge loss of water resources for a country suffering from water shortage problems. However, as mentioned also in the results of the 2D model, some compromises could be done in which the propagation of saltwater could be allowed to a certain extent to limit increasing the discharge and losing the water.

Other options such as the use of a vertical barrier (sheet piles) to limit the saltwater intrusion can be also implemented. However, that will affect the navigation in the Nile. So, the option cannot be adopted. Increasing the river flow through using drainage water can be an alternative to increasing the discharge of Edfina barrage. But, this could have environmental implications such as eutrophication problems.

6.5 **Comparison between the 2D and the 3D models**

Comparing the results of the 2D and the 3D models with respect to hydrodynamics and salinity transport, some similarities and differences were noticed. The similarities and differences are detailed hereafter.

**6.5.1 Hydrodynamics**

The 2D and the 3D models showed similar results in terms of water level. Higher velocities were recorded in the 3D model (the maximum velocity was 0.09 m/s) than those of the 2D model (the maximum velocity was 0.078 m/s) due to the fact that in the 2D model the velocity is averaged over the water column. The variations of the water velocity over the vertical could be only simulated by the 3D model. In both the 2D and the 3D models some eddies near the meanderings of the river were noticed. Therefore, a 1D model was not suitable for the Nile Estuary.

Generally, a 2D model is sufficient for simulating the water levels and velocities in parts of the domain without meanders. In the parts with meanders secondary currents occur which cannot be resolved with a 2D model.
6.5.2 Salinity transport

If we consider the results of the 2D and the 3D models, it can be concluded that the intrusion length was totally different, in the 2D model for the current status the intrusion length was limited to only 400 m and in the 3D model the intrusion length near the bottom was about 16 km which is very close to the empirical equation 5.1 although the equation is a 1D equation. The big difference in the intrusion length is mainly due to the 3D nature of the phenomenon which is better simulated by the 3D model, moreover the averaging of the concentration over the vertical that is done in the 2D model causes underestimation of the intrusion length, as the salinity is diluted when it is averaged.

In terms of the sea level rise scenarios, the 2D model showed an increase in the intrusion length by 0.5, 1.9 and 4.2 km while the 3D model showed an increase of 1.2 km, 5.1 km and 6.6 km for sea level rise by 0.24 m, 0.69 m and 1.0 m respectively. So, the 3D model showed much higher influence of the sea level rise as the values were almost as high as twice the ones of the 2D model.

The stratification can be captured by a 3D model only and cannot by simulated with a 2D model which can include only the horizontal density variation. Thereof, 2D model is not suitable here as the stratification is much stronger than the horizontal density variation. For smaller water depths (i.e. 1.0 m) both 2D and 3D may have the same results.

So, through both models, it is believed that a 3D model is better for salinity transport simulation, however a 2D model could give a first rough estimation of the salinity intrusion inside the Nile Estuary. 3D model is also recommended for the simulation of the transport of other substances (e.g. contaminants, sediments or heat).
7 Summary, conclusions and outlook

The summary and the conclusions of the research in addition to the outlook for further research are presented in this chapter.

7.1 Summary and conclusions

This research focused on the hydrodynamics and salinity transport processes in the Nile Estuary through setting up multi-dimensional models to simulate these processes. The main concern of the research was investigating and evaluating the saltwater intrusion inside the Nile Estuary and the anticipated impact of sea level rise on it.

The study area is the last reach of Rosetta branch of the Nile River, the reach is characterized by its complex geometry and bathymetry. It extends about 30 km starting from Edfina barrage which controls its flow and ends with the Mediterranean Sea. The interaction between the Nile and the Sea includes water and salinity transport, the latter is governed mainly by the gravity currents.

The TELEMAC-MASCARET modeling system was used for the simulations. It includes several modules, only TELEMAC2D and TELEMAC3D were used in this research to set up the 2D and the 3D models respectively. In addition, several tools for pre- and post-processing were used, namely MATISSE, JANET, POSTEL3D, RUBENS and BleuKenue.

The main approach of the research was to use 2D model to get more in depth into the main processes in the reach under study and to improve the understanding of such processes, then to use 3D model for more precise results to the processes that have 3D nature (gravity currents). To verify the models especially with respect to salinity transport, test cases were first modeled. For both the 2D and the 3D models, the
Summary, conclusions and outlook

current status was first analyzed and then scenarios for the sea level rise were analyzed.

Basic background information and state of the art were first given, and a literature review for the previous research was also done to find out the gaps of the research that can be filled (totally or partially) with this research.

2D simulations

The first step in this research was to set up a 2D model for the Nile Estuary. The hydrodynamics of the Nile Estuary were first analyzed using TELEMAC2D. It was found that, for the mean 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 7.8 cm/s) and changing through the domain according to the water depth. The meanderings of the river caused the formation of eddies making a 2D approach necessary. The sensitivity of the model to friction coefficient and turbulence viscosity was very small.

