Modelling the influence of the Abu Nakhla pond on the phreatic aquifer in Qatar: present and future scenarios

Joren De Tollenaere

Academiejaar 2014–2015

Scriptie voorgelegd tot het behalen van de graad
Van Master of Science in de geologie

Promotor: Prof. Dr. L. Lebbe
Leescommissie: J. Claus, Prof. Dr. V. Cnudde
VOORWOORD

Eerst en vooral wil ik m’n promotor prof. dr. Lebbe bedanken voor de mogelijkheid om dit onderwerp als masterproef te doen. Ook wil ik hem bedanken voor zijn verhelderende uitleg over de resultaten van de modellen en over de hydrogeologie. Ik wil ook Jasper Claus bedanken voor het gebruik van zijn python scripts om de input van de modellen te maken alsook voor zijn inzicht en aanpassingen aan het model. Gert-Jan Devriese wil ik bedanken voor de morele steun en voor het gebruik van zijn bureau waar we vele leuke uren hebben doorgebracht. En als laatste wil ik Devlin Depret bedanken voor zijn rationele benadering in het steunen bij het schrijven van deze masterproef en zijn kritisch inzicht inzake de resultaten.
# Table of contents

1. INTRODUCTION............................................................................................................. 1

2. STUDY AREA................................................................................................................ 3

3. GEOLOGY ...................................................................................................................... 5
   3.1 Structural geology ........................................................................................................ 5
   3.2 Surface geology .......................................................................................................... 5
   3.3 Stratigraphy .............................................................................................................. 6
      3.3.1 *Umm er Radhuma Formation* ............................................................................. 7
      3.3.2 *Rus Formation* ................................................................................................ 7
      3.3.3 *Dammam Formation* ......................................................................................... 10
      3.3.4 *Dam Formation* ................................................................................................ 11
      3.3.5 *Hofuf Formation* .............................................................................................. 11
      3.3.6 *Sabkhas* ............................................................................................................ 12

4. HYDROGEOLOGY ........................................................................................................ 13
   4.1 General hydrogeology .............................................................................................. 13
   4.2 Head distribution ..................................................................................................... 14
   4.3 Hydrogeological parameters .................................................................................. 19
   4.4 Fresh and salt water distribution ............................................................................. 20

5. CLIMATE AND HYDROLOGY .................................................................................. 23

6. MODELLING SOFTWARE .......................................................................................... 29
   6.1 Evolution of the modelling software ...................................................................... 29
   6.2 MODFLOW .............................................................................................................. 29
      6.2.1 Code concepts ..................................................................................................... 30
      6.2.2 Discretisation of the groundwater reservoir ....................................................... 30
      6.2.3 Finite difference approximation of the groundwater flow ................................ 32
      6.2.4 Iteration with the Strongly Implicit Procedure .................................................. 34
      6.2.5 Cell and boundary types .................................................................................... 35
   6.3 MOC3D .................................................................................................................... 36
   6.4 MOCDENS3D .......................................................................................................... 37
6.5 Packages ........................................................................................................... 38

6.5.1 MODFLOW packages .................................................................................. 38

6.5.1.1 Basic package (.bas-file) ........................................................................ 38
6.5.1.2 Block-Centred-Flow package (.bcf-file) .................................................. 39
6.5.1.3 Well package (.wel-file) ....................................................................... 40
6.5.1.4 Evapotranspiration package (.evt-file) .................................................... 41
6.5.1.5 Strongly Implicit Procedure package (.sip-file) ....................................... 41
6.5.1.6 Name file (Infile.nam) ....................................................................... 41

6.5.2 MOCDENS3D packages ................................................................................ 42

6.5.2.1 MOC package (.moc-file) .................................................................... 42
6.5.2.2 Densin.dat-file .................................................................................. 42
6.5.2.3 Name file (moc.nam) ....................................................................... 42

7. MODEL CONSTRUCTION ..................................................................................... 43

7.1 Base model ...................................................................................................... 43

7.1.1 Location and discretisation of the study area ........................................... 43
7.1.2 Hydrogeological parameters .................................................................... 46
7.1.3 Boundary conditions and initial head values ............................................ 48
7.1.4 Fresh and salt water distribution .............................................................. 51
7.1.5 Recharge .................................................................................................... 53
7.1.6 Evapotranspiration .................................................................................... 53
7.1.7 Time discretisation and closure criterion ............................................... 54

7.2 Adding the pond into the base model ............................................................ 54

7.2.1 Sub-model one: Steady state flow with pond ............................................ 55

7.2.2 Sub-model two: Mimicking steady state with an unsteady state model ...... 57

7.2.3 Sub-model three: From mimicking steady state to full unsteady state ....... 61

7.2.4 Sub-model four: Desiccation and dissipation of the Abu Nakhla pond ....... 62
List of figures

Figure 1: Location of Abu Nakhla in Qatar (Google Earth) ......................................................... 3
Figure 2: Evolution of the Abu Nakhla pond from 1972 to 2009 (ESC Archives) ........ 4
Figure 3: Location of geological structures and surface geology in Qatar (Al-Saad, 2005). .................................................. 5
Figure 4: Stratigraphy and lithology of the Eocene sediments in Qatar (Al-Saad, 2005) ..... 6
Figure 5: The depositional facies of the Rus Formation in Qatar (Eccleston, et al., (1981) modified by Elobaid) ................................................................. 9
Figure 6: Head distribution in the Umm er Radhuma Formation aquifer of Qatar (Lloyd, et al., 1987) ................................................................. 15
Figure 7: Head distribution in the Rus Formation aquifer of Qatar (Lloyd, et al., 1987) . 16
Figure 8: Head distribution in the Dammam Formation aquifer of Qatar (Alsharhan, et al., 2001). ......................................................................................... 17
Figure 9: Potentiometric surface map in meter amsl of Qatar based on results from April 2009 (Schlumberger, 2009). ........................................................................ 18
Figure 10: Total Dissolved Solids (TDS) isoconcentration map in ppm (Schlumberger, 2009). ......................................................................................... 21
Figure 11: Total annual rainfall (mm yr\(^{-1}\)) of Qatar from 1972 to 2005 (Amer, et al., 2008). ......................................................................................... 23
Figure 12: Average annual total rainfall (mm yr\(^{-1}\)) between 1989 and 2007 (Schlumberger, 2009). ......................................................................................... 24
Figure 13: A hypothetical discretised aquifer system with five rows, nine columns and five layers (McDonald & Harbaugh, 1988). ........................................................................ 31
Figure 14: Block-centred finite difference cells (McDonald & Harbaugh, 1988) .... 31
Figure 15: Flow into cell i, j, k from cell i, j-1, k (McDonald & Harbaugh, 1988) .... 33
Figure 16: Discretised aquifer showing boundaries and cell designations (McDonald & Harbaugh, 1988). ........................................................................ 35
Figure 17: Discretisation of the simulation time in stress periods and time steps including the formulas to calculate the first time step and the following steps (McDonald & Harbaugh, 1988) ........................................................................ 39
Figure 18: Volumetric evapotranspiration \(Q_{ET}\) as a function of head h, in a cell where d is the extinction depth and \(h_s\) the ET surface elevation (McDonald & Harbaugh, 1988). .... 41
Figure 19: A georeferenced Google Earth image visualising the study area with a large grid (1 km x 1 km cells) and the normal grid (100 m x 100 m cells). ......................... 44
Figure 20: Potentiometric surface map of Qatar with the study area visualised as the black rectangle (Schlumberger, 2009). .......................................................... 48

Figure 21: Cross-section through Qatar with the different hydrogeological units with their respectively TDS values (Harhash & Yousif, 1985). ............................................... 52

Figure 22: Overview of the different sub-models with the input and output used. ........ 55

Figure 23: Picture of the water level of the Abu Nakhla pond on 8 May 2015 measuring 35.10 m amsl. ........................................................................................................ 56

Figure 24: Boundary conditions for sub-model one. 1 are the active cells, -1 are the constant-head cells with TDS 3,000 ppm from the Dammam and upper Rus Formation aquifer and -4 are the constant-head cells with TDS 2,000 ppm from the Abu Nakhla pond. .................................................................................. 56

Figure 25: Interpolated initial heads of each layer of sub-model one. ................. 57

Figure 26: Visualisation of the raster file with the bathymetry of the Abu Nakhla pond with: (1) Light green is the A basin with interpolated values, (2) Dark blue is the B basin with interpolated values, (3) Red is the C Basin with no direct measurements and is put at 33 m, (4) Light blue are manually interpolated cells with their neighbour and (5) Purple are the cells surrounding the pond with values set at 32 m. ............................................ 59

Figure 27: Visualisation of the measured bathymetry lines with their spatial variability, used for the interpolation for the bottom of the Abu Nakhla pond........................................... 60

Figure 28: Horizontal cross-section of the groundwater head (m) through layer five of the steady state flow base model, stress period five. ...................................................... 66

Figure 29: Horizontal cross-section of the groundwater head (m) through layer five of the unsteady state base model, stress period fifteen. The dark red colour in the upper left corner represents inactive cells ................................................................................. 67

Figure 30: Vertical cross-section of the groundwater head (m) along row 10 of the unsteady state base model, stress period fifteen. The dark red colour represents inactive cells... 67

Figure 31: Vertical cross-section of the groundwater head (m) along row 71 of the unsteady state base model, stress period fifteen. The dark red colour represents inactive cells... 68

Figure 32: Horizontal cross-section of the groundwater head (m) through layer one of sub-model one, stress period five. ................................................................. 69

Figure 33: Vertical cross-section of the groundwater head (m) along row 71 of sub-model one, stress period five. ...................................................................................... 69

Figure 34: Horizontal cross-section of the groundwater head (m) through layer one of sub-model two, stress period fifteen. The blue colour represents dry cells...................... 70

Figure 35: Horizontal cross-section of the groundwater head (m) through layer five of sub-model two, stress period fifteen. The dark blue colour in the upper left corner represents dry cells................................................................. 71
Figure 36: Vertical cross-section of the groundwater head (m) through layer five of sub-model two, stress period fifteen. The dark blue colour represents dry cells. .............................. 71

Figure 37: Horizontal cross-section of the groundwater head (m) through layer five of sub-model three, stress period fifteen. The dark red colour in the upper left corner represents inactive cells........................................ 72

Figure 38: Vertical cross-section of the groundwater head (m) along row 10 of sub-model three, stress period fifteen. The dark red colour represents inactive cells...................... 72

Figure 39: Vertical cross-section of the groundwater head (m) along row 71 of sub-model three, stress period fifteen. The dark red colour represents inactive cells.......................... 73

Figure 40: Difference figure of the groundwater head (m) through layer five of sub-model four, stress period ten minus stress period one. ................................................................. 73

Figure 41: Horizontal cross-section of the groundwater head (m) through layer five of sub-model four, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells. .............................. 74

Figure 42: Vertical cross-section of the groundwater head (m) along row 71 of sub-model four, stress periods three, five, eight and ten. The dark red colour represents inactive cells. .............................................................................. 74

Figure 43: Head (m) versus time (d) of layer one and layer five of a cell at the centre of the Abu Nakhla pond (sub-model four). ............................................................................. 76

Figure 44: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (sub-model four). .............................................. 77

Figure 45: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (sub-model four). .............................................. 77

Figure 46: Head (m) versus depth (expressed as layers) of the ten stress periods (sub-model four). When the head of a cell drops to 0 m, it represents a dry cell.................. 78

Figure 47: Horizontal cross-section of the groundwater head (m) through layer five with max K_h, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells. .............................. 80

Figure 48: Vertical cross-section of the groundwater head (m) along row 71 with max K_h, stress periods three, five, eight and ten. The dark red colour represents inactive cells... 81

Figure 49: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (max K_h). ......................................................................................... 81

Figure 50: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max K_h). ......................................................... 82
Figure 51: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max $K_h$).

Figure 52: Head (m) versus depth (expressed in layers) of the ten stress periods (max $K_h$). When the head of a cell drops to 0 m, it represents a dry cell.

Figure 53: Horizontal cross-section of the groundwater head (m) through layer five with min $K_h$, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.

Figure 54: Vertical cross-section of the groundwater head (m) along row 71 with min $K_h$, stress periods three, five, eight and ten. The dark red colour represents inactive cells.

Figure 55: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (min $K_h$).

Figure 56: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min $K_h$).

Figure 57: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min $K_h$).

Figure 58: Head (m) versus depth (expressed in layers) of the ten stress periods (min $K_h$).

Figure 59: Horizontal cross-section of the groundwater head (m) through layer five with max $K_v$, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.

Figure 60: Vertical cross-section of the groundwater head (m) along row 71 with max $K_v$, stress periods three, five, eight and ten. The dark red colour represents inactive cells. Continued on the next page.

Figure 61: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (max $K_v$).

Figure 62: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max $K_v$).

Figure 63: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max $K_v$).

Figure 64: Head (m) versus depth (expressed in layers) of the ten stress periods (max $K_v$). When the head of a cell drops to 0 m, it represents a dry cell.
Figure 65: Horizontal cross-section of the groundwater head (m) through layer five with min $K_v$, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells. ......................................................... 94

Figure 66: Vertical cross-section of the groundwater head (m) along row 71 with min $K_v$, stress periods three, five, eight and ten. The dark red colour represents inactive cells. Continued on the next page ........................................................................ 94

Figure 67: Head (m) vs time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (min $K_v$). ........................................................................................................ 95

Figure 68: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min $K_v$). ...................................................... 96

Figure 69: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min $K_v$). ...................................................... 96

Figure 70: Head (m) versus depth (expressed in layers) of the ten stress periods (min $K_v$). When the head of a cell drops to 0 m, it represents a dry cell......................................................... 97

Figure 71: Horizontal cross-section of the groundwater head (m) through layer five with max SF$[1]$, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells. ......................................................... 98

Figure 72: Vertical cross-section of the groundwater head (m) along row 71 with max SF$[1]$, stress periods three, five, eight and ten. The dark red colour represents inactive cells. Continued on the next page. ........................................................................ 98

Figure 73: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (max SF$[1]$)........................................................................................................ 99

Figure 74: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max SF$[1]$). ...................................................... 100

Figure 75: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max SF$[1]$). ...................................................... 100

Figure 76: Head (m) versus depth (expressed in layers) of the ten stress periods (max SF$[1]$). ......................................................................................................................... 101

Figure 77: Horizontal cross-section of the groundwater head (m) through layer five with min SF$[1]$, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells. ......................................................... 102
Figure 78: Vertical cross-section of the groundwater head (m) along row 71 with min SF[1], stress periods three, five, eight and ten. The dark red colour represents inactive cells. Continued on the next page. ................................................................. 102

Figure 79: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (min SF[1]). .......................................................................................... 103

Figure 80: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min SF[1]). .................................. 104

Figure 81: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min SF[1]). .................................. 105

Figure 82: Head (m) versus depth (expressed in layers) of the ten stress periods (min SF[1]). When the head of a cell drops to 0 m, it represents a dry cell. .......................................................... 105

Figure 83: Horizontal cross-section of the groundwater head (m) through layer five with max SF[2], stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells. .................................................. 106

Figure 84: Vertical cross-section of the groundwater head (m) along row 71 with max SF[2], stress periods three, five, eight and ten. The dark red colour represents inactive cells. 107

Figure 85: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (max SF[2]). ................................................................. 108

Figure 86: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max SF[2]). .................................. 108

Figure 87: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max SF[2]). .................................. 109

Figure 88: Head (m) versus depth (expressed in layers) of the ten stress periods (max SF[2]). .................................................................................................................. 109

Figure 89: Horizontal cross-section of the groundwater head (m) through layer five with min SF[2], stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells. 110

Figure 90: Vertical cross-section of the groundwater head (m) along row 71 with min SF[2], stress periods three, five, eight and ten. The dark red colour represents inactive cells. 111

Figure 91: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (min SF[2]). ........................................................................................................ 112
Figure 92: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min SF[2]). ................................................................. 112

Figure 93: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward, eastward northward and southward directions (min SF[2]). ........................................................................................................ 113

Figure 94: Head (m) versus depth (expressed in layers) of the ten stress periods (min SF[2]). When the head of a cell drops to 0 m, it represents a dry cell. ................. 114

Figure 95: Difference figure of the groundwater head (m) through layer five of the last stress period from sub-model one minus the last stress period from the steady state base model. ................................................................. 115

Figure 96: Difference figure of the groundwater head (m) through layer five of the last stress period from sub-model three minus the last stress period from the unsteady state base model. ........................................................................................................ 116

Figure 97: Difference figure of the groundwater head (m) through layer five of the last stress period from sub-model four minus the last stress period from the unsteady state base model. ................................................................. 116

Figure 98: Overview the head (m) versus time (d) of a cell in the centre of the pond in layer five of sub-model four and the sensitivity analyses. ................................................. 118
List of tables

Table 1: Surface runoff estimates for Qatar (Schlumberger, 2009)......................... 26
Table 2: Direct and indirect recharge area with the percentage of the direct and indirect recharge of the total annual rainfall (Eccleston, et al., 1981). ............................. 26
Table 3: The vertical discretisation of the modelled area with the number of layers, thickness of the layers and the geology and lithology they represent. ......................... 45
Table 4: Overview of the transmissivity, storage factor and vert (reciprocal of the hydraulic resistance) of each layer. ........................................................................... 47
Table 5: Overview of the heads of the constant-head cells for the western boundary (north to south direction), eastern boundary (north to south direction), northern boundary (west to east direction) and southern boundary (west to east direction). ................................. 49
Table 6: TDS values and salt water concentrations used in the models. ....................... 53
Table 7: Extinction depths for different soil types and land covers (Shah, et al., 2007). 54
Table 8: The hydraulic conductivities, storage factors, TOP, BOT and verts for the six layers with LAYCON set at three................................................................. 59
Table 9: The hydraulic conductivities, storage factors, TOP, BOT and verts for the six layers with LAYCON set at three........................................................................ 62
Table 10: Minimum and maximum horizontal conductivity for each of the six layers including the transmissivity................................................................. 63
Table 11: Minimum and maximum vert for each of the eleven layers of the gypsiferous Rus Formation................................................................. 64
Table 12: Minimum and maximum storage factor near the water table and storage factor of the aquifer................................................................. 64
Table 13: Volume difference between sub-model three and the unsteady state base model with the corresponding infiltrated water column over the pond area. .......... 117
Table 14: On the left: the head (m) of stress period (SP) five to ten of sub-model four and the sensitivity analyses of layer five; On the right: the difference in head of the sensitivity analyses compared to sub-model four expressed as a percentage (%) of stress period (SP) five to ten of layer five. ...................................................... 120
Table 15: The duration of each of the fifteen stress periods in days with their cumulative duration expressed in days and years. ...................................... 154
Table 16: The incrementally increasing time steps (d) of the fifteen stress periods used in sub-model two and three. Sub-model four only uses ten of the fifteen stress periods while sub-model two uses the same values but 100 times smaller. .......................... 155
The Abu Nakhla pond is located just outside of Doha city, Qatar. It is an artificial lake that was created in the late 1970s by dumping excess treated sewage effluent (TSE) from the Doha West and the Doha South sewage water treatment plants into a natural depression. Ever since, water from this pond has been infiltrating into the subsoil and is recharging the groundwater reservoir, raising the groundwater heads in the vicinity of the pond. Due to the rapid urbanisation and expansion of the city of Doha, it was decided to shut down the water supply towards this pond and to let it desiccate so the area can be used for future building projects. By infiltration into the subsoil, evapotranspiration and injecting water of the pond into the deeper subsoil, the water level in the pond will lower until no traces are left at the surface. In the groundwater reservoir however, relicts of this pond will be present for a far longer time.

The aim of this study is to simulate the desiccation and dissipation of the Abu Nakhla pond in the future under natural conditions, and this mainly in respect to the groundwater reservoir. In other words, how will the groundwater heads in the surrounding groundwater reservoir evolve once the water supply towards this pond has stopped? ‘Under natural conditions’ refers to the natural conditions under which the pond desiccates and dissipates: infiltration into the subsoil and evapotranspiration. This evapotranspiration is high due to the desert climate in Qatar and exceeds the rainfall. Injection of water from the pond into the deeper subsoil has been neglected as it is only a minor component that influences the desiccation of the pond compared to the infiltration and evapotranspiration.

To start, a model of the current situation of the Abu Nakhla pond is created and simulated until an equilibrium is reached between the pond and the groundwater reservoir. This model is then used for the simulation of the desiccation and dissipation of the pond, by removing the constant water level of the pond (as in removing the water supply towards the pond). This last model was then subjected to a series of sensitivity analyses to better understand the influence of each hydrogeological parameter on the dissipation of the pond.

For the construction of this model both the geology and hydrogeology present in the study area are important. There are three geological formations of importance for this study, from oldest to youngest: the Umm er Radhuma Formation, the Rus Formation and the Dammam Formation. Together they form two aquifers and one aquitard. The lower aquifer comprises of the Umm er Radhuma Formation and the upper (phreatic) aquifer of the Upper Rus and Dammam formations. The intermediate aquitard consists out of several thick gypsum layers from the Lower Rus Formation. This lower Rus aquitard forms a flow barrier between the upper aquifer and the lower aquifer which strongly decrease the influence of the Abu Nakhla pond on this lower aquifer.

Besides this discretisation of the geology and hydrogeology, initial hydrogeological parameters are needed to conceptualise the hydrogeological characteristics of the
aquifers and the aquitard into the model. The base hydrogeological parameters, to form the basis of the desiccation and dissipation model of the Abu Nakhla pond, are obtained from literature. To simulate this model, specialised software is used which is based on the MODFLOW-code and is called MOCDENS3D. With this software it is possible to model density dependant flow in three-dimensions.

The study is divided in several chapters. First of all, chapter 2 will give a more in depth overview of the study area and the history of the Abu Nakhla pond. Then, an overview of the stratigraphy, including the surface and structural geology, will be given in chapter 3. A detailed discussion of the hydrogeology is given in chapter 4 followed by a literature study of the climate and hydrology in chapter 5. A technical discussion of the software is given in chapter 6. Chapter 7 discusses the conceptualisation of the aquifers and aquitard into the model and includes a quantification of the initial and hydrogeological parameters. The results and discussion are elucidated in chapter 8 and a conclusion can be found in chapter 9. Last but not least, a Dutch summary is presented in chapter 10.
2. STUDY AREA

Qatar is a peninsula located in the Middle-East and lies within the Persian Gulf. In the south, Qatar shares a border with Saudi Arabia. The total length of Qatar is approximately 189 km in north to south direction and the width ranges between approximately 55 km to 85 km in east to west direction. The total surface area is 11,586 km².

The terrain of Qatar is characterised by a mostly flat and barren desert with elevations ranging between 0 m at the coast to approximately 55 m above mean sea level (amsl) in the central-north region. The highest point in Qatar lies in the south called Tuwayyir al Hamir which is approximately 103 m amsl. Qatar’s economy is best known for its petroleum, natural gas and fish production (Qatar.com, 2014).

The sewage pond of Abu Nakhla is located approximately 20 km outside the capital city centre of Doha. The dimensions of the Abu Nakhla pond are approximately 3.1 km in east to west direction and approximately 2.5 km in north to south direction with an approximate surface area of 5.1 km². This was measured using a satellite image from Google Earth taken on the 2nd of July 2014.

The origin of the Abu Nakhla pond is around the year 1972. It was then that the need to store large volumes of sewage effluent was needed and thus a small natural depression (small valley) was used. Aerial photographs from 1972 to 2009 show an overview of the variation of the pond (Figure 2). This variation is caused by the daily variation in discharged effluent and due to the infiltration and high evaporation rates. In July of 1985, effluent pumping facilities were constructed while the construction of the embankment around the pond weren’t started until February 2008 (finished in March 2008). In September 2009,
construction of dykes were started to enclose the pond even further and the construction was completed in October 2009.

The estimated volume capacity of the pond, in a stable scenario, is about 20,000,000 m³. Between 2006 and 2009, an average discharge rate in the Abu Nakhla pond was approximately 50,000 m³ d⁻¹ to 100,000 m³ d⁻¹ with an average infiltration and evaporation rate of 50,000 m³. Because of the expansion of the city of Doha and the close proximity of the pond to the city, it was decided to remove the water of the pond and use the area for future expansions. In January 2009 the discharge in the pond was stopped and an incentive was started to inject the treated sewage effluent into two injection wells next to the pond with an average discharge rate of 11,000 m³ d⁻¹. In March 2014, 80% of the pond was desiccated while in November 2014, the water level of the pond was below one meter (ASHGAL). It was planned that the pond should be completely dry at the end of 2014 (Gulf times, 2014).

Figure 2: Evolution of the Abu Nakhla pond from 1972 to 2009 (ESC Archives).
3. GEOLOGY

3.1 Structural geology

A large anticline runs throughout Qatar in the north to south direction called the Qatar Arch and declines towards the north. Smaller longitudinal folds are superposed onto this anticline: in the northeast there is the smaller anticline the Simsima Dome or Simsima Arch and on the west side there is the Dukhan anticline. Around the Dukhan anticline multiple anticlinal and synclinal structures are present, as can be seen on Figure 3. It is believed that these structural elements represent the eastern to northern extension of the central Arabian Arch (Sugden, 1962). These large geological structures have also controlled the distribution of the exposed Eocene Rus and Dammam formations (Al-Saad, 2003). Besides these large arches and folds, one of the most significant features expressed on the surface are a large number of shallow depressions related to dissolution of gypsiferous and calcareous beds underlying Qatar. These structures are circular in shape and the diameters of the roughly 850 depressions ranges from a few hundreds of meters up to about three kilometres (Lloyd, et al., 1987).

3.2 Surface geology

The most widespread outcropping formation in Qatar is the Dammam Formation, which represents about 80% of the total land surface. The Middle Eocene Rus Formation is exposed on about 10% of the land surface, distributed as smaller patches spread widely over the whole of Qatar. In south Qatar there is a small area of outcropping Middle to Late Miocene Dam and Hofuf formations. Along the coastline several Sabkhas are present. This is visualised in Figure 3 (Al-Saad, 2003, 2005).
3.3 Stratigraphy

The Umm er Radhuma Formation, the Rus Formation and the Dammam Formation are the geological formations of importance to this study, as these formations occur in the subsoil at the Abu Nakhla site. However, a short geological description will be given of the Dam Formation, the Hofuf Formation and sabkhas as well.

![Figure 4: Stratigraphy and lithology of the Eocene sediments in Qatar (Al-Saad, 2005).](image-url)
3.3.1 Umm er Radhuma Formation

The oldest formation of the Palaeogene or early Eocene is the Umm er Radhuma Formation (UER). Unlike the other Eocene and Miocene formations, the UER has no outcrops in Qatar. The UER is conformably overlying the Aruma Formation, the uppermost Cretaceous unit, which is a hard marine crystalline limestone. The sedimentation process of the UER is characterised by a marine transgression over the Persian Gulf area at the beginning of the Palaeocene to Lower Eocene where it was deposited in a shallow marine (neritic) environment (Mukhopadhyay, et al., 1996). The transition of the Aruma Formation and the basal section of the UER can be lithological identified by the occurrence of dark coloured shales and marl beds with the presence of local anhydrite layers (Lloyd, et al., 1987).

The lithology of the Umm er Radhuma Formation is dominated by calcareous facies depositions consisting of dolomites and limestones. The thickness ranges from 270 m to 370 m. Even though the UER underlying Qatar consists of a well-bedded calcareous sequence, some silicified zones do occur in the form of chert and silicified limestone or dolomite. This zone is present at about 18 m to 20 m below the top of the formation and constrains the hydraulic continuity between the upper UER and lower UER where the part of the UER above the siliceous limestone has a higher permeability and the part of the UER below the siliceous limestone has a lower permeability (Lloyd, et al., 1987).

3.3.2 Rus Formation

The Rus Formation conformably lies on top of the Umm er Radhuma Formation. The contact between the two formations is not always obvious because the lithologies of both formations are rather similar. In some places however, evidence of dissolution and dolomitization can be noticed on the boundary (Al-Hajari & Kendall, 1992). According to Eccleston & Harhash (1982) the contact between the UER Formation and the Rus Formation is characterised by a general facies change and the disappearance of marine fauna. This abrupt facies change from the UER Formation depositional character to the Rus Formation depositional character over a large part of the area suggest a possible sedimentary hiatus after the deposition of the UER Formation. It is deposited in a shallow marine environment and the hiatus can be associated with uplift and land emergence in some positive structurally controlled areas (Lloyd, et al., 1987).

The Rus Formation deposits are the oldest outcropping rocks in Qatar. Because of scarcity of fossils in the Rus Formation some dispute exists on the dating of the formation. Based on the presence of planktonic foraminifera in the underlying Umm er Radhuma Formation, the Rus Formation was dated as Lutetian in Al-Saad (2003), but the same author changed the age to Ypresian in Al-Saad (2005). The thickness in Qatar ranges between 33 m and 128 m. It is subdivided into two members: (1) the lower Traina Member and (2) the upper Al-Khor Member (Al-Saad, 2003).
The Traina Member has a thickness up to 78 m. The lithology consists of a white to light grey gypsiferous, marly, clayey, dolomitic limestone with thin yellow beds. The boundary between the Traina Member and the Umm er Radhuma Formation can be characterised by a change from the dolomitic limestone of the UER Formation to the gypsiferous limestone of the Traina Member. The upper boundary is defined by the contact between the grey gypsiferous dolomitic limestone from the Traina member and the white chalky limestone from the Al-Khor Member. No significant fauna is found within the Traina Member. Gypsum represents the thickest facies in this member and towards the north of Qatar, this facies gradually changes to a dolomitic cherty limestone. It was believed to be deposited in a restricted lagoon to supratidal setting (Al-Saad, 2003).

The Al-Khor Member has a thickness up to 50 m. The lithology consists of a white to light grey, yellowish dolomitic chalky limestone with some gypsum, marls and clay intercalation. The top of the Al-Khor Member is placed at the contact between the grey dolomitic limestone of the Al-Khor Member and the yellowish shale of the overlying Dammam Formation. Shark teeth, foraminifera, Mollusca and echinoid fragments can very rarely be found. It was believed to be deposited in an open marine tidal to subtidal zone (Al-Saad, 2003).

The Rus Formation is subdivided into two major provinces: A northern province characterised by the occurrence of a depositional carbonate facies (dolomitic limestone) and a residual gypsum facies and a southern province characterised by the occurrence of a depositional sulphate facies (evaporitic, argillaceous, gypsiferous dolomitic limestone). This has been visualised in Figure 5. The boundary between the two provinces is clearly reflected as a V-shaped line with its apex at the Qatar Arch. The distribution and thickness of the different facies in the provinces are influenced by the structural elements such as the Simsima Arch and Qatar Arch. The basic lithology of both provinces is the same, dolomitic limestone, but the gypsum present in the northern region was eliminated due to post-depositional dissolution effects (present in the Traina member as discussed above). This results in the depositional sulphate facies, which is present at the study area, containing more gypsum than the residual sulphate facies, making it less permeable for groundwater to flow. North of the residual sulphate facies the gypsum is completely eliminated and a depositional carbonate facies remains.

Looking at the depositional setting of the Rus Formation it is believed that the southern province was deposited in a relatively deep environment while the northern province was deposited in a shallower environment (Al-Saad, 2003). Even though a clear dissimilarity exists between the two facies, the dissolution of gypsum has complicated the identification of the boundary. Collapse features due to this dissolution process also occurs in both facies (Lloyd, et al., 1987).

In the southwest of Qatar, another small band of a depositional carbonate facies can be depicted which runs along the Dukhan anticline.
Figure 5: The depositional facies of the Rus Formation in Qatar (Eccleston, et al., 1981) modified by Elobaid

3. GEOLOGY

9
3.3.3 Dammam Formation

The Dammam Formation is subdivided into four members, from eldest to youngest: the Midra Shale Member, the Dukhan Member, the Umm Bab Member and the Abaruq Member. The thickness of the formation ranges between 30 m to 52 m and the boundary between the Dammam Formation and the Rus Formation appears to be conformable on the regional scale, as the light grey marly limestone of the Rus Formation gradually changes into the light yellow or green claystone of the Dammam Formation. However, the contact between the two formations represents the boundary between the Ypresian and Lutetian which is considered to be a disconformity. In the northeast of Qatar an abrupt facies change is present as the Umm Bab Member there lies disconformably on top of the Rus Formation while the Midra Shale and Dukhan members are missing. This is probably related to the activation of paleohighs in the northern part of Qatar, such as the Simsima Dome (Al-Saad, 2005; Holail, et al., 2005).

The Midra Shale Member is only exposed in southwest and central Qatar as explained in the previous paragraph. In southwest Qatar, the Midra Shale Member consists of a soft, grey to light green, fossiliferous, fissile, calcareous and gypsiferous shale with two thin beds of marl ranging between 0.3 m and 0.5 m in thickness. The thickness of the Midra Shale Member ranges here between 2 m and 6 m. In central Qatar the Midra Shale Member consists of compact, massive, hard, grey to light green fossiliferous, partially gypsiferous, calcareous claystone interbedded with two beds of argillaceous limestone at the base and in the middle. Thin bands of marl, with a thickness ranging from 2 cm to 4 cm, are intercalated within this facies. The thickness of the Midra Shale Member ranges here between 4 m and 9 m. The boundary between the base of the Midra Shale Member and the Rus Formation is characterised by the presence of shark teeth, while in the upper part Mollusca fossils can be depicted. In some beds of the Midra Shale Member some ironstone nodules can occur.

Above the Midra Shale Member lies the Dukhan Member. This member is also only exposed in southwest and central Qatar. It consists of a massive, nodular grey to light yellow to brown limestone and is abundant in fauna such as Nummulites and Alveolina. The base of the Dukhan Member is characterised by mudstone facies because of a shallowing upward cycle due to transgression of the Eocene Sea, while wackestone and packstone textures become abundant towards the top. This member is the thinnest unit within the Dammam Formation with a thickness ranging between 1 m and 2 m.

The Umm Bab Member is exposed in whole of Qatar. It consists of a hard, massive light grey to creamy dolomitic limestone including a very thin marly bed at the base and a thin cherty lens at the top. The boundary between the Dukhan Member and the Umm Bab Member is characterised by a yellowish, fossiliferous marly limestone of about a 0.3 m thickness, which contains Alveolines, molds of pelecypods and gastropods. The total thickness of this member ranges between 15 m to 30 m.
The Abaruq Member is only exposed in southwest Qatar and consists of dark yellow, hard marly limestone at the base that gradually changes upwards into light grey massive thin-bedded, partially nodular dolomitic limestone with numerous molds and casts of molluscs. Some chert occurs as intercalation zones with dolomitic limestones. The thickness is approximately 12 m (Al-Saad, 2005).

The Palaeocene is characterised by a major transgression of the Tethyan Ocean establishing shallow marine conditions over a vast area. These conditions persisted until the Middle Eocene when the sea started to retreat. This is reflected in the lithological facies and biofacies of the Dammam Formation. The formation is believed to be deposited in a warm shallow marine environment in the tidal to subtidal zones which is implied by the presence of intensive dolomitization, Alveolines and Nummulites. The Midra Shale Member sediments suggest a relatively deep, low energy marine environment with a high rate of terrigenous sediment influx. The Dukhan Member suggest a more protected marine basin due to the limestone and Alveolina and Nummulites while the Umm Bab and Abaruq members suggest a more laid down and protected shallow marine environment indicated by the presence of gypsum crystals (Al-Saad, 2005).

3.3.4 Dam Formation

After the deposition of the Dammam Formation widespread emergence occurred and caused considerable erosion. During the Miocene, the marine conditions were re-established and the Dam Formation could be deposited and consists of marls, chalks and limestones (Lloyd, et al., 1987). The thickness ranges between 0 m to 80 m (Sadiq & Nasir, 2002). As visualised in Figure 4, the Dam Formation has only few outcrops in the whole of Qatar.

The Dam Formation is subdivided into three members: the Salwa Member, the Al Nakhsh Member and the Abu Samrah Member.

The Salwa Member consists of a calcareous-siliciclastic series interbedded with a few brown and red layers in the overall pale grey lithofacies.

The Al Nakhsh Member consists of evaporates, calcareous rocks, claystone and siltstone at the bottom while at the top brown and red coloured argillaceous and arenaceous rocks rest on a thick gypsum layer.