Before simulating the salinity transport in the Nile Estuary, TELEMAC2D was first tested using two cases of a rectangular and a trapezoidal channel. The test cases were used to understand and quantify the impact of the spatial variation of density in a 2D model. In addition, the impacts of diffusion and density variation on the flow were compared. The simulation of the two case studies revealed that the impact of density variation was higher than the turbulent diffusion. The shape influenced the results, where much faster saltwater propagation was noticed in the trapezoidal channel (approximately the whole domain turned to be saltwater in 10 days simulation time), while the propagation was quite slow in the rectangular channel. However, the impact of the shape was recorded only for the case of horizontal variation of density and it was not observed for the case of diffusion, thereof the diffusion was independent of the shape. The effect of the water depth was observed also; higher salt concentration was combined with higher water depth. So, it was concluded that a 2D model such as TELEMAC2D can be used for density-induced salinity transport, but certain limitations had to be expected (Mahgoub and Hinkelmann, 2012).
The salinity transport in the Nile Estuary was then simulated using TELEMAC2D. Two cases were analyzed, the first was the current mean conditions of flow and the second was a sea storm in which the sea level increased by 50 cm in 10 hours. For the mean conditions, the salinity intrusion length was limited to 400 m near the D.S. boundary and for the storm event the intrusion length was 4.8 km.

Using the same 2D model, three scenarios for sea level rise were analyzed which are a sea level rise of 0.24, 0.69 and 1.0 m. According to the model results, the sea level rise caused further intrusion for the saltwater inside the river, the intrusion was about 500 m, 1900 m, and 4,200 m for the mean conditions and 7.1 km, 10.1 km and 12.7 km for the case of the storm event in case of a sea level rise of 0.24 m, 0.69 m and 1.0 m respectively. That 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 more water has to be discharged from Edfina barrage and that could affect the water budget of the country.

The sensitivity of the model to turbulent diffusivity was found to be very small. The impact of diffusion on the salinity transport was also found to be very small if compared with horizontal variation of density. This result is consistent with the results of the test cases.

**3D simulations**

As the second main step of the research, a 3D model for the Nile Estuary was set up using TELEMAC3D. The results of the hydrodynamics were similar to those of the 2D model in terms of water levels and discharge. The maximum velocity was higher in the 3D model (0.09 m/s) than the 2D model (0.078 m/s) due to the fact that the velocity in the 2D model is averaged over the depth. Also, the formation of secondary currents could be seen in 3D simulations, this effect could not be simulated in 2D model.

Here also, before going to simulate the salinity transport in the Nile Estuary, TELEMAC3D was first tested by using 2D and a 3D set of lock-exchange
7 Summary, conclusions and outlook

experiments. As the main phenomenon that governs the salinity transport between the Nile and the sea, gravity currents were the main focus of the verification test cases.

The first set of experiments (2D lock-exchange) was characterized by a negligible transverse effect. The model was able to simulate the experiments very well. In addition, the impact of changing the mass of the denser fluid by changing its length in the tank was analyzed. It was found that the propagation velocity and hence the front position is directly related to the length of the denser fluid.

Unlike the first set of experiments, the second set of experiments was a 3D phenomenon due to the presence of a gate, separating the two tanks of the denser fluid and the lighter one, with a width less than the width of the tanks. In this case, the numerical results agreed fairly well with the experimental ones. Larger differences between numerical and experimental results are observed in the 3D cases compared to the 2D cases. The differences may be because the numerical simulation did not simulate the initial gate release.

The non-hydrostatic approach was essential for both 2D and 3D lock-exchange experiments, in addition to the necessity of using suitable turbulence models (Prandtl’s mixing length model and the k-ε model were used to define the vertical and the horizontal eddy viscosity). Overall, the non-hydrostatic 3D simulation using TELEMAC3D proved to achieve satisfactory results in simulating the complex phenomenon of gravity currents in regular geometry, and it can be used for the Nile Estuary.

The bottom roughness was found to have insignificant influence on the results because of its small values and the short simulation time. The impact of the gate width was also analyzed, it was noticed that the increase of the gate width mainly affects the propagation transverse to the flow direction and its influence on the propagation in the flow direction was smaller.

Gravity currents in the Nile Estuary were then simulated using TELEMAC3D. The mean conditions of flow in the Nile and the water level of the sea were used first to
model the current status and to quantify the propagation of saline water inside the Nile Estuary. A quasi steady state condition was reached after 27 days of simulation. The length of the salt wedge was fluctuating near the surface in a range of 700 m while near the bottom minor fluctuations were noticed. Such fluctuations, although no tides and steady flow conditions, are probably due to the weak balance between the barotropic and baroclinic gradients in tideless estuaries as the case of the Nile Estuary; therefore a changeable direction of the flow occurs. It was also noticed that at the D.S. boundary an outflow occurred at the surface (and in the upper layers) while there was inflow near the bottom.