The Abu Samrah Member is lithological similar to the Salwa Member. It consists of dolomitic limestones and limestones classified as grain- to rudstones (Dill, et al., 2005).

3.3.5 Hofuf Formation

The Hofuf Formation was deposited in the Upper Miocene to Pliocene. It consists of fluvial sediments with coarse sand and sandstone with pebbles of various rocks which are derived from the Arabian shield and the Arabian Shelf and transported by large river
systems. The Hofuf Formation is approximately 18 m thick (Sadiq & Nasir, 2002; Al-Saad, et al., 2002).

### 3.3.6 Sabkhas

Sabkhas are saline planes developed in the Holocene. Two types of sabkhas exist: inland sabkhas and coastal sabkhas. Combined, they cover approximately 7% of the land surface with coastal sabkhas being the most widespread type covering an area of 590 km². Sabkhas are silty soils with high salinities and contain mainly quartz grains, mud and evaporites. Their thickness ranges from 0 m to 20 m (Ashour, 2013).
4. HYDROGEOLOGY

4.1 General hydrogeology

Qatar has two major aquifers which are dominated by dissolution induced permeability: the Umm er Radhuma Formation and the Rus Formation (Lloyd, et al., 1987). Both aquifers have very different characteristics due to their different geologies. The main outcropping Dammam Formation is only considered to be a small aquifer.

Below the Umm er Radhuma Formation the Aruma Group is present. The basal shales of the UER act as aquitards separating the Aruma Group sediments from the overlying calcareous facies of the UER aquifer. The middle part of the UER consists of calcareous limestone with many fissures and is the most permeable aquifer layer. The top part of the UER aquifer is dolomitic and karstified, infilled with argillaceous sediments. The aquifer properties are rather moderate where these dolomitic zones with fissures occur (Mukhopadhyay, et al., 1996). A siliceous limestone zone occurring near the top of the UER (at about 20 m) constrains the continuity between the UER aquifer and the Rus aquifer. Water in the UER aquifer is mainly transported through secondary porosity induced by dissolution processes as intergranular permeability is rather low (Sharaf, 2001).

The Rus Formation has two different provinces with characteristic facies. The north contains a depositional carbonate facies and a residual sulphate facies, the south contains a depositional sulphate facies (Figure 5). Pleistocene groundwater flow mainly occurred during pluvial periods leading to post-depositional permeability development, i.e. dissolution of the evaporites. During such periods, the northern province acted as a discharge zone for the UER aquifer with groundwater flowing from this aquifer through the depositional carbonate facies of the Rus Formation. In the south, groundwater is mainly present in fissures and cavernous parts in the depositional sulphate facies created by dissolution of the evaporites, but where the Midra Shale Member is present, the dissolution of the evaporites is retarded (Schlumberger, 2009). It can be concluded that hydraulic continuity exists between the UER and Rus aquifer which is only constrained by the siliceous limestone in the upper part of the UER, illuminated in previous paragraph, and due to some shales present in the lower Rus Formation. When the depositional sulphate facies overlies the UER, the hydraulic continuity between the two aquifers diminishes rapidly away from the depositional calcareous facies because of the presence of basal shales. A transition can be depicted from hydraulic continue aquifers in the north to two distinct aquifers in the south (Lloyd, et al., 1987).

The Dammam Formation is considered to be a shallow aquifer. The dolomitic and chalky limestone part forms the most important aquifer while the shaly and marly limestones of the basal member acts as an aquitard (Mukhopadhyay, et al., 1996).

Karstification occurs near the surface aquifers of Qatar. Sinkholes created by the karstification penetrate the Dammam Formation and links the surface with the Rus
Formation. During rainfall events, the water level in the sinkholes will rise as the regional water table rises and they can be flooded by the surface water runoff. The depressions found over the whole of Qatar are former sinkholes filled with autochthonous material which explains the high storage coefficient and transmissivity measured around the margins (Sadiq & Nasir, 2002).

4.2 Head distribution

The head distribution of the main aquifers, the Umm er Radhuma and Rus aquifer, and the head of the Dammam aquifer are visualised in respectively Figure 6, Figure 7 and Figure 8. The distribution of the heads of the Umm er Radhuma Formation aquifer is quite uniform as it shows a regional scale distribution, visualised on Figure 7. The head ranges from about 6 m amsl in the south of Qatar to 3 m amsl in the north of Qatar.

The head of the Rus Formation at the lateral boundaries is controlled by the sea. A change in head relationship between the Umm er Radhuma and Rus aquifer across the peninsula can be seen. In the calcareous part of the Rus Formation in the north of Qatar, the head of the Rus Formation exceeds the head of the underlying UER, resulting in downward flow in the central part where recharge occurs. Towards the sea, the heads decrease and the difference in head between the Rus and the UER is reversed, thus the head of the UER exceeds the head of the Rus Formation (Lloyd, et al., 1987). The head of the Rus Formation clearly follows the Qatar Arch, with the highest values being located on the southern part in the depositional sulphate facies. At the western side of Qatar, near the Dukhan anticline, a big drop in head can be depicted. A sabkha which forms an evaporative discharge area for the Rus Formation aquifer is situated there. Heads can be as low as -3 m amsl in this area (Lloyd, et al., 1987).

In the Dammam Formation aquifer (Figure 8) a similar trend can be noticed as in the Rus Formation aquifer in central and southern Qatar. The heads show a high in the Qatar Arch in the southern part and decrease towards the edges of the peninsula. In northern Qatar a more gradual distribution can be depicted, the heads are lower than in the south and never exceed the Rus Formation aquifer heads.

A more recent potentiometric surface map is presented by Schlumberger (2009) in Figure 9. The map represents the heads of the upper aquifer system (Dammam and upper Rus formations). The largest heads mostly occur along the central axis of Qatar while the heads decrease towards the sea. Starting in the centre and going towards the northeast, a zone of depression cones can be depicted. These depression cones have heads as low as -20 m amsl. These depressions are induced by extensive pumping by farmers (irrigation, cattle) or by municipal wells.
Figure 6: Head distribution in the Umm er Radhuma Formation aquifer of Qatar (Lloyd, et al., 1987).
Figure 7: Head distribution in the Rus Formation aquifer of Qatar (Lloyd, et al., 1987).
Figure 8: Head distribution in the Dammam Formation aquifer of Qatar (Alsharhan, et al., 2001).
Figure 9: Potentiometric surface map in meter amsl of Qatar based on results from April 2009 (Schlumberger, 2009).
4.3 Hydrogeological parameters

In the Umm er Radhuma aquifer, groundwater is mainly transmitted through the secondary porosity. This makes an estimation of the average permeability and transmissivity complicated. This is reflected in the many different values and wide ranges found in literature. The average permeability found in previous studies show values of 3.46 m d$^{-1}$ to 864 m d$^{-1}$ and average transmissivity values range between 6.05 m² d$^{-1}$ to 53568 m² d$^{-1}$. The large variation seen in the permeability and the transmissivity can be attributed to the increasing permeability as a result of dolomitisation. For the vertical permeability, an average value of 2747.5 m d$^{-1}$ can be noted while for the horizontal permeability an average value of 3.84 x 10$^{-3}$ m d$^{-1}$ is depicted. The large anisotropy of the UER aquifer system can easily be seen due to the large differences in the vertical and horizontal permeability. The average storativity can be estimated in the range between 10$^{-5}$ to 10$^{-3}$, which are values that can be expected for a confined aquifer (Sharaf, 2001).

Similar values are described in a paper of a study in eastern Saudi Arabia (Rasheeduddin, et al., 1989). Values described for the transmissivity of the UER are between 2000 m d$^{-1}$ and 55296 m d$^{-1}$ and values found for the storativity are between 2.50 x 10$^{-5}$ to 1.50 x 10$^{-2}$. Values for the dispersivity of the UER range from 10 m to 150 m, the effective porosity is approximately 0.2 m (Streetly & Kotoub, 1998).

El-Sayed (1986) researched the formation parameters of the Rus Formation in Qatar. Thirteen samples of the upper part of the Rus Formation were taken thus the derived parameters only represent the upper part of the Rus Formation. By analysis in the laboratory, values for hydraulic conductivity were measured between 2.25 x 10$^{-4}$ m d$^{-1}$ to 0.355 m d$^{-1}$. These values represent the upper part of the Rus Formation in the residual sulphate facies (Figure 5). There are no direct measurements for the depositional sulphate facies of the Rus Formation available in literature. Therefore an estimation can be made, based on Domenico & Schwartz (1998), where the hydraulic conductivities found in anhydritic layers are described: horizontal hydraulic conductivity values range from 3.456 x 10$^{-8}$ m d$^{-1}$ to 1.728 x 10$^{-3}$ m d$^{-1}$. Dispersivity values are in the range of 0.5 m to 5 m and the effective porosity is approximately 0.2 m, the same value as the UER (Streetly & Kotoub, 1998).

For the Dammam Formation, no studies of direct measurements of the horizontal hydraulic conductivity or transmissivity are available. As elucidated in part 3.3.3, the Dammam Formation is a calcareous dolomitic limestone with an abundance in karst features such as fissures and sinkholes (Sadiq & Nasir, 2002). If looked at the literature for hydrogeological parameters of dolomitic limestone aquifers, a vast range of horizontal hydraulic conductivities can be found. However, most studies indicate a similar range for the horizontal hydraulic conductivity of a limestone aquifer matrix which varies between 8.64 x 10$^{-6}$ m d$^{-1}$ and 0.0216 m d$^{-1}$. The horizontal hydraulic conductivity for karstified dolomitic limestone aquifers vary between 1 m d$^{-1}$ and 8.64 m d$^{-1}$ (Dar, et al., 2014; Perrin, et al., 2011). Higher values for the horizontal hydraulic conductivity can occur if the aquifer has even more fissures and cracks, but this is not the case for the Dammam Formation.
4.4 Fresh and salt water distribution

Total Dissolved Solids (TDS) fluctuate from fresh to brackish to salt water. Figure 10 shows the TDS values of the phreatic aquifer in Qatar during April 2009. The phreatic aquifers consist of the Dammam Formation and the upper Rus Formation. The measurements are taken between a depth of 13 m to 70 m with an average depth of 35 m. Near the coast the values are rather high which can be higher than 30 000 ppm due to the very salt water of the Persian Gulf, explained in paragraph 7.1.4. A clear difference between northern and southern Qatar can be depicted. This is due to the higher recharge in the north compared to the south (Table 2). The TDS values on the central axis of Qatar ranges between 514 ppm to 7000 ppm. Near Abu Nakhla, the values ranges between 4000 ppm and 7760 ppm.
Figure 10: Total Dissolved Solids (TDS) isoconcentration map in ppm (Schlumberger, 2009).
5. CLIMATE AND HYDROLOGY

Qatar has a desert climate with sporadic rainfall, mainly occurring during November to March. The Persian Gulf affects the climate in terms of temperature and humidity but also in terms of the occurrence and distribution of rainfall. Due to these climatic conditions the summer temperatures can climb up to more than 40°C and persist throughout most of the year. During winter, the temperatures can be as low as 4°C but they generally are between 10°C to 20°C (Lloyd, et al., 1987).

The mean annual total rainfall for the period from 1972 to 2005 is 80.2 mm yr\(^{-1}\) (Amer, et al., 2008). As depicted on Figure 11, a big variation in annual rainfall can be noticed with an absolute high in 1995 with a total annual rainfall of 276.8 mm. The annual evaporation rate is around 2200 mm yr\(^{-1}\) with the daily evaporation rate varying from 2.5 mm d\(^{-1}\) during winter months and 11.5 mm d\(^{-1}\) during summer months (Shomar, et al., 2014; Lloyd, et al., 1987). Only a part of the precipitation will infiltrate into the soil, while the other part will runoff or evaporate. Due to the high evaporation rate, recharge will only occur during storm events when larger volumes of surface runoff occur. The annual natural recharge in Qatar is estimated on 58 Mm\(^3\) yr\(^{-1}\) or approximately 5 mm yr\(^{-1}\) (Shomar, et al., 2014).

![Figure 11: Total annual rainfall (mm yr\(^{-1}\)) of Qatar from 1972 to 2005 (Amer, et al., 2008).](image)

The average annual rainfall distribution over Qatar in the period 1989 and 2007 has been visualised in Figure 12. The north of Qatar receives approximately 20% to 30% more rainfall than the south.
Figure 12: Average annual total rainfall (mm yr$^{-1}$) between 1989 and 2007 (Schlumberger, 2009).
Numerous studies have been made to estimate the surface runoff in Qatar because of its importance to the indirect recharge of the groundwater reservoir, which will be discussed later on. Table 1 lists a selection of available estimations, where runoff is given as a percentage of the total rainfall. All these estimations of surface runoff are based on mass balance calculations since no direct observations of surface runoff are made. From these studies it can be concluded that rainfall over relatively small catchment areas is likely to be evenly distributed. This causes short flow paths of surface water towards depressions which result in less infiltration and evaporation loss and increases the potential surface runoff. Soil moisture conditions prior to a rainfall event is another important factor. When soils are close to their field capacity, infiltration will come to a halt and more runoff is produced. Gemmel (1976) suggested that runoff is most likely to occur when a rainfall event exceeds 10 mm. Pike et al. (1975) concluded that if rainfall exceeds 10 mm per day, surface runoff can be estimated to be between 15% and 25%. Detailed analysis of rainfall events and their resulting surface runoff showed that the distribution of rainfall over the catchment area is of greater importance than the total amount of rainfall. This is based on two storm events observed on the 5th and 12th of February 1976 in the Ghuwairayah catchment area (central part of northern Qatar). Both storms produced a mean rainfall of 19 mm over the catchment area and yet the runoff was different in both cases: 18% and 8% respectively. The largest volume of runoff was produced by the storm event on the 5th of February, which was the most intense with a mean rainfall of 13 mm predominantly over the area with depressions and less rainfall at the boundary of the depressions. The storm on the 12th of February produced a more evenly distributed rainfall across the catchment area with an average rainfall of 10 mm. Even though the soil conditions were considered to be more favourable for surface runoff generation (they were already wetted by the previous storm), less than half of the runoff volume was generated by the second storm (Gemmel, 1976; Eccleston, et al., 1981). However, it should be noted that no account has been taken of the effect of the infiltration capacity of the soils. The first storm is said to be more intense so it is possible that the rainfall rate exceeded the infiltration rate of the soils in the catchment area producing more surface runoff compared to a less intense storm which does not exceed the infiltration capacity of the soil. No data is given related to the intensity of the storm but it can be noted that calculated hydraulic conductivities of the soils, based on observed soil textural properties, are in the range of 9 mm h\(^{-1}\) to 18 mm h\(^{-1}\).

In a recent study by Schlumberger (2009) measurements revealed that surface runoff can already occur with a total rainfall of only 5.9 mm without previous wetting of the soil, which is in contrast with the minimum 8 mm to 10 mm described in previous studies. This lead to the conclusion that rainfall intensity is of more importance to the surface runoff than the total amount of rainfall as the soils only have a limited permeability. When rainfall intensity exceeds the permeability of the soil, runoff will be generated even if the total amount of rainfall is rather small (Schlumberger, 2009).
Table 1: Surface runoff estimates for Qatar (Schlumberger, 2009).

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimated runoff (% of given rainfall event)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Gemmel, 1976)</td>
<td>40 to 70</td>
<td>Runoff associated with rainfall events greater than 20 mm. Observations of rainfall and flooding in depressions.</td>
</tr>
<tr>
<td>(Pike, et al., 1975)</td>
<td>10 to 15</td>
<td>Rainfall event &gt;12.5 mm.</td>
</tr>
<tr>
<td>(Pike, et al., 1975)</td>
<td>15 to 25</td>
<td>Based on rainfall and flooding observations for two storm events at two locations</td>
</tr>
<tr>
<td>(Eccleston, et al., 1981)</td>
<td>8 to 18</td>
<td>Based on rainfall and flooding observations of two storm events at one location</td>
</tr>
<tr>
<td>(Lloyd, et al., 1987)</td>
<td>24</td>
<td>Mean weighted value based on hydrological mass balance studies of individual depressions.</td>
</tr>
</tbody>
</table>

The infiltration rate depends on many different parameters, as was mentioned in the previous paragraph. Wetting of the soil (i.e. gradually filling of the field capacity and pore spaces) is one of the main factors which will decrease the permeability drastically over the course of a rainfall event. Other factors include: washing of fine particles into cracks and fissures in the soil and closing of fissures, cracks and pores due to swelling of the clay particles in the soil. It was found that the average infiltration rate is 0.039 m d$^{-1}$ with a minimum value of 0.012 m d$^{-1}$ and a maximum value of 0.112 m d$^{-1}$ (Gemmel, 1976).

The amount of recharge is also influenced by a number of other factors such as topography, soil type, silting up of depressions (causing lower permeability), vegetation cover and the duration of the runoff events (Hendrickx & Walker, 1997). A difference between direct recharge and indirect recharge can be made. Direct recharge is a result of infiltration from rainfall events in the catchment area itself, while indirect recharge is a result of surface water runoff which is accumulated in the numerous depressions in Qatar.

A differentiation between northern and southern Qatar is made because of the presence of the confining Midra Shale Member in the south and it is assumed that this would inhibit any direct recharge. In Table 2 an overview is made of the direct and indirect recharge in percentages of the total annual rainfall. These values are based on 18 rainfall events monitored between 1972 and 1979 (Eccleston, et al., 1981).

Table 2: Direct and indirect recharge area with the percentage of the direct and indirect recharge of the total annual rainfall (Eccleston, et al., 1981).

<table>
<thead>
<tr>
<th>Area</th>
<th>Direct recharge area (km$^2$)</th>
<th>%</th>
<th>Indirect recharge area (km$^2$)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Qatar</td>
<td>3863</td>
<td>2</td>
<td>3168</td>
<td>10</td>
</tr>
<tr>
<td>Southern Qatar</td>
<td>5369</td>
<td>-</td>
<td>4059</td>
<td>6</td>
</tr>
</tbody>
</table>
With an average total annual rainfall of 80.2 mm yr\(^{-1}\), as described by Amer et al. (2008), recharge in the southern part would be about 4.8 mm yr\(^{-1}\) if the above mentioned 6% from Table 2 is applied. This estimation coincides with the value of 5 mm yr\(^{-1}\) as mentioned in the study by Shomar, et al., (2014).
6. MODELLING SOFTWARE

6.1 Evolution of the modelling software

Two- and three-dimensional finite difference models existed long before the creation of MODFLOW by the U.S. Geological Survey (USGS). These older models are described in Trescott (1975), Trescott & Larson (1976) and Trescott et al. (1976). These models have been extensively used by the USGS and others for the computer simulation of groundwater flow. MODFLOW was created with the intention to be modular and it should be easy to expand so it can be adjusted to any problem. Due to the modular build new functions can be added without the necessity to change existing modules and subroutines and due to the lower memory usage, because only modules are used which are necessary, it could run on most computers (McDonald & Harbaugh, 1988).

To be able to simulate solute transport, the Method-of-Characteristics Solute Transport Model (MOC) was created by Konikow & Bredehoeft (1978). With MOC, the solute transport in a horizontal layer could be simulated. Lebbe (1983) adjusted the MOC code so it could simulate density dependant flow in a vertical plain and the potentials are expressed as freshwater heads. Sanford & Konikow (1985) made further adjustments to MOC so that different densities and viscosities could also be simulated and the potentials are expressed here as pressures. Later on, Konikow et al. (1996) created the successor of MOC, named MOC3D, which can simulate solute transport in three-dimensions. Oude Essink (1998) made adjustments to MOC3D so density dependent flow could be simulated and named the software package MOCDEN3D. Here, the potentials are expressed as freshwater heads.

6.2 MODFLOW

The flow equation which is used in MODFLOW is based on the law of Darcy and on the continuity equation. Both equations will be used to simulate groundwater flow in a finite difference network. MODFLOW can calculate steady state or unsteady state flow, i.e. time independent and time dependant flow, in one-, two- or three-dimensions. MODFLOW simulates in “real” three-dimensions or quasi-three-dimensions. If opted for the quasi-three-dimensions, the aquitards will be represented by the horizon between the aquifers so only the aquifers will be calculated as real layers, while the aquitards will be calculated as the boundary between two aquifers. In the “real” three-dimensional simulation, the aquitards will be discretised in multiple layers which will make it possible to accurately simulate the head evolution in the aquitards on a specified level within a specified timeframe. MODFLOW is created as modular simulation software, as elucidated in part 6.1, and exists out of a main module with a set of subroutines and a bunch of independent modules with independent subroutines which are not mandatory but can be used if needed (McDonald & Harbaugh, 1988).
6.2.1 Code concepts

To convert a real physical groundwater system to a mathematical model, some assumptions and conjectures need to be made. These conjectures include: (1) schematisation of the groundwater system which can be discretised in a finite difference grid, (2) no flow beyond the boundary of the model, (3) the modelled groundwater reservoir can be heterogeneous and anisotropic, (4) the groundwater flow can be calculated in "real" three-dimensions or as quasi-three-dimensional, (5) the simulated periods of both steady state and unsteady state can be divided further into a series of time steps and (6) in MODFLOW the density of the water is considered to be constant and cannot be changed (McDonald & Harbaugh, 1988).

6.2.2 Discretisation of the groundwater reservoir

The spatial discretisation of an aquifer system into a finite difference grid is visualised in Figure 13. Each different block is a cell and the location of all these cells is described with three indices called rows, columns and layers. The indexation system used is i, j, k. For a system consisting of “nrow” rows, “ncol” columns and “nlay” layers, the index for the row will be i = 1, 2, 3, …, nrow, for the column the index will be j = 1, 2, 3, …, ncol, and for the layer the index will be k = 1, 2, 3, …, nlay. A system with five rows, nine columns and five layers is represented on Figure 13. In formulating the equations of the model, an assumption is made that the layers generally correspond to horizontal hydrogeological units or intervals. In terms of Cartesian coordinates this means that the k index denotes changes along the vertical axis, z, since the followed convention of this discretisation is that the layer numbers increase from the top down. In other words, an increase in the k index corresponds with an increase in depth or a decrease in elevation. Rows would be considered to be parallel to the x-axis meaning an increase in the row index i, corresponds to a decrease in the y-value. Similarly for the columns, they are considered to be parallel to the y-axis meaning an increase in the column index j corresponds with an increase in the x-value (McDonald & Harbaugh, 1988).

Following the same convention used in Figure 13, the width of the cells along the row direction at a given column j is $\Delta r_j$, the width of the cells along the column direction at a given row i is $\Delta c_i$ and the thickness of the cells in a given layer k is $\Delta v_k$.

In the centre of each cell there is a point called a node. In this node, the head will be calculated. There are two conventions to define the configuration of cells with respect to the location of the nodes: the block-centred formulation and the point-centred formulation. Only the block-centred formulation will be discussed as it is the only one presently used in the model. As visualised in Figure 14, the blocks or cells are formed by sets of parallel lines and the nodes are situated in the centre of each cell. The assumption is made that within a finite difference cell the groundwater reservoir is homogeneous and that the head calculated in the node is representative for the cell (McDonald & Harbaugh, 1988).
Figure 13: A hypothetical discretised aquifer system with five rows, nine columns and five layers (McDonald & Harbaugh, 1988).

Figure 14: Block-centred finite difference cells (McDonald & Harbaugh, 1988).
6.2.3 Finite difference approximation of the groundwater flow

The finite difference equation for the groundwater flow can be derived from the continuity equation which states that the sum of all flows into the cell and out of the cell must be equal to the rate of change in storage within the cell. Adding the assumption that the density of the groundwater is constant, the continuity equation expressing the balance of flow for a cell, which is not confined by the water table, can be written as:

$$\sum_{i=1}^{6} Q_i = S_s \Delta V \frac{\Delta h}{\Delta t}$$

(1)

- $Q_i$ ($m^3 d^{-1}$) is the flow rate into the cell
- $S_s$ ($m^{-1}$) is the specific elastic storage
- $\Delta V$ ($m^3$) is the volume of the cell
- $\Delta h$ (m) is the change in head over a time interval with length $\Delta t$ (d)

The equation is stated in terms of inflow and storage gain, meaning that outflow and loss are represented by a negative inflow and negative gain. Equation (1) is summed six times to take into account the six sides of the cell.

The cell with indices $i, j, k$ is surrounded by six other cells $i-1, j, k; i+1, j, k; i, j-1, k; i, j+1, k; i, j, k-1; i, j, k+1$. To derive the inflow and outflow of the cell from the six adjacent cells, the flow is considered to be positive if it enters the $i, j, k$ cell meaning the negative sign from Darcy’s law for all terms will be dropped. Following these conventions, the flow into cell $i, j, k$ in the row direction from cell $i, j-1, k$, visualised in Figure 15, is given by Darcy’s law as:

$$Q_{i,j-1/2,k} = K R_{i,j-1/2,k} \Delta c_i \Delta v_k \frac{h_{i,j-1,k} - h_{i,j,k}}{\Delta r_{j-1/2}}$$

(2)

- $Q_{i,j-1/2,k}$ ($m^3 d^{-1}$) is the flow rate through the cell boundary between cells $i, j, k$ and $i, j-1,k$
- $K R_{i,j-1/2,k}$ ($m d^{-1}$) is the hydraulic conductivity along the row between the nodes of the cells $i, j, k$ and $i, j-1/2, k$
- $\Delta c_i \Delta v_k$ ($m^2$) is the area of the boundary surface
- $h_{i,j,k}$ (m) is the head at node $i, j, k$
- $h_{i,j-1,k}$ (m) is the head at node $i, j-1, k$
- $\Delta r_{j-1/2}$ (m) is the distance between the nodes $i, j, k$ and $i, j-1, k$
Analogue expressions as equation (2) can be made for the remaining five boundaries surfaces.

Further simplifications can be made by expressing the equations in terms of a single constant, the hydraulic conductance or simply conductance. This constant is a combination of the grid dimensions with the hydraulic conductivity. It can be written as:

$$CR_{i,j-1/2,k} = \frac{KR_{i,j-1/2,k} \Delta c_i \Delta v_k}{\Delta r_{j-1/2}}$$

$$CR_{i,j-1/2,k} (m^2 d^{-1})$$ is the conductance in row i and layer k between nodes i, j-1, k and i, j, k

Substituting the conductance into equation (2) gives:

$$Q_{i,j-1/2,k} = CR_{i,j-1/2,k} (h_{i,j-1,k} - h_{i,j,k})$$

Previous equations only account for flow into cell i, j, k from cell i, j-1, k, but to account for flow into the cell from external sources such as rivers, drains, areal recharge, evapotranspiration or wells some additional terms are required. These flows can either be dependent on the head of the receiving cell or completely independent on the head of the receiving cell. Following expression represents flow from external sources:
\[ a_{i,j,k,n} = p_{i,j,k,n} h_{i,j,k} + Q_{i,j,k,n} \]  \hspace{1cm} (5)

\( a_{i,j,k} \) (m³ d⁻¹) is the flow from the \( n^{th} \) external source into cell \( i, j, k \)

\( h_{i,j,k} \) (m) head in node \( i, j, k \)

\( p_{i,j,k,n} \) (m² d⁻¹) and \( Q_{i,j,k,n} \) (m³ d⁻¹) are constants

By summing all the equations from the flow between the boundary surfaces (equation (4) and the five other analogue equations) and adding the flow of all the \( n^{th} \) external sources into one formula, the finite difference approximation for cell \( i, j, k \) can be given by:

\[
\begin{align*}
CR_{i,j,k} &\left( h_{i,j,k-1} - h_{i,j,k} \right) + CR_{i,j,k} \left( h_{i,j,k+1} - h_{i,j,k} \right) \\
+ CC_{i,j,k} &\left( h_{i-1,j,k} - h_{i,j,k} \right) + CC_{i,j,k} \left( h_{i+1,j,k} - h_{i,j,k} \right) \\
+ CV_{i,j,k} &\left( h_{i,j,k-1} - h_{i,j,k} \right) + CV_{i,j,k} \left( h_{i,j,k+1} - h_{i,j,k} \right) \\
+ P_{i,j,k} h_{i,j,k} + QT_{i,j,k} &= S_{i,j,k} \left( \Delta r_j \Delta c_i \Delta v_k \right) \frac{\Delta h_{i,j,k}^m - \Delta h_{i,j,k}^{m-1}}{t_m - t_{m-1}}
\end{align*}
\]  \hspace{1cm} (6)

\( P_{i,j,k} \) is equal to \( \sum_{n=1}^{N} p_{i,j,k,n} \)

\( QT_{i,j,k} \) is equal to \( \sum_{n=1}^{N} Q_{i,j,k,n} \)

\( h_{i,j,k}^m \) is the head at time step \( m \)

\( h_{i,j,k}^{m-1} \) is the head at time step \( m-1 \)

\( t_m \) is the time at the end of time step \( m \)

\( t_{m-1} \) is the time at the end of time step \( m-1 \)

**6.2.4 Iteration with the Strongly Implicit Procedure**

An iterative method is used to obtain the solution to the finite difference equations for each time step. The calculation of the head in the nodes for the end of a given time step is started by assigning an estimated (or a known) value for the head at each node at the beginning of that time step. A procedure of calculation, in this case the Strongly Implicit Procedure or SIP, is then used to calculate a new set of heads which are closer in agreement with the finite difference equations. These new calculated heads replace the initial head values and the procedure is repeated. The iteration continues until the maximum difference of head between two consecutive iterations for all respective cells of the grid is lower than a specified closure criterion (McDonald & Harbaugh, 1988).

The Strongly Implicit Procedure or SIP is a method of solving a large system of simultaneous linear equations by iteration (McDonald & Harbaugh, 1988). As can be seen in equation (6), the number of unknown variables can be up to seven: the head in the node...
of the cell itself and the heads in the nodes of the six surrounding cells. It is therefore necessary to solve the entire grid simultaneously at each time step.

To be able to solve all these equations at the same time, they are written in matrix form (McDonald & Harbaugh, 1988):

$$[A] \cdot \{h\} = \{q\} \quad (7)$$

[A] is a matrix of the coefficients of head for all active nodes in the grid

{h} is a vector of head values at the end of time step m for all nodes in the grid

{q} is a vector of the constant terms for all the nodes in the grid

6.2.5 Cell and boundary types

In general, there are three types of cells: active cells, inactive cells and constant-head cells. The active or variable-head cells are the most abundant in the model. In these cells the head will be calculated at the nodes and the heads can vary in time. The inactive or no-flow cells will not be part of the calculations and thus the head will not be calculated for these cells. They will have no participation in the flow of the groundwater, i.e. no flow will go in or out of these cells. The constant-head cells, just as the name says, are cells which will have a constant-head over time. A theoretical unlimited flow could go into the cell or out of the cell to maintain this constant head.

*Figure 16: Discretised aquifer showing boundaries and cell designations (McDonald & Harbaugh, 1988).*

Constant-head and inactive cells are usually used as input for boundary conditions. Inactive cells can be used for places where the aquifer is not present in the grid, constant-head cells are mostly used to define boundaries of major surface water features such as rivers or lakes. If water flows into the model or an excess of water is present in the model, it can be injected or extracted through these constant-head cell boundaries. Combinations of constant-head cell boundaries and variable-head cell boundaries are often made. If for
example the eastern and western boundary are constant-head cells and the northern and southern boundary are variable-head cells, the variable-head cell boundaries will act as impervious boundaries as the exchange of water will preferentially flow through the constant-head cell boundaries. This will result in a flow along the variable-head boundaries and a flow perpendicular on the constant-head boundaries. An example of the different possible boundary types can be seen in Figure 16 where inactive cells represent parts where the aquifer is not present in the model (McDonald & Harbaugh, 1988).

6.3 MOC3D

MOC3D development started from the existing two-dimensional MOC code documented by Konikow & Bredehoeft, (1978). MOC was developed to simulate solute transport in a horizontal plane and MOC3D made it possible to simulate the solute transport in three-dimensions. MOC3D is developed as a module for MODFLOW and is therefore compatible with it.

MOC3D simulates the concentration evolution of a single solute in a three-dimensional groundwater flow system. The calculations are done by simultaneous numerical solving of two partial differential equations. The first one is the groundwater flow equation which describes the head distribution in the aquifer while the second one is the solute transport equation which describes the solute concentration within the flow system. By coupling the flow equation with the solute transport equation, the model can be applied to both steady-state and unsteady-state groundwater flow problems (Konikow, et al., 1996).

The purpose of the model is to simulate the concentration of a dissolved chemical species in an aquifer at any specified place and time. Changes in concentration of the solute can primarily be described by four distinct processes: (1) advective transport, (2) hydrodynamic dispersion, (3) fluid sources where water of one composition is introduced to water with a different composition and (4) reactions which can remove or add to the solute by physical, chemical or biological processes in the water or between the water and the aquifer matrix (Konikow, et al., 1996).

Advective transport is a process which is dependent of the flow velocity of the groundwater. These flow velocities are derived from the heads calculated with MODFLOW and by applying Darcy’s law, Darcian velocities can be derived. Dividing the Darcian velocities with the effective porosity, the average interstitial velocities are found. In essence, the dissolved particles will be carried by the flowing groundwater (Konikow, et al., 1996).

Hydrodynamic dispersion is also dependant on the flow velocity of the groundwater. It consists of molecular and ionic diffusion together with mechanical dispersion which is related mostly to variations in fluid velocity through the porous media. These processes cause the dissolved molecules and ions to diverge from the average direction of the groundwater flow (Konikow, et al., 1996).

It should be noted that types of reactions incorporated into MOC3D are restricted to only those that can be represented by first-order rate reactions such as radioactive decay or by
a retardation factor such as instantaneous reversible sorption-desorption reactions written as a linear isotherm with a constant distribution coefficient \( K_d \) (Konikow, et al., 1996).

The solute transport equation comprising of advective transport, hydrodynamic dispersion, injection or extraction of external sources, reversible adsorption/desorption and radioactive decay can be written as:

\[
\frac{\delta C}{\delta t} = -V_i \frac{\delta C}{\delta x_j} + \frac{\delta}{\delta x_j} \left( D_{ij} \frac{\delta C}{\delta x_j} \right) + \frac{\delta}{\delta x_j} \left( \sum (R (C' - C)) - \frac{\delta \left( \rho_b \dot{C} \right)}{\delta t} \right) - \lambda \left( C + \frac{\rho_b \dot{C}}{n} \right)
\]

(8)

\( C \) (kg m\(^{-3}\)) is the volumetric concentration

\( V_i \) (m d\(^{-1}\)) is the interstitial velocity

\( D_{ij} \) is the dispersion coefficient

\( R \) (m\(^3\) d\(^{-1}\)) is the flow rate from the external source

\( C' \) (kg m\(^{-3}\)) is the concentration from the external source

\( \rho_b \) (kg m\(^{-3}\)) is the bulk density

\( \dot{C} \) (kg m\(^{-3}\)) is the adsorbed concentration

\( n \) is the effective porosity

\( \lambda \) (d\(^{-1}\)) is the decay constant

6.4 MOCDENS3D

Oude Essink, (1998) adapted the MOC3D model and created MOCDENS3D which can simulate density dependent groundwater flow. The code is able to simulate both steady and unsteady state groundwater flow of fresh, brackish and saline groundwater. In addition, it is still possible to simulate “ordinary” solute transport without density differences, such as displacement of contaminants in the subsoil.

MOCDENS3D comprises of two modules: a solute transport module to displace the density field and a groundwater flow module adapted to simulate density dependent groundwater flows induced by density differences. This is possible by inserting a buoyancy term in the basic groundwater flow equation. Viscosity differences are usually very small and can be neglected in normal hydrogeological systems (Oude Essink, 1998).