The salt concentration was found to be variable longitudinally, laterally and vertically. In the longitudinal direction, the concentration decreased from the D.S. towards the U.S. side. In the lateral direction, the higher the water depth the higher was the concentration. In the vertical direction, the concentration increased towards the bottom direction and clear stratification with a brackish water layer at the surface was noticed.

The same three scenarios for the sea level rise that were simulated in the 2D model were simulated also in the 3D model. The results revealed that the sea level rise caused more propagation of saline water towards the Nile with values of 1.2 km, 5.1 km, and 6.6 km in case of sea level rise of 0.24 m, 0.69 m and 1.0 m respectively. To mitigate the sea level rise impact, discharging more water from Edfina Barrage could be required. The discharge of Edfina barrage will be increased by about 1.15, 3.67 and 5.88 BCM/year, such amount is considered as a considerable loss of the Egyptian water budget (55.5 BCM/year). Some compromises could be done in which more salt water intrusion can be allowed to a certain extent.

**Similarities and differences between 2D and 3D models**

Comparing 2D and 3D results, it was found that both had the same results with respect to the water level. A bit higher velocities were recorded in the case of the 3D model (the maximum velocity was 0.09 m/s) if compared to the 2D model (the maximum velocity was 0.078 m/s). Some horizontal eddies were found in both the 2D and the 3D models. The 3D effect of the bathymetry caused variations in the velocity over the
vertical and the formation of secondary currents, those effects were only found in the results of the 3D model while the 2D model could not simulate such phenomena. With respect to salinity transport, the 3D model showed much higher intrusion length (16 km near the bottom) than the 2D model (400 m). Also the 3D model showed a much higher influence of the sea level rise as the values were almost twice as high as the ones of the 2D model. For sea level scenarios of 0.24, 0.69 and 1.0 m, the 2D model resulted an intrusion length of 0.5, 1.9 and 4.2 km, respectively, while the values resulted from the 3D model were 1.2, 5.1 and 6.6 km, respectively.

So, it can be recommended that the 2D model can be used for simulating the water levels and velocities of the Nile Estuary except near the meandering parts. The 3D model is more suitable for simulating the salinity transport in the Nile Estuary, but a 2D model can be also used for a first rough estimation for the intrusion length. 3D model is also recommended for simulating the transport of other substances (e.g. contaminants, sediments or heat).

**Limitations**

Some limitations faced the work in this research and may affect the results. Data availability in terms of bathymetry data or flow data were in general enough. However, it would be better to have more data for calibration purposes, such as the flow in other locations in the domain not only at the boundaries. No measurements for the salinity in the Nile were found, so it was not possible to calibrate the turbulent diffusivity or to compare the numerical results with data collected from the field.

Extending the model by using a wider mesh to include the flood plain, to simulate possible flooding that may occur due to the different sea level rise scenarios, was not considered in this research. However, the impacts on a wider mesh are expected to be very small.

TELEMAC-MASCRIPT modeling system is well established and it is used since many years in different types of numerical models. However, it has some limitations. One of the limitations which related to this research is the sigma transformation used in the
simulation; the sigma transformation can cause numerical errors in some cases (i.e. steep bottom gradient). This problem is known in the literature since decades and no solution for it till now. Using another method or adjusting the code of the model to deal with the sigma transformation was beyond the scope of the research, and it was not possible to quantify the error that could result from the sigma transformation. Some of the numerical schemes which exist in TELEMAC2D or TELEMAC3D cannot be used together, so several trials to choose the suitable schemes and their suitable combinations were carried out.

### 7.2 Outlook

In the following there are suggestions for further research:

1. Setting up an integrated model for the Nile water, the groundwater and the sea water in the Nile Estuary using coupling techniques

2. Using the same procedure and the same modeling tools used in this research to model the last reach of Damietta branch of the Nile River

3. Setting up a larger model to include the two branches of the Nile River (Rosetta branch and Damietta branch) and the groundwater aquifer in the North of Delta to study the saltwater intrusion

4. Developing a management system for the Nile Estuary, the irrigation activities and the groundwater aquifer in the context of saltwater intrusion by using numerical modeling

5. Simulating sediment transport and morphodynamics in the Nile Estuary

6. Studying water quality in the Nile Estuary using a suitable numerical model, for example DELWAQ module, which is mainly from Delft3D but it is coupled with TELEMAC3D, can be used in this context
7 Summary, conclusions and outlook

7. Studying the impact of wind on the gravity currents and salinity transport in tideless estuaries

8. The model is also suitable for investigating the spreading of brine from desalinization (Shehata, 2014; Shehata et al., 2015)
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169
References