In hydrogeological studies it is common to express the potentials in fresh water heads. The fresh water head can be defined as:
\[ h_f = h_z + \frac{p}{\rho_f g} \]  \hspace{1cm} (9)

\( h_1 \) (m) is the fresh water head

\( h_2 \) (m) is the height of the filter of the observation well

\( p \) (kg m\(^{-1}\) s\(^{-2}\)) is the pressure around the observation well filter

\( \rho_f \) (kg m\(^{-3}\)) is the density of fresh water

\( g \) (m s\(^{-2}\)) is the gravitational acceleration

The density dependent Darcian velocity, expressed as fresh water head, can be given by the following formula in the z-direction:

\[ q_z = -K_{fz} \frac{\mu_f}{\mu_i} \left( \frac{\partial h_f}{\partial z} + \frac{\rho_i - \rho_f}{\rho_f} \right) \]  \hspace{1cm} (10)

\( q_z \) (m d\(^{-1}\)) is the Darcian velocity in the z-direction

\( K_{fz} \) (m d\(^{-1}\)) is the hydraulic conductivity of porous medium for freshwater

\( \frac{\mu_f}{\mu_i} \) is the viscosity of freshwater divided by the viscosity of saltwater

\( \frac{\rho_i - \rho_f}{\rho_f} \) is the buoyancy factor with the density of the aquifer water \( \rho_i \) and the density of freshwater \( \rho_f \)

From this formula, it can be deducted that the groundwater flow velocities are a function of the fresh-, brackish-, and saltwater distribution. At every time step the groundwater flow will be recalculated with a new distribution of fresh-, brackish-, and saltwater (Oude Essink, 1998). If a steady state flow occurs with invariant boundary conditions, the groundwater flow velocity and the freshwater heads will vary as a function of the fresh-, brackish-, and saltwater distribution (Lebbe, 1983).

### 6.5 Packages

Both MODFLOW and MOCDEN3D are build up modularly. Different packages can be used where some are mandatory while others are optional. The input file of each package is in the form of a text file. In this section the different packages are elucidated.

#### 6.5.1 MODFLOW packages

**6.5.1.1 Basic package (.bas-file)**

In this package the number of rows, columns, layers and stress periods (including the time unit) are defined. The boundary condition grid for each layer is also defined here where a cell with number smaller than zero is a constant-head cell, a cell with a zero is an inactive
cell and a cell with a number higher than zero is an active or variable-head cell. Different numbers can be used to depict constant head cells of different concentrations. For example: Layer one has water with a concentration x and the constant-head boundary cells will be defined as -1 while for layer two the concentration is y and the constant-head boundary cells will be defined as -2. If water will flow into the model through these cells, the concentration will be x in the case of the -1 boundary and y in the case of the -2 boundary. It also includes the initial heads for each cell, the time discretisation and the time step multiplier (TSMULTI). The simulation time of the model is subdivided into stress periods with time steps. Time steps will discretise the stress periods into smaller blocks to obtain a more accurate simulation. The TSMULTI is used to calculate the length of each time step. If the TSMULTI is equal to one, all the time steps will have the same length, being the stress period length divided by the number of time steps. If the TSMULTI is different than one, the time steps will increase in length if TSMULTI is larger than one and decrease in length if the TSMULTI is lower than one. Figure 17 shows how the simulation time is discretised into stress periods and time steps including the formulas to calculate the first time step and the following steps (McDonald & Harbaugh, 1988).

![Discretisation of the simulation time in stress periods and time steps including the formulas to calculate the first time step and the following steps](image)

6.5.1.2 Block-Centred-Flow package (.bcf-file)

In this package fundamental variables controlling the cell-to-cell flow and the storage are defined, either as single values or as an array (NROW, NCOL). These variables include the length and width of the cells (DELR and DELC), steady or unsteady state flow, anisotropy, transmissivity in horizontal direction, horizontal hydraulic conductivity, storage factor near the water table (the unconfined storage coefficient), storage factor of the aquifer (confined storage coefficient multiplied with the layer thickness), layer bottom elevation, layer top elevation and vertical leakance (reciprocal value of the hydraulic conductivity).
resistance). In addition, a layer-type code (LAYCON) is defined to classify layers according to the simulation options used (McDonald & Harbaugh, 1988).

There are four types of layer simulation options. They are identified with their respective LAYCON number and are summarised in following section:

- **LAYCON = 0**: There will be no modification of the transmissivity and the storage factor as the water level varies over time. No limitation of vertical flow will occur if the water level drops below the top of the cell. This layer-type is normally used to simulate confined conditions, but a layer with unconfined conditions can also be simulated if these conditions will always prevail. The hydrogeological parameter input for this layer-type will be the transmissivity, storage factor and the vertical leakance.

- **LAYCON = 1**: This layer-type can only be used in a single layer model or for the top layer of a model where unconfined conditions are expected throughout the entire simulation period. This is because no anticipation is made to limit flow from above under dewatered conditions. The storage factor will remain constant throughout the simulation but the transmissivity will be calculated at each iteration as the product of the hydraulic conductivity and the saturated thickness of the layer. The storage factor will be given while for the calculation of the transmissivity, the horizontal hydraulic conductivity (HY) and the bottom elevation of each cell (BOT) need to be defined. If the model has more than one layer, the vertical leakance need to be defined as well.

- **LAYCON = 2**: This layer-type is used when the situation in the layer alternates between confined and unconfined conditions. This means that the storage factor will vary and that a limitation of flow from above, under dewatered conditions, is desired. However, a constant saturation thickness is expected thus a recalculation of the transmissivity is not necessary and will remain constant. Two values for the storage factor can be defined which are usually the confined storage factor and the unconfined storage factor. To limit the flow under dewatered conditions, the top elevation of each cell (TOP) should also be given.

- **LAYCON = 3**: This layer-type incorporates all capabilities of the Block-Centred-Flow package. The transmissivity of the layer will be recalculated at each iteration using the hydraulic conductivity and the saturated thickness and the storage factors are able to vary between confined and unconfined conditions. The flow will also be limited from above under dewatered conditions. The required input parameters are the hydraulic conductivity, the storage coefficients (confined and unconfined), the bottom elevation of each cell, the top elevation of each cell and the vertical leakance.

**6.5.1.3 Well package (.wel-file)**

This package is designed to simulate well features such as withdrawal of water or injection of water with a specified rate and during a specified stress period (McDonald & Harbaugh, 1988). This file can also be used to induce a recharge from precipitation in the upmost layer of the model.
6.5.1.4 Evapotranspiration package (.evt-file)

The evapotranspiration package is created to simulate the effects of plant transpiration and direct evaporation by removing water from the saturated ground water regime. Following assumptions forms the basis of the package: (1) when the water table is above or at the evapotranspiration (ET) surface (specified elevation) the evapotranspiration loss will be at a maximum rate, (2) when the depth of the water table is below the ET surface but above the extinction depth (i.e. the depth where no water loss will occur due to evapotranspiration) the evapotranspiration rate will decrease linearly with depth and (3) when the water table drops below the extinction depth, no evapotranspiration will occur. A graph of the three distinct zones is plotted in Figure 18 (McDonald & Harbaugh, 1988).

![Graph of the three distinct zones](image)

*Figure 18: Volumetric evapotranspiration $Q_\text{ET}$, as a function of head $h$, in a cell where $d$ is the extinction depth and $h_s$ the ET surface elevation (McDonald & Harbaugh, 1988).*

6.5.1.5 Strongly Implicit Procedure package (.sip-file)

In the .sip-file the maximum number of iterations is given that the model can do. A second parameter that is given in the .sip-file is the closure criterion. If the closure criterion is not reached after the maximum iterations, the model will be terminated (McDonald & Harbaugh, 1988).

6.5.1.6 Name file (Infile.nam)

This file consists of a list of all the different files that MODFLOW should read to calculate the groundwater flow and includes the name of the output file. If MOCDENS3D is used, it also refers to the name file for the solute transport (Vandenbohede, 2008).
6.5.2 MOCDENS3D packages

6.5.2.1 MOC package (.moc-file)

The MOC file, which stands for Method-Of-Characteristics, contains all information to simulate the solute transport. The first and last layer, row and column are given for which solute transport should be calculated. On the next line flags are defined for if dispersion, decay or diffusion is/are present. It also includes the number of particles present in each cell. Other parameters include the concentration in no-flow cells (or inactive cells) and a grid of the concentration for each cell. Finally, the longitudinal dispersion and both transversal dispersions, the retardation factors, thicknesses and porosities are defined (Vandenbohede, 2008).

6.5.2.2 Densin.dat-file

This file contains the information regarding the density driven transport. Two parameters are defined that will introduce the density difference to the different concentrations. A certain concentration is given along with its density difference in regard to a reference state of concentration equal to 0 (buoyancy factor). Densities for all other concentrations are calculated proportionally to these two values (Vandenbohede, 2008).

6.5.2.3 Name file (moc.nam)

This file is similar to the infile.nam file in the sense that it also lists the different files needed for MOCDENS3D to run and calculate the solute transport. An output file is also defined here (Vandenbohede, 2008).
7. MODEL CONSTRUCTION

The study of the influence of the Abu Nakhla pond on the phreatic aquifer has been subdivided into two parts. The first part comprises of the simulation of the present state and the dissipation and desiccation of the Abu Nakhla pond. For this simulation, a base model is constructed which represents the phreatic aquifer in equilibrium with the hydraulic and climatic conditions, without the presence of the Abu Nakhla pond. Next, the Abu Nakhla pond is added to the numerical model and is simulated until equilibrium with the groundwater reservoir is obtained. This is a simplification of the reality as it hasn’t been verified yet whether the pond is in equilibrium with the aquifer. However, for the scope of this study it is justified to make this assumption. The last step of the first part is the simulation of the desiccation of the pond. The volume of the pond slowly diminishes, due to the evaporation and infiltration, and the influence of this on the evolution of the groundwater reservoir is followed. The second part of the study comprises of a sensitivity analysis to check which hydrogeological parameters have the most influence on the dissipation of the pond, under constant evaporation conditions.

7.1 Base model

This base model represents the groundwater reservoir in equilibrium with its surroundings if the Abu Nakhla pond would not be present. This base model includes all hydraulic parameters that are independent of the presence of the Abu Nakhla pond and thus all parameters that will remain constant throughout the models.

7.1.1 Location and discretisation of the study area

To investigate the extent of the influence of the Abu Nakhla pond on the phreatic aquifer, a rectangular study area is chosen with a length from west to east of 18 km and a width from north to south of 15 km with the pond in the centre (Figure 19). The lower left corner has the coordinates $x = 206200$ and $y = 370500$ and the upper right corner has the coordinates $x = 224200$ and $y = 385500$, expressed in the Qatar 1974 reference system. Square cells with dimensions of 100 m x 100 m are used which results in a grid of 150 rows and 180 columns.

To be able to make a sound vertical discretisation in layers, a detailed understanding of the geology is necessary. An interpretation of the upper 31 m is made with corings taken around the Abu Nakhla pond (Appendix A). The Umm Bab Member is the only member present of the Dammam Formation. It is up to 21.9 m thick and consists of off-white to light grey limestone. Below the Umm Bab Member the Midra Shale Member is present. It reaches a depth of 26.55 m which results in a thickness of 4.65 m. It is followed by the upper Rus Formation which consists of pale brown limestones and is considered a part of the upper southern aquifer. The Rus Formation changes to a depositional sulphate

---

1 Formerly known as the Simsima Member. It was changed to stop the confusion with the Simsima Formation present in Cretaceous deposits.
deposit with the presence of thick gypsum layers at a depth of approximately 47 m. The depositional sulphate Rus facies extend to a depth of about 97 m where it changes into the more permeable Umm er Radhuma Formation. The bottom of the model is put at 117 m where the silicified limestone layer is present which represents the transition of a relatively good permeable UER to a relatively bad permeable UER. Three hydrogeological units are defined: (1) Dammam Formation + upper Rus Formation aquifer, (2) Gypsiferous Rus Formation aquitard and (3) UER Formation aquifer.

Based on the local geology, the model is subdivided into 21 layers, each layer being five meter in thickness with the base of the first layer at 18 m amsl and the base of the model at -77 m amsl. As simplification, the Midra Shale Member is represented by a five meter thick layer between a depth of 22 m and 27 m. An overview of the vertical discretisation with the corresponding geology is given in Table 3.
Table 3: The vertical discretisation of the modelled area with the number of layers, thickness of the layers and the geology and lithology they represent.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Hydrogeological Unit</th>
<th>Thickness (m)</th>
<th>Depth upper boundary amsl (m)</th>
<th>Geology</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5</td>
<td>23</td>
<td>Umm Bab</td>
<td>Limestone</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>5</td>
<td>18</td>
<td>Umm Bab</td>
<td>Limestone</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>5</td>
<td>13</td>
<td>Midra Shale</td>
<td>Shale</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>5</td>
<td>8</td>
<td>Upper Rus</td>
<td>Limestone</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>Upper Rus</td>
<td>Limestone</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>5</td>
<td>-2</td>
<td>Upper Rus</td>
<td>Limestone</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>5</td>
<td>-7</td>
<td>Upper Rus</td>
<td>Limestone</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>5</td>
<td>-12</td>
<td>Lower Rus</td>
<td>Gypsum</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>5</td>
<td>-17</td>
<td>Lower Rus</td>
<td>Gypsum</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>5</td>
<td>-22</td>
<td>Lower Rus</td>
<td>Gypsum</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>5</td>
<td>-27</td>
<td>Lower Rus</td>
<td>Gypsum</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>5</td>
<td>-32</td>
<td>Lower Rus</td>
<td>Gypsum</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>5</td>
<td>-37</td>
<td>Lower Rus</td>
<td>Gypsum</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>5</td>
<td>-42</td>
<td>Lower Rus</td>
<td>Gypsum</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>5</td>
<td>-47</td>
<td>Lower Rus</td>
<td>Gypsum</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>5</td>
<td>-52</td>
<td>Lower Rus</td>
<td>Gypsum</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>5</td>
<td>-57</td>
<td>Lower Rus</td>
<td>Gypsum</td>
</tr>
<tr>
<td>18</td>
<td>3</td>
<td>5</td>
<td>-62</td>
<td>UER</td>
<td>Limestone</td>
</tr>
<tr>
<td>19</td>
<td>3</td>
<td>5</td>
<td>-67</td>
<td>UER</td>
<td>Limestone</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>5</td>
<td>-72</td>
<td>UER</td>
<td>Limestone</td>
</tr>
<tr>
<td>21</td>
<td>3</td>
<td>5</td>
<td>-77</td>
<td>UER</td>
<td>Limestone</td>
</tr>
</tbody>
</table>
7.1.2 Hydrogeological parameters

Steady state and unsteady state flow models use the same basic hydraulic parameters but unsteady state flow models need an extra set of parameters, the storage factors. While the storage factors will be discussed in this part, only unsteady state flow models will use them.

The transmissivity is the horizontal conductivity multiplied with the thickness of the layer it represents. The transmissivity of the upper layer is 68 m² d⁻¹ (calculated for a layer thickness of 8.5 m, which is a rough estimation) while the other Dammam layer (layer two) has a transmissivity of 40 m² d⁻¹. The Midra Shale Member, which is an aquitard, is estimated to have a transmissivity of 1 m² d⁻¹ which is 40 times lower than the surrounding layers. The upper Rus Formation has the same 40 m² d⁻¹ transmissivity of the Dammam Formation as it is part of the upper aquifer system. The gypsiferous Rus Formation has a very low transmissivity due to the depositional sulphate present. Based on the parameters illuminated in part 4.3 for gypsiferous and anhydritic deposits, a transmissivity is estimated of 0.01 m² d⁻¹. The transmissivity used for the Umm er Radhuma Formation is 42 m² d⁻¹ which is based on the fact that the formation can be extensively karstified and thus a slightly higher value, compared to the Dammam and upper Rus formations, is used.

The vertical conductivity is expressed as the reciprocal value of the hydraulic resistance, i.e. vertical conductivity divided by the thickness of the layers and expressed in d⁻¹. For the ease of use, this parameter is abbreviated as ‘vert’ further on. The estimation of the initial vertical conductivity is done by assuming an anisotropy of 25. This means that the vertical hydraulic conductivity (Kᵥ) is 25 times smaller than the horizontal hydraulic conductivity (Kₕ) of the layer. When the vert gets smaller, the hydraulic resistance of the layer will get higher and thus less water will be able to flow between the layers. The vert is a value representative for the boundary between two layers so only 20 verts are defined for the 21 layers in the model. The same principle is used as with the hydraulic conductance, where the vert is defined by half of the layer above the boundary and half of the layer below the boundary. The vert for the bottom boundary of the top layer will have a different value due to the fact that it will have an influence of the whole top and bottom layer compared to the rest which will only have half the influence. The vert for the first layer is thus 0.0427 d⁻¹ (calculated for a layer thickness of 5 m). Both at the top and bottom of the Midra Shale Member the vert is 0.0032 d⁻¹ and is mainly influenced by the Midra Shale itself. For the upper Rus Formation the vert is 0.064 d⁻¹. The top and bottom of the gypsiferous Rus Formation will mostly be influenced by the low conductive gypsum and thus the influence of the high conductive upper Rus and UER layer can be neglected. A value of 0.000032 d⁻¹ is defined and inside the gypsiferous Rus Formation a vert of 0.000016 d⁻¹ is used. The UER vert is estimated at 0.0672 d⁻¹.

Data of storage coefficients are scarce and reasoning is used to obtain an estimated value. The storage factor for the layer confined by the water table is equal to the specific elastic storage (Sₑ) multiplied by the thickness (D) plus the storage coefficient near the water table.
(S₀) and is referred to as the storage factor near the water table. For layers which are not confined by the water table, the storage factor is equal to the S₀ multiplied with the thickness and is referred to as the storage factor of the aquifer. Schlumberger (2009) conducted a pumping test in the southern aquifer and the storage factors are deduced from the pumping test. These are valid for the upper aquifer, consisting of the upper Rus Formation and the Dammam Formation, which is confined by the water table. Together with known values from Flanders, the storage factor near the water table is estimated as 0.0104 and the storage factor of the aquifer is estimated as 0.002. These values are rough estimations and their influence will be checked in the sensitivity analysis.

Table 4 gives a summation of the three above discussed parameters: the transmissivity, the storage factor and the reciprocal of the hydraulic resistance.

Table 4: Overview of the transmissivity, storage factor and vert (reciprocal of the hydraulic resistance) of each layer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Transmissivity (m² d⁻¹)</th>
<th>Storage Factor</th>
<th>Vert (d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68.00</td>
<td>0.0104</td>
<td>0.042700</td>
</tr>
<tr>
<td>2</td>
<td>40.00</td>
<td>0.0020</td>
<td>0.003200</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>0.0020</td>
<td>0.032000</td>
</tr>
<tr>
<td>4</td>
<td>40.00</td>
<td>0.0020</td>
<td>0.064000</td>
</tr>
<tr>
<td>5</td>
<td>40.00</td>
<td>0.0020</td>
<td>0.064000</td>
</tr>
<tr>
<td>6</td>
<td>40.00</td>
<td>0.0020</td>
<td>0.064000</td>
</tr>
<tr>
<td>7</td>
<td>40.00</td>
<td>0.0020</td>
<td>0.064000</td>
</tr>
<tr>
<td>8</td>
<td>0.01</td>
<td>0.0020</td>
<td>0.000032</td>
</tr>
<tr>
<td>9</td>
<td>0.01</td>
<td>0.0020</td>
<td>0.000016</td>
</tr>
<tr>
<td>10-16</td>
<td>0.01</td>
<td>0.0020</td>
<td>0.000016</td>
</tr>
<tr>
<td>17</td>
<td>0.01</td>
<td>0.0020</td>
<td>0.000032</td>
</tr>
<tr>
<td>18</td>
<td>42.00</td>
<td>0.0020</td>
<td>0.067200</td>
</tr>
<tr>
<td>19</td>
<td>42.00</td>
<td>0.0020</td>
<td>0.067200</td>
</tr>
<tr>
<td>20</td>
<td>42.00</td>
<td>0.0020</td>
<td>0.067200</td>
</tr>
<tr>
<td>21</td>
<td>42.00</td>
<td>0.0020</td>
<td>0.067200</td>
</tr>
</tbody>
</table>

7. MODEL CONSTRUCTION
7.1.3 Boundary conditions and initial head values

The four boundaries consist of constant-head cells with values for the head extracted from the potentiometric surface map (Figure 20). There are a number of reasons why the four boundaries are added as constant-head cells. First of all, it is to be able to accommodate the huge depression cone in the northwest corner of the study area, as can be seen on the potentiometric surface map. This is probably related to extended pumping, creating heads as low as -5 m amsl in the north-western part of the study area. Secondly, a watershed runs from the south-western corner to the north-eastern corner. As water will flow to the north-western corner and to the south-eastern corner, it is opted to make all four boundaries constant-head cells.

A salt water concentration has to be specified for every constant-head cell. If water enters the groundwater model through this boundary, it will have a salt water concentration equal to this given value. The salt water concentrations of these cells equal the values that are appointed to their respective model layer as discussed in the following part 7.1.4.

Figure 20: Potentiometric surface map of Qatar with the study area visualised as the black rectangle (Schlumberger, 2009).
An overview of the heads used for the constant-head cells for layer one is given in Table 5. One average value for every ten cells was derived from the potentiometric surface map.

Table 5: Overview of the heads of the constant-head cells for the western boundary (north to south direction), eastern boundary (north to south direction), northern boundary (west to east direction) and southern boundary (west to east direction).

<table>
<thead>
<tr>
<th>Cell number (along row or column)</th>
<th>Western boundary head (m)</th>
<th>Eastern boundary head (m)</th>
<th>Northern boundary head (m)</th>
<th>Southern boundary head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 10</td>
<td>-3</td>
<td>10.5</td>
<td>-5</td>
<td>4.75</td>
</tr>
<tr>
<td>11 – 20</td>
<td>-1</td>
<td>10.5</td>
<td>-5</td>
<td>5</td>
</tr>
<tr>
<td>21 – 30</td>
<td>1</td>
<td>10.5</td>
<td>-5</td>
<td>5.1</td>
</tr>
<tr>
<td>31 – 40</td>
<td>3.5</td>
<td>10</td>
<td>-5</td>
<td>5.1</td>
</tr>
<tr>
<td>41 – 50</td>
<td>3.5</td>
<td>10</td>
<td>-2</td>
<td>5.3</td>
</tr>
<tr>
<td>51 – 60</td>
<td>3</td>
<td>10</td>
<td>2</td>
<td>5.4</td>
</tr>
<tr>
<td>61 – 70</td>
<td>3</td>
<td>10</td>
<td>4</td>
<td>5.5</td>
</tr>
<tr>
<td>71 – 80</td>
<td>3</td>
<td>9.5</td>
<td>5</td>
<td>5.5</td>
</tr>
<tr>
<td>81 – 90</td>
<td>3</td>
<td>9</td>
<td>6</td>
<td>5.5</td>
</tr>
<tr>
<td>91 – 100</td>
<td>3</td>
<td>8</td>
<td>7</td>
<td>5.5</td>
</tr>
<tr>
<td>101 – 110</td>
<td>3.5</td>
<td>7</td>
<td>8</td>
<td>5.4</td>
</tr>
<tr>
<td>111 – 120</td>
<td>3.5</td>
<td>6</td>
<td>9</td>
<td>5.3</td>
</tr>
<tr>
<td>121 – 130</td>
<td>4</td>
<td>5</td>
<td>10</td>
<td>5.2</td>
</tr>
<tr>
<td>131 – 140</td>
<td>4.5</td>
<td>4</td>
<td>10.5</td>
<td>5.1</td>
</tr>
<tr>
<td>141 - 150</td>
<td>4.75</td>
<td>3</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>151 – 160</td>
<td>-</td>
<td>-</td>
<td>11</td>
<td>4.5</td>
</tr>
<tr>
<td>161 – 170</td>
<td>-</td>
<td>-</td>
<td>10.5</td>
<td>4</td>
</tr>
<tr>
<td>171 - 180</td>
<td>-</td>
<td>-</td>
<td>10.5</td>
<td>3</td>
</tr>
</tbody>
</table>

The initial heads of the constant-head cells in the other layers are derived from the initial heads in layer one. The calculation takes into account two distinct processes which can influence the heads: (1) the flow of the water in vertical direction and (2) the density of the water. Analogue to the calculations of the hydraulic conductance (Equation 3), the calculation is based on interpolating between the nodes of the layers, with half the thickness of the layer itself and half the thickness of the layer above it. It can be written as:
\[ h_k = h_{k-1} - \frac{1}{2} \left[ \left( \frac{r_{k-1}}{365.25} \right) \times \left( \frac{1}{V_{k-1}} \right) \right] + \left( \frac{100 \times D\text{CONC}}{\rho_f} \right) \times \left( \frac{D_{k-1}}{2} \right) \]

\[ - \frac{1}{2} \left[ \left( \frac{r_k}{365.25} \right) \times \left( \frac{1}{V_{k-1}} \right) \right] + \left( \frac{100 \times D\text{CONC}}{\rho_f} \right) \times \left( \frac{D_k}{2} \right) \]

(11)

\( h_k \) and \( h_{k-1} \) (m) the head in layer \( k \) and \( k-1 \)

\( r_k \) and \( r_{k-1} \) (m) the amount of water which will infiltrate through the layers starting from the main infiltration rate

\( V_{k-1} \) (d\(^{-1}\)) the vertical conductivity divided by the thickness of the layer \( k-1 \)

\( c_{k-1} \) (%) the TDS of the layer \( k-1 \) in percentage

\( D\text{CONC} \) (-) the saltwater density subtracted by the freshwater density

\( D_k \) and \( D_{k-1} \) (m) thickness of layer \( k \) and \( k-1 \)

In the Dammam, upper Rus and Umm er Radhuma formations, the \( r_k \) factor is zero. This is due to the fact that the infiltrating water will move laterally and will have a negligible vertical flow through these aquifers. In other words, the first term compensating for the vertical flow will be zero. In the Midra Shale Member the amount of water which will effectively infiltrate through the layer is estimated at 2.25 mm. When using the top half of the layer in the calculation, parameter \( r_k \) will be set at 2.25 mm since \( r_{k-1} \) will still be zero as it is represented by a Dammam layer. When using the bottom half in the calculation, the values of the parameters will be switched. The same principle is used for the top and bottom layer of the gypsiferous Rus Formation. The only difference is that the infiltration is estimated to be at 1 mm instead of 2.25 mm. Between the Rus Formation layers, both \( r_k \) and \( r_{k-1} \) will be put as 1 mm.

As described above, a depression cone is present in the north-western corner of the study area. This depression cone is created in the upper aquifer (Dammam and Rus formations) and will, due to the presence of the less permeable gypsiferous Rus Formation, only have a small effect in the Umm er Radhuma Formation. To accommodate this smaller effect, equation (11) has been modified. The calculation of the heads in the UER will take into account an influence of 10% of the depression cone and 90% from an average value representing the heads in the UER outside the influence zone of the depression cone. The chosen average value used is 3.5 m and corresponds with cell \( i,j,k \) (30,0,1), while the depression cone value is -5 m. Along the northern boundary, the first 60 cells are recalculated while for the western boundary, the first 30 cells are recalculated.

The initial heads of the first layer for the active cells are put as 6 m. This is an average derived from the potentiometric surface map. This head is, just as the constant-head cells,
adjusted for the lower lying layers according to equation (11). This initial estimated head for cells with variable-head cells will be recalculated in each iteration of the simulation process.

7.1.4 Fresh and salt water distribution

To accommodate the density driven flow in the model, salt water concentrations for every cell of the model have to be provided. These salt water concentrations are expressed relative to the TDS value of the Gulf water, therefor it is necessary to have a look at the salt water concentration of the Persian Gulf.

The Persian Gulf contains very dense and warm salt water bodies. This is due to the high evaporation rate which ranges from 2 to 5 m yr\(^{-1}\) m\(^2\) which exceeds the net freshwater input by precipitation and river discharge of 0.15 to 0.30 m yr\(^{-1}\)m\(^2\) creating waters with a salinity of 39 psu to 70 psu or higher (1 psu = 1,000 ppm) (Elhakeem & Elshorbagy, 2013). If expressed as TDS, a value of 45,000 ppm is given to represent the sea water surrounding Qatar. The average depth of the Persian Gulf is 36 m but around Qatar and Bahrain, a shallow zone exists with depths of less than 20 m. Due to these shallow conditions, the density of the salt water is higher than in most parts of the Gulf. The average temperature of the salt water in winter, surrounding Qatar and Bahrain, is approximately 20°C and the density ranges between 1028.5 kg m\(^{-3}\) to 1029.5 kg m\(^{-3}\). The average temperature of the salt water in summer can exceed 32°C with the density exceeding 1030 kg m\(^{-3}\) (Kämpf & Sadrinasab, 2006). An average density of 1029 kg m\(^{-3}\) for the salt water is used in this study which corresponds to a TDS of 45,000 ppm.

As this study focuses on the evolution of groundwater heads, evolution of salt water concentrations is not studied in detail, a simplified discretisation has been made: only one value for TDS is derived for every hydrogeological unit. These salinities of the groundwater reservoir have been derived from literature. Figure 21 shows a cross-section through Qatar with the different hydrogeological units and the variation of the TDS values with the depth (Harhash & Yousif, 1985).

The Ummer Radhuma shows a large distribution between TDS values of 10,000 ppm to values greater than 30,000 ppm. Since the models only take into account the first 20 m of the UER, the value used in the models is put as 16,000 ppm to take into account the large increase in TDS and taking an average value for the first twenty metres.

The TDS used for the depositional sulphate Rus facies is 7,000 ppm. The reason for the higher value than depicted on Figure 21 is that in northern Qatar, where the cross-section is taken, the Rus Formation consists of the carbonate facies and the cross-section is also taken through the fresh water lens present in Qatar (Figure 10) meaning the average TDS values present in the study area will be lower. Combined with the fact that the TDS will be higher due to the presence of gypsum a value of 7,000 ppm is chosen to get a more representative value.
Because of the limited thickness of the Midra Shale Member, the upper Rus Formation and the Dammam Formation are seen as one aquifer. For this aquifer, the TDS is also derived from Figure 10. Because of the presence of the Abu Nakhla pond, which has a TDS value of 2,000 ppm, the visualised TDS values are too high. This is because the measurements were done to the north of the pond and to the south of the pond, where the influence of the pond itself is rather small. Because of the large infiltration, due to the Abu Nakhla pond, in the phreatic aquifer, with a known TDS value, combined with the depicted TDS of 5000 ppm, a TDS of 3,000 ppm is derived.

As explained in the paragraph above, the Abu Nakhla pond has a TDS value of 2,000 ppm which was measured in the Abu Nakhla pond at the 7th of May 2014. An overview of all the TDS values used in the model are shown in Table 6.

In the model the salinity of the water in the layers is expressed as a relative percentage to the salinity of the Persian Gulf. The equation to calculate the concentration (%) from the TDS values is as followed:

\[ C_i = \left( \frac{TDS_k - TDS_f}{TDS_s - TDS_f} \right) \times 100 \]  

\( TDS_k \) (ppm) the TDS value of the water present in layer k
\( TDS_f \) (ppm) being the TDS of fresh water equals to 800 ppm
\( TDS_s \) (ppm) the TDS of the salt water in the Persian Gulf equals to 45,000 ppm
Table 6: TDS values and salt water concentrations used in the models.

<table>
<thead>
<tr>
<th>Units</th>
<th>Persian gulf</th>
<th>Fresh water</th>
<th>Abu Nakhla pond</th>
<th>Dammam and upper Rus</th>
<th>Gypsiferous Rus</th>
<th>UER</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDS</td>
<td>ppm</td>
<td>45,000</td>
<td>800</td>
<td>2,000</td>
<td>3,000</td>
<td>7,000</td>
</tr>
<tr>
<td>Salt water concentration</td>
<td>%</td>
<td>100.00</td>
<td>0.00</td>
<td>2.71</td>
<td>4.98</td>
<td>14.03</td>
</tr>
</tbody>
</table>

7.1.5 Recharge

Recharge is derived from the average rainfall visualised in Figure 12. The average rainfall at the Abu Nakhla site over the time period from 1989 to 2007 is 75.61 mm yr\(^{-1}\). As stated in Table 2, the recharge in southern Qatar is mainly due to indirect recharge. Multiplying the average rainfall with the percentage of rainfall that will contribute to the recharge (6%, Table 2) gives a recharge rate of 4.5366 mm yr\(^{-1}\).

This recharge is introduced in the model through the well-package. This yearly recharge rate is recalculated to a corresponding volume of water that will infiltrate in each cell per day, recharge per cell per day = 0.0045366 m yr\(^{-1}\) * 100 m * 100 m / 365.25 d yr\(^{-1}\) which is 0.12 m\(^3\) d\(^{-1}\). This recharge is only appointed to the cells of the uppermost layer of the model.

7.1.6 Evapotranspiration

As elucidated in part 5, the evapotranspiration is very high in Qatar with an average evaporation of 2200 mm yr\(^{-1}\) or about 6.023 mm d\(^{-1}\). This is the open water evaporation rate and it is assumed in this study that it represents the total evapotranspiration present in the study area. The surface topography is defined as the ET surface, which is the level above which maximal evaporation occurs, and the extinction depth, the level below which no evaporation occurs, is put at 1.8 m below the surface topography. The extinction depth is derived from Shah et al., (2007) where the extinction depth is measured for different kinds of soils and vegetation cover (Table 7). The top layer present in the study area consists either of filling material (sand, asphalt …) or limestone. Since extinction depths for limestone are not measured in the article, it is assumed that it will behave as sand to silty clay for bare soil and with an estimation of the average, a value of 1.8 m is derived.
7.1.7 Time discretisation and closure criterion

A total of five stress periods are simulated. Each stress period consists of 31 days, adding up to a total simulation time of five months. Each stress period is discretised in ten time steps. The time step multiplier is put at one, so each time step will be 3.1 days long. Since the model simulates steady state flow, five stress periods of 31 days is more than enough to reach the equilibrium of the heads.

In the .sip-file the closure criterion or HCLOSE of 0.80 m is specified. The value is obtained by trial-and-error by starting with a smaller value and gradually increase it until a convergence of the iterations is obtained and so the model is able to simulate the problem.

7.2 Adding the pond into the base model

This chapter discusses how the Abu Nakhla pond is added into the numerical groundwater model. As the addition of the pond into the model has a big influence on the groundwater heads, some intermediate steps have to be taken to limit the numerical dispersions in order to maintain a stable simulation. These intermediate steps are translated into four sub-models.

Each sub-model uses information which is calculated in the previous model, i.e. the results of the previous model is used as initial conditions for the next model. This is necessary since no changes can be made to the boundary conditions, defined in the .bas-file. The pond can therefore only be added or removed when a new model is started since it requires totally different boundary conditions. Four models are simulated, with the pond in equilibrium with the water level measured on the 8th of May 2015, with increasing complexity: (1) steady state flow with the Abu Nakhla pond present, (2) unsteady state flow with the Abu Nakhla pond present with 100 times smaller storage factors (i.e. mimicking a steady state flow), (3) unsteady state flow with the Abu Nakhla pond present and (4) unsteady state flow with the Abu Nakhla pond desiccating. A discussion of the
base parameters used is elucidated in the base model while the differences of each sub-model compared to the base model, is elucidated in their own paragraphs. An overview of the main differences between the four sub-models is given in Figure 22.

The second part of the study comprises of sensitivity analyses of the desiccation and dissipation of the Abu Nakhla pond. There are four parameters changed: (1) the horizontal conductivity of the upper aquifer, (2) the vertical conductivity of the gypsiferous Rus Formation, (3) the storage factor near the water table and (4) the storage factor of the aquifer. Each parameter has been multiplied and divided by a sensitivity factor:

\[
\text{SenFac} = \sqrt{10} = 10^{0.5}
\]

A comparison can then be made which parameter influences the desiccation the most.

<table>
<thead>
<tr>
<th>Sub-model one</th>
<th>Sub-model two</th>
<th>Sub-model three</th>
<th>Sub-model four</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction of the Abu Nakhla pond</td>
<td>Mimicking steady state flow</td>
<td>Fully unsteady state</td>
<td>Removal of the Abu Nakhla pond</td>
</tr>
<tr>
<td>Input</td>
<td>• Steady state flow</td>
<td>• Unsteady state flow</td>
<td>• Unsteady state flow</td>
</tr>
<tr>
<td></td>
<td>• Interpolated heads &amp; concentrations</td>
<td>• Initial heads &amp; concentrations</td>
<td>• Initial heads &amp; concentrations</td>
</tr>
<tr>
<td></td>
<td>• Introduction of the Abu Nakhla pond (constant-head cells)</td>
<td>• Introduction storage factors (100)</td>
<td>• Changed storage factors (normal)</td>
</tr>
<tr>
<td></td>
<td>• Time discretisation</td>
<td>• Time discretisation</td>
<td>• Time discretisation</td>
</tr>
<tr>
<td></td>
<td>→ 5 stress periods</td>
<td>→ 15 stress periods</td>
<td>→ 15 stress periods</td>
</tr>
<tr>
<td></td>
<td>→ Equal length time steps</td>
<td>→ Incremental time steps</td>
<td>→ Incremental time steps</td>
</tr>
<tr>
<td></td>
<td>→ 5 months accumulated</td>
<td>→ 0.802 years accumulated</td>
<td>→ 80.00 years accumulated</td>
</tr>
<tr>
<td>Output</td>
<td>Grasle.out</td>
<td>Grasle.out</td>
<td>Grasle.out</td>
</tr>
</tbody>
</table>

Figure 22: Overview of the different sub-models with the input and output used.

### 7.2.1 Sub-model one: Steady state flow with pond

With the base model running solid, sub-model one simulates steady state flow with the presence of the Abu Nakhla pond. Only a short simulation time is needed to reach equilibrium.

### 7.2.1.1 Discretisation of the Abu Nakhla pond

To add the Abu Nakhla pond, a polygon with the outline of the Abu Nakhla pond is created with QGIS. By intersecting the model grid with this polygon, a raster file is created that indicates the location of the pond within the model grid. The pond is added in the uppermost model layer as constant-head cells with a TDS of 2,000 ppm. The water level of the Abu Nakhla pond is chosen as the water level which was present on the 8th of May 2015 (Figure 24). The level of the pond is measured at 35.10 m amsl and is rounded down to a value 35 m amsl. The location of the pond in the model grid is shown in Figure 24.
To accommodate the big difference between the heads of the model without the presence of the pond compared to the model with the pond, a new initial estimate of the hydraulic heads is made. Starting from the middle of the pond (row 71, column 91, head 35 m amsl) an interpolation is made to the closest boundary of the model (row 1, column 91, head 6 m amsl). Following calculation is made to obtain this interpolation factor, based on the distance of the cell compared to the middle of the pond and the closest model boundary to this middle cell:

\[
\sum_{i=1,j=1}^{n,m} f = 1.0 - \frac{\sqrt{(R_i - row)^2 + (C_j - column)^2}}{r} \]

\[
f < 0 => f = 0
\]

\[f = \frac{35 - 6}{70} = 0.4286
\]

f is the factor being calculated for cell i,j

R_i is the row i

C_j is the column j

row and column are the coordinates of the middle of the pond (71,91)

r is the distance between the boundary and the middle of the pond, which is 70 cells.

The influence of the pond will decrease dramatically in the Rus aquitard and thus following formula is used to decrease the factor with depth starting from layer 7 until layer 21:

\[\sum_{i=1,j=1}^{n,m} f = 1.0 - \frac{\sqrt{(R_i - row)^2 + (C_j - column)^2}}{r} \]

\[f < 0 => f = 0
\]
\[ f_{7 \to 21} = f_{7 \to 21} \times \frac{(1 - (\text{layer} - 7))}{(\text{NLAY} - 7)} \]  

NLAY is the total number of layers  
layer is the number of the layer for which the correction is calculated  
The final formula to calculate the corrected head with the distance of the pond is:  
\[ h = h_i + (h_p - h_i) \times f \]  

\( h \) (m) is the interpolated head  
\( h_i \) (m) is the initial head, in this case 6 m  
\( h_p \) (m) is the head of the Abu Nakhla pond, in this case 35 m  
This interpolation gives a circular pattern with higher values near the Abu Nakhla pond and lower values near the edges. This is visualised in Figure 25.  

\[ \text{Figure 25: Interpolated initial heads of each layer of sub-model one.} \]

\textbf{7.2.2 Sub-model two: Mimicking steady state with an unsteady state model}  
This model is needed to make the transition from steady state flow to a model with unsteady state flow. In the steady state model all layer-types (LAYCON) are set to zero, while in the unsteady state flow model the first six layer-type are set to three (for more information on LAYCON, see part 6.5.1.2). Using a LAYCON equal to three enables the first six layers to become dry and this will affect the transmissivities and storage factors compared to having fully saturated layers. It is therefore necessary to introduce the LAYCON as soon as possible, but since there is no layer-type (other than zero) which can
be used in this study for steady state flow, this model will simulate steady state flow while being actually an unsteady state flow simulation. This is done by using 100 times smaller storage factors than the unsteady state flow sub-model three.

7.2.2.1 Hydrogeological parameters

To simulate the desiccation of the pond in the fourth sub-model, it is necessary that the storage factors and transmissivities are able to change in time. To remove the influence of solely adding a different LAYCON flag to a model, the LAYCON set at three is introduced starting from sub-model two. For the first six layers the value for the LAYCON is set at three so that the transmissivity will be able to vary in time and that the storage factors can vary in time between two defined values. The transmissivity is calculated with the horizontal conductivity and the saturation thickness of the layers. To be able to assess the saturation of the layer, two extra parameters need to be defined: (1) BOT, which defines the bottom of the layer and (2) TOP, which defines the top of the layer, both expressed in m amsl. Depending on the water table level compared to the TOP and BOT of the layer, the saturation can be calculated. The horizontal conductivity is derived from the transmissivity divided through the thickness of the layer and the values are presented in Table 8. The layer-type is put at three for every cell in the first six layers, including the constant-head cells at the boundaries. When a constant-head cell becomes dry, the model will produce an error so a correction must be made: If the head of a constant-head cell is equal or lower than the elevation of the cell, the constant-head cell is changed into an active cell.

The storage factor will change between the storage factor of the aquifer and the storage factor near the water table. However, the storage factors are 100 times smaller than normal (Table 4) so a steady state flow is mimicked. The storage factor near the water table is defined as 0.000104, the storage factor of the aquifer is defined as 0.00002. The parameter TOP is used to validate which storage factor needs to be used in the calculations as SF[1], in the MODFLOW code, is defined as the storage factor of the aquifer and SF[2] is defined as the storage factor near the water table. For layers two to six this means that, if the water table is above TOP of the layer, SF[1] will be used and if the water table is equal or lower than TOP of the layer, SF[2] will be used. In layer one it is a bit more complicated. The TOP for layer one is a matrix where the topography is equal to an average of 32 m while the bottom of the pond is added in detail (Figure 26). The bottom of the pond is derived from bathymetry values measured. It is measured by driving a boat from edge to edge of the pond in a line, measuring at a regular interval along that line. The next line is then measured with a certain amount of space between the previous line. It should be noted that the depth at each measured point is correct but without sophisticated GPS appliances it is difficult to drive in a straight line as seen in Figure 27. Based on these measurements, which have a large spatial variability between the different lines, an interpolation is done giving a good estimation of the bottom of the Abu Nakhla pond.
Table 8: The hydraulic conductivities, storage factors, TOP, BOT and verts for the six layers with LAYCON set at three.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Hydraulic conductivity (m d(^{-1}))</th>
<th>Layer top elevation (TOP) (m)</th>
<th>Layer bottom elevation (BOT) (m)</th>
<th>SF[1]</th>
<th>SF[2]</th>
<th>Vert (d(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.0</td>
<td>Bottom of pond</td>
<td>18</td>
<td>0.000104</td>
<td>0.000104</td>
<td>0.0427</td>
</tr>
<tr>
<td>2</td>
<td>8.0</td>
<td>18</td>
<td>13</td>
<td>0.000020</td>
<td>0.000104</td>
<td>0.0032</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>13</td>
<td>8</td>
<td>0.000020</td>
<td>0.000104</td>
<td>0.032</td>
</tr>
<tr>
<td>4</td>
<td>8.0</td>
<td>8</td>
<td>3</td>
<td>0.000020</td>
<td>0.000104</td>
<td>0.064</td>
</tr>
<tr>
<td>5</td>
<td>8.0</td>
<td>3</td>
<td>-2</td>
<td>0.000020</td>
<td>0.000104</td>
<td>0.064</td>
</tr>
<tr>
<td>6</td>
<td>8.0</td>
<td>-2</td>
<td>-7</td>
<td>0.000020</td>
<td>0.000104</td>
<td>0.064</td>
</tr>
</tbody>
</table>

Figure 26: Visualisation of the raster file with the bathymetry of the Abu Nakhla pond with: (1) Light green is the A basin with interpolated values, (2) Dark blue is the B basin with interpolated values, (3) Red is the C Basin with no direct measurements and is put at 33 m, (4) Light blue are manually interpolated cells with their neighbour and (5) Purple are the cells surrounding the pond with values set at 32 m.
In sub-model four, a large difference between the storage factor of the Abu Nakhla pond and the surrounding cells (factor of the difference is about 100) creates a numerical error resulting in a mirroring of the heads of the top layers into the bottom four layers. To compensate for this numerical error, the bottom layer of the Umm er Radhuma Formation (layer 21) is put as constant-head cells. To be able to compare the models, the constant-head cells of the bottom layer are also added in sub-model two and three.

7.2.2.2 Time discretisation and closure criterion

In this model fifteen stress periods, each divided into twenty time steps, are considered. It was opted to have incremental increasing time steps, i.e. the first time step of period n is larger than the last time step of period n-1. This will assure detailed simulation in the beginning when the changes will be large and less details due to longer time steps when the changes will become small. Following principle is used to calculate the time step multiplier in combination with the chosen stress period factor:

$$ TSMULTI = 10^{\log(F) / T} $$

TSMULTI is the time step multiplier

F is the stress period factor

T is the amount of time steps
The stress period factor will define the increase in length of the stress periods. A factor $F$ equal to 1.515 is used with a starting stress period length of 30 days for stress period one. Combined with twenty time steps, a value of 1.021 for TSMULTI is derived. An overview of the length of the stress periods (Table 15) and the length of the time steps is presented in Table 16 (Appendix B).

This model mimics steady state flow with an unsteady state model, so only small changes in head are expected to occur. Due to the small storage factors a very fast equilibrium should be obtained. Therefore short stress periods are used, 100 times shorter than presented in Appendix B. If normal stress periods would be used, small numerical errors will start to occur at each calculation because no water flows in or out of the storage. These errors will accumulate and cause a faulty simulation.

The closure criterion is set very strict at 0.005 m. This is possible since the only difference between the first and the second sub-model is the change from steady state to unsteady state with adjusted LAYCONs. Only changes due to the addition of LAYCON are expected and thus a strict HCLOSE can be used.

### 7.2.3 Sub-model three: From mimicking steady state to full unsteady state

This model represents the step from a mimicked steady state flow model to a full unsteady state flow model. In essence, the model parameter input is exactly the same as the previous model, except for the storage factors which now have normal values. So only a small correction is needed in comparison with the previous sub-model.

#### 7.2.3.1 Boundary conditions and storage factors

The boundary conditions are the same compared to sub-model two, but a correction is needed due to the way MODFLOW is written in respect to the layer-types. When a head drops below the bottom of the layer, the cell will become dry and the head is put at 0.0 m by the MODFLOW code. No problems arise for the first four layers, but the bottom of layer five is at -2 m amsl, when the heads from the previous sub-model are read and used as the new initial heads for sub-model three, these dry cells are considered as active cells as their heads (0.0 m amsl) are above the base of the model layer five. This creates a large numerical error after simulation. To fix this error, all active cells with a head of 0.0 m are converted to inactive cells. By doing so, no calculations will happen in the dry cells which eliminates the arisen problem.

Storage factors are already introduced in the previous sub-model, however they were set 100 times smaller than their normal values. In this sub-model the storage factors are changed to their normal values. The storage factors used can be found in Table 4 and the reasoning why these storage factors are used is extensively discussed in part 7.1.2.

#### 7.2.3.2 Time discretisation and closure criterion

The time discretisation used is, just like with the storage factors, equal to sub-model two but 100 times larger. Fifteen stress periods, which accumulate to a total of 80.92 years
(Table 15, Appendix B), are used with the same stress period factor $F$ and TSMULTI. The time steps are thus also incremental (Table 16, Appendix B).

The closure criterion HCLOSE is set at 0.015 m.

### 7.2.4 Sub-model four: Desiccation and dissipation of the Abu Nakhla pond

The last sub-model simulates the desiccation and dissipation of the Abu Nakhla pond.

#### 7.2.4.1 Boundary conditions and hydrogeological parameters

To simulate the desiccation of the Abu Nakhla pond, it is necessary for the transmissivities and especially storage coefficients to be able to vary in time. As explained in previous parts, this was done by changing the LAYCON flag from zero to three and this was already changed in previous models with the prospect of sub-model four. The variation of the storage factor for this model can be divided into two parts: (1) In the uppermost model layer, the storage factor will change between the storage factor of the Abu Nakhla pond, SF[1] to the storage factor near the water table, SF[2], and (2) in layer two to six it changes between the storage factor of the aquifer, SF[1], and the storage factor near the water table SF[2]. The storage factors used are as defined in Table 4 but the storage factor for the pond itself is set at one. The reasoning for this is that the pond represents open water which will give 1 m³ of water when the water table is lowered by 1 m. SF[1] of layer one is a matrix where every cell, which lies within the Abu Nakhla pond, has a value of one while the other cells have a value of 0.0104. This is shown in Table 9.

**Table 9: The hydraulic conductivities, storage factors, TOP, BOT and verts for the six layers with LAYCON set at three.**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Hydraulic conductivity (m d⁻¹)</th>
<th>Layer top elevation (TOP) (m)</th>
<th>Layer bottom elevation (BOT) (m)</th>
<th>SF[1]</th>
<th>SF[2]</th>
<th>Vert (d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.0</td>
<td>Bottom of pond</td>
<td>18</td>
<td></td>
<td></td>
<td>0.0104</td>
</tr>
<tr>
<td>2</td>
<td>8.0</td>
<td>18</td>
<td>13</td>
<td>0.0020</td>
<td>0.0104</td>
<td>0.0427</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>13</td>
<td>8</td>
<td>0.0020</td>
<td>0.0104</td>
<td>0.0032</td>
</tr>
<tr>
<td>4</td>
<td>8.0</td>
<td>8</td>
<td>3</td>
<td>0.0020</td>
<td>0.0104</td>
<td>0.032</td>
</tr>
<tr>
<td>5</td>
<td>8.0</td>
<td>3</td>
<td>-2</td>
<td>0.0020</td>
<td>0.0104</td>
<td>0.064</td>
</tr>
<tr>
<td>6</td>
<td>8.0</td>
<td>-2</td>
<td>-7</td>
<td>0.0020</td>
<td>0.0104</td>
<td>0.064</td>
</tr>
</tbody>
</table>

#### 7.2.4.2 Time discretisation and closure criterion

The same principle of incremental time steps with the same multipliers is applied but less stress periods are considered. A total of ten stress periods with twenty time steps are
simulated with a cumulative time period of ten years (Table 16, Appendix B). A closure criterion of 0.005 m is used.

### 7.3 Sensitivity analysis

Four hydraulic parameters are tested \((K_h, K_v, \text{SF near the water table and SF of the aquifer})\) for their sensitivity in terms of how fast the pond dissipates and how fast the heads of the aquifer normalises when no recharge occurs in the pond. This is done by multiplying and dividing the parameters by a sensitivity factor \(\text{SenFac}\), i.e. a maximum and minimum value is thus obtained. To maintain comparability, the \(\text{SenFac}\) used for each parameter is kept the same \((\text{SenFac} = 10^{0.5})\). However, only for the minimum horizontal conductivity, the \(\text{SenFac}\) was changed to \(\text{SenFac} = 10^{0.1}\) as the model would otherwise not run. Each model used the same four sub-models elucidated above, the details of each parameter is discussed below.

#### 7.3.1 Horizontal conductivity of the upper aquifer

The horizontal conductivity is changed for the first six layers, i.e. the upper aquifer. Starting with the initial horizontal conductivity, the normal \(\text{SenFac}\) is used to calculate the maximum while a smaller \(\text{SenFac}\) is used for the minimum value. The horizontal conductivity is rather sensitive for the change and when lowering the value, it could be seen as compressing the layers (i.e. the transmissivity lowers). Because the transmissivities are a function of the saturated thickness and the calculated head, a non-linearity between the transmissivity and the calculated head occur resulting in a faulty model. Using a lower \(\text{SenFac}\) solves this error. The used parameters are given in Table 1.

*Table 10: Minimum and maximum horizontal conductivity for each of the six layers including the transmissivity.*

<table>
<thead>
<tr>
<th>Layer</th>
<th>Minimum (K_h) (m d(^{-1}))</th>
<th>Maximum transmissivity (m(^2) d(^{-1}))</th>
<th>Maximum (K_h) (m d(^{-1}))</th>
<th>Minimum transmissivity (m(^2) d(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.35</td>
<td>54.01</td>
<td>25.30</td>
<td>215.03</td>
</tr>
<tr>
<td>2</td>
<td>6.35</td>
<td>31.77</td>
<td>25.30</td>
<td>126.49</td>
</tr>
<tr>
<td>3</td>
<td>0.16</td>
<td>0.79</td>
<td>0.63</td>
<td>3.16</td>
</tr>
<tr>
<td>4 - 6</td>
<td>6.35</td>
<td>31.77</td>
<td>25.30</td>
<td>126.49</td>
</tr>
</tbody>
</table>

#### 7.3.2 Vertical conductivity of the gypsiferous Rus Formation

The vertical conductivity for the gypsiferous Rus Formation is changed. In the models it is expressed as the reciprocal value of the hydraulic resistance, \(\text{vert}\). The \(\text{vert}\) used as the minimum and maximum value are depicted in Table 11.
Table 11: Minimum and maximum vert for each of the eleven layers of the gypsiferous Rus Formation.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Minimum vert (d⁻¹)</th>
<th>maximum vert (d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.000010</td>
<td>0.000101</td>
</tr>
<tr>
<td>8 - 16</td>
<td>0.000005</td>
<td>0.000051</td>
</tr>
<tr>
<td>17</td>
<td>0.000010</td>
<td>0.000101</td>
</tr>
</tbody>
</table>

7.3.3 Storage factors

The storage factors are split into the storage factor near the water table, SF[1] and the storage factor of the aquifer, SF[2]. Both are changed independently of each other to be able to see which storage factor has the greatest influence and how they relate to each other. The used minimum and maximum values of the storage factors are given in table.

Table 12: Minimum and maximum storage factor near the water table and storage factor of the aquifer.

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF[1]</td>
<td>0.00329</td>
<td>0.0329</td>
</tr>
<tr>
<td>SF[2]</td>
<td>0.00063</td>
<td>0.0063</td>
</tr>
</tbody>
</table>
8. RESULTS AND DISCUSSION

In this chapter, the results are presented and discussed of the simulations according to the above-mentioned model constructions. To be able to compare the results with each other, the same horizontal and vertical cross-sections are visualised.

The horizontal cross-section is taken of layer five because the number of dry cells are relatively small and the influence of the pond is still well noticeable. If the cross-section would be of a layer above layer five, the amount of dry cells would grow and the amount of information seen on the cross-section would decrease. Layer five is also the middle layer between the Midra Shale Member and the lower Rus Formation.

The vertical cross-section is taken along row 71 (west to east direction). Row 71 runs through the middle of the pond and gives a good overview of the head distribution in and around the pond.

Both in the horizontal and vertical cross-section, there will be dry cells or inactive cells present. The dry cells are represented by a head of 0.0 m and will be visualised by a dark blue colour on the cross-sections while the inactive cells have a head of 99.9 m and will be visualised by a dark red colour. The visualisation software will interpolate between the isolines of the head of a real value and the dry or inactive cells head causing multiple isolines to be plotted over each other. This interpolation is wrong and may be ignored. In the horizontal cross-section, the dry cells and inactive cells will mostly be present in the upper left corner, while for the vertical cross-section, these will be present along the top layers.

For the results of sub-model four and the sensitivity analyses, four graphs are plotted, three with the head (m) versus the time (d) and one with the head (m) versus the depth (expressed in layers). These will show the head in the centre of the pond (row 71, column 91, dark blue) for layer one and five, at a distance of 2 km and 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions of the centre of the pond.

8.1 Base model

8.1.1 Steady state flow

Figure 28 shows the distribution of the head if no pond would be present in the study area. The influence of the heads at the boundaries is well pronounced. A trend of higher heads in the east and lower heads towards the west are a representation of the head distribution caused by extensive pumping in the west. Groundwater will flow from north to south at the eastern boundary while in the north-western quadrant, the groundwater flow will be from south to north. At the centre, only a small groundwater flow is present which is divided in a flow which goes to the north-western corner and a flow that will go to the south-eastern
corner. This represents a watershed which roughly runs from the north-east to the south-west.

![Diagram](image.png)

**Figure 28**: Horizontal cross-section of the groundwater head (m) through layer five of the steady state flow base model, stress period five.

### 8.1.2 Unsteady state flow

As the final model of the groundwater reservoir with the presence of the pond is an unsteady state model (sub-model three) in which model layers of layer-type three (LAYCON) are used, the base model is also transformed to an unsteady state model with model layers of layer-type three. This allows a comparison between both models.

A horizontal cross-section of this model through layer five is visualised in Figure 29. The full effect when LAYCON is set to three for the first six layers is now clearly illustrated. While the difference between a steady state and unsteady state flow is only some small numerical dispersion, a different head distribution is obtained. An increase in the north-eastern part of the study area with a head of almost 15 m can be seen. Otherwise, compared to the steady state model, the heads over the whole study area are increased slightly but still shows the same patterns. The large head increase in the northeast is due to the fact that the layers above become dry or unsaturated, which alters the transmissivity and the storage of the layer. Water present in those layers must now dissipate in the layers below.
Figure 29: Horizontal cross-section of the groundwater head (m) through layer five of the unsteady state base model, stress period fifteen. The dark red colour in the upper left corner represents inactive cells.

To better understand why accumulation of water is only present in the northeast, a closer look is necessary at a vertical cross-section through the heads of the groundwater reservoir along row 10 (Figure 30). It is due to the fact that when the groundwater head is lower than the bottom of the layer, the layer will become dry. Due to the decrease of head in westward direction, only two layers are dry at the eastern boundary while up to layer five is dry at the western boundary. The water can thus only dissipate vertically because at the western border of the increased head, the third layer is dry. However, the gypsiferous Rus Formation, starting at layer eight, can be considered as an aquitard and will slow down the dissipation leading to a head distribution with a higher head in the north-eastern part of the study area.

Figure 30: Vertical cross-section of the groundwater head (m) along row 10 of the unsteady state base model, stress period fifteen. The dark red colour represents inactive cells.
When looking at a vertical cross-section along row 71 (Figure 31), it can be noticed that less of the top layers are dry compared to the cross-section along row 10 (Figure 30). In the east the top two layers are dry while more to the west, the top three layers are dry. The influence of the higher head in the north-eastern quadrant, due to the change in layer-type, is well noticeable with heads above 10 m.

![Figure 31: Vertical cross-section of the groundwater head (m) along row 71 of the unsteady state base model, stress period fifteen. The dark red colour represents inactive cells.](image)

8.2 Desiccation of the Abu Nakhla pond

8.2.1 Sub-model one: Steady state flow with pond

The heads decreasing in concentric circles around the Abu Nakhla pond can still be depicted in the results of layer one at stress period five (406 days) (Figure 32). The watershed that could be seen in the base model, running from the north-eastern corner to the south-western corner, is now more pronounced. This is because of the low heads in the north-western corner and the south-eastern corner compared to the pond. Around the pond, a circular head distribution is clearly present while the outer circle isoline is much more influenced by the watershed.

Looking at the vertical cross-section along row 71 (Figure 33) the same trends can be seen as in the horizontal cross-section of layer one. The influence of the pond is clearly visible showing an increase in heads along the row. A flow pattern of mainly horizontal flow in the aquifers and mainly a vertical flow in the aquitards is reflected by the isoline of the head being vertical in the aquifers and inclined in the aquitards. In the upper aquifer the isolines are almost vertical, only showing a small offset at the Midra Shale Member (layer three), which can be best seen right under the pond itself. This results in a smaller area under the pond, with heads of 35 m, starting at layer three. In the Umm er Radhuma Formation the horizontal flow is again larger than in the gypsiferous Rus Formation, resulting in the sharp angle of the isoline of the heads at the border between the two formations.
8.2.2 Sub-model two: Mimicking steady state with an unsteady state model

The step from sub-model one to sub-model two is the introduction of the different LAYCON setting, which is best visible in layer one. When a cell becomes dry, the head of that cell will automatically be set at 0.0 m and if a horizontal cross-section of layer one is taken at the last stress period (80.92 years), it is clear that more than half the layer has become dry (Figure 34).
Figure 34: Horizontal cross-section of the groundwater head (m) through layer one of sub-model two, stress period fifteen. The blue colour represents dry cells.

If looked at the visualisation of a cross-section of layer five and along row 71 of stress period fifteen (80.92 years) (Figure 35 and Figure 36), it is clear that a difference exists between the results of sub-model one and the results of this model. The most noticeable difference is the increased head at the north side of the pond. The 25 m and 20 m isoline extended extensively northwards with an average head increase of about 9 m. This increase is due to the change of the LAYCON flag. This causes layers to be able to become dry and thus have their transmissivities changed according to the saturated thickness. This explains the rather large difference between sub-model one and sub-model two.

The full extent in depth of the cells which become dry can be seen on the vertical cross-section (Figure 36). At the western side the vertical extent reaches until layer three while for the eastern side only layer two fall dry. In the north-western corner the heads drop even below the bottom elevation of layer five due to the extensive pumping in this area.
8. RESULTS AND DISCUSSION

8.2.3 Sub-model three: From mimicking steady state to full unsteady state

When looked at the horizontal cross-section of layer five (Figure 37), no big differences are present compared with sub-model two. This is to be expected since this model represents the transition from small storage factors to normal storage factors. The only noticeable difference is the movement of the head isolines towards the north-western corner of the model area.
RESULTS AND DISCUSSION

Figure 37: Horizontal cross-section of the groundwater head (m) through layer five of sub-model three, stress period fifteen. The dark red colour in the upper left corner represents inactive cells.

Figure 38 visualises a vertical-cross section along row 10. It shows the increased head in the northern part, due to the change in layer-type, and it shows the distribution of inactive, or dry, cells. This distribution is similar as was seen on the vertical cross-section along row 10 of the unsteady state base model (Figure 30).

Figure 38: Vertical cross-section of the groundwater head (m) along row 10 of sub-model three, stress period fifteen. The dark red colour represents inactive cells.

At the vertical cross-section along row 71 (Figure 39) no difference can be depicted besides the transition from dry cells to inactive cells, explained in part 7.2.3.1.
8. RESULTS AND DISCUSSION

8.2.4 Sub-model four: Desiccation and dissipation of the Abu Nakhla pond

As expected, the pond desiccates quite rapidly under the dry desert conditions. To visualise the overall head decrease, a difference figure is made of layer five where the difference is taken of stress period ten minus stress period one (after 10 years and after 30 days) (Figure 40). This shows the decrease in heads between those two stress periods. In almost 10 years the head at the centre of the pond has dropped by almost 19 m. The largest drop is at the centre of the pond and the decrease in head lowers towards the edge of the model area.

In Figure 41, a horizontal cross-section is made through layer five of the third, fifth, eighth and tenth stress period (144, 406, 1558 and 3652 days). An evolution of a head of nearly
35 m in stress period three (144 days) to a head of just under 20 m in stress period ten (3652 days) can be depicted. It should be noted that the stress periods increase with a factor $F$ of 1.515 causing a rather large difference between stress period five and eight (406 and 1558 days). This can be noticed in the jump of the max head from over 30 m to under 25 m. The highest heads remain in the northern part of the study area, which is to be expected since the initial heads are higher in that vicinity. Nevertheless, an overall large decrease in head, with a maximum decrease of almost 19 m at the centre of the Abu Nakhla pond can be depicted.

Figure 41: Horizontal cross-section of the groundwater head (m) through layer five of sub-model four, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.

A vertical cross-section along row 71 of stress periods three, five, eight and ten (144, 406, 1558 and 3652 days) is also made (Figure 42). The evolution in head in vertical direction is similar as seen for layer five. At stress period eight (1558 days) it can be noticed that in the top of the gypsiferous Rus Formation, between layer eight and ten, a slightly larger head is present compared to the surrounding heads. This is due to the fact that there is nearly no horizontal flow present in the gypsiferous Rus Formation combined with a very small vertical conductivity, the head needs more time to drop as the water cannot dissipate as fast as in the upper aquifer. At the last stress period (3652 days), the head in layer one drops below 18 m which is the bottom of layer one, causing layer one to be unsaturated.
Figure 42: Vertical cross-section of the groundwater head (m) along row 71 of sub-model four, stress periods three, five, eight and ten. The dark red colour represents inactive cells.

The change between the storage factor of the pond and the storage factor of the aquifer, when the head drops below the bottom of the pond, can be seen when the head is plotted versus the time for a cell in the centre of the Abu Nakhla pond (Figure 43). Three phases can be depicted in the evolution of layer one: (1) a gentle decrease in head until stress period six (645 days), (2) a sharp drop which stabilises over the course of three stress periods (between 1008 and 2391 days) and (3) a drop to 0 m at the last stress period (3652 days).

The first phase is when the storage factor of one is present at the pond. A large volume of water can be stored in this huge storage factor and the head decrease will go quite gently. The head in layer five decreases slightly faster than in layer one due to a smaller storage factor compared to layer one. The second phase starts at stress period six. When the head falls below the bottom of the pond (which is 30 m for row 71, column 91) in layer one, the storage factor of the pond changes from 1 to 0.0104, this is phase two. When the storage factor becomes smaller, the volume which can be released from the storage will also become smaller. When the head drops, the storage factor counteracts this drop by releasing water and the less water able to be released, the larger the drop in head will be. The threshold of 30 m is exceeded between stress period six and seven as the heads are
RESPECTIVELY 32.7 M AND 26.4 M. AS INTERMEDIATE RESULTS WITHIN A STRESS PERIOD ARE NOT STORED, THE DROP APPEARS TO OCCUR EARLIER BUT IN FACT, THE GENTLE DROP GOES ON IN THE BEGINNING OF STRESS PERIOD SIX UNTIL THE THRESHOLD OF 30 M IS REACHED. THE DECREASE IN HEAD STABILISES AND IS ABOUT THE SAME FOR LAYER ONE AND FIVE. THE THIRD PHASE, WHICH STARTS AT STRESS PERIOD NINE (2391 DAYS), IS CHARACTERISED BY A BIG DIFFERENCE BETWEEN BOTH LAYERS. LAYER FIVE SHOWS AN EVEN LESS STEEP CURVE INDICATING A VERY SLOW DROP IN HEAD, JUST UNDER 2.5 M DECREASE OVER 1261 DAYS, WHILE LAYER ONE DROPS TO A HEAD OF 0 M. AGAIN, THE CURVE DOES NOT REPRESENT PERFECTLY WHAT HAPPENS BECAUSE NO DATA IS AVAILABLE BETWEEN STRESS PERIODS. THE BOTTOM OF LAYER ONE IS 18 M AND WHEN THE HEAD FALLS BELOW THE BOTTOM OF THE LAYER, IT IS UNSATURATED AND THE HEAD IS AUTOMATICALLY PUT AT 0.0 M BY THE MODELLING SOFTWARE. A CORRECT VISUALISATION WOULD BE A GENTLE DROP TO 18 M WITH THEN A CURVE GOING DOWN VERTICALLY TO 0 M TO THEN STAY AT 0 M FOR THE REST OF THE TIME.

Figure 43: Head (m) versus time (d) of layer one and layer five of a cell at the centre of the Abu Nakhla pond (sub-model four).

In Figure 44 a comparison is made of a cell in in the centre of the pond in model layer five and a cell at a distance of 2 km from the centre in westward, eastward, northward and southward directions. The heads show a similar trend in respect to the decrease but show a much smaller effect of the changing storage factor of the pond. In westward direction (row 71, column 71), the influence is larger than in the other directions. The head in the centre of the pond drops below the head in the north quite rapidly, between stress periods seven (1008 days) and eight (1558 days), and drops just below the head in the west around stress period nine (2391 days).
Figure 44: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (sub-model four).

In Figure 45 a comparison is made of a cell in the centre of the pond of model layer five and of a cell at a distance of 5 km from the centre in westward, eastward, northward and southward directions. It is clear that the pond has no large influence at 5 km distance and the heads show only a small decrease. Eventually the head of the cell in the centre of the pond even drops below the head of the cell to the north.

Figure 45: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (sub-model four).

An interesting graph is plotted when for each stress period, the head (m) versus the depth (expressed in layers) is visualised for the centre of the pond (Figure 46). This gives an
overview of how the head evolves in each layer over time. The drop in head becomes larger as the stress periods becomes larger. The first six stress periods (until 665 days) are relatively close to each other in time. This can be seen as the decrease in heads are closely spaced indicating that the drop in head is relatively small. It’s only when the storage factor changes between stress period six (665 days) and seven (1008 days) that a large drop in head can be noticed. Another interesting feature of the decrease in head between those two stress periods is the larger decrease below the Midra Shale Member (layer three) than above the Midra Shale Member. This is solely due to the fact that the influence of the large storage factor of the pond, is blocked by the Midra Shale Member as it is an aquitard. When the storage factor changes to the normal value, the difference in head above and below the Midra Shale Member disappears. As seen at the last stress period (3652 days), only the first layer becomes dry at the centre of the pond while the other layers stay saturated during the modelled period.

![Figure 46: Head (m) versus depth (expressed as layers) of the ten stress periods (sub-model four). When the head of a cell drops to 0 m, it represents a dry cell.](image)

Starting at layer 18 to 21, the Umm er Radhuma Formation is present. Layer 21 is a constant-head cell layer which explains why the head in each layer is the same for the whole upper part of the UER Formation. It is clear that, if the pond has any influence on these layers, it will not be visible. The constant-head boundary also shows its influence on the gypsiferous Rus Formation. The gradient present in the gypsum is quite large when the head at the top is high and decreases when the head at the top decreases. The influence of the pond is mostly present in the upper layers of the gypsiferous Rus Formation over the modelled period. Starting at stress period seven (1008 days), a higher head is present in the first two layers of the gypsum compared to the heads in the upper aquifer. As explained at the vertical cross-sections, the water in the gypsum needs more time to dissipate because of the low horizontal and vertical conductivity. The change in
storage factor has only a small effect on the speed of the lowering of the head in the gypsum compared to the upper aquifer.

8.3 Sensitivity analyses

8.3.1 Horizontal conductivity of the upper aquifer

A horizontal cross-section of the groundwater heads through layer five, when the horizontal conductivities of the upper aquifer are multiplied by the sensitivity factor (max Kₕ) is represented in Figure 47. In stress period three (144 days), the pond is still prominently present with a head in the centre of over 30 m. A clear evolution can be depicted going to stress period five (406 days) where the original pond shape is still visible but made a significant drop in head of around 10 m. A big change can be noticed between stress period five and eight (406 and 1558 days). There, the shape of the pond is completely gone, as the pond is completely dry meaning the storage factors are lower and thus a larger drop in head will be present, and an almost equilibrium is formed. Between stress period eight and ten (1558 and 3652 days), there are 1094 days but besides a minor change in head, not much is different.

Figure 48 shows a vertical cross-section of the groundwater heads along row 71. The same evolution as in the horizontal cross-section can be depicted as well as some other features. Layers one, two and three becomes dry between stress period five and eight (406 and 1558 days). In the gypsiferous Rus Formation, the water needs more time to dissipate than the layers above.
Figure 47: Horizontal cross-section of the groundwater head (m) through layer five with max $K_h$, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.

To have a clearer vision on the evolution of the groundwater heads, the same graphs are made as in sub-model four (Figure 49, Figure 50, Figure 51, Figure 52). The first graph shows a comparison between the heads of layer one and five at a cell in the centre of the Abu Nakhla pond. The layer five head evolution is as seen on the horizontal and vertical cross-sections. A slow decrease in head occurs until the head falls below the bottom of the pond at stress period five (406 days) and, due to the large change of the storage factor, a large drop in head is induced. This results in an equal head for both layer one and five. However, in the next stress period (stress period six, 645 days) the head in the upper layer drops below the bottom of the layer, resulting in a dry layer one. Layer five stays saturated and around stress period eight (1558 days), it reaches an equilibrium.
Figure 48: Vertical cross-section of the groundwater head (m) along row 71 with max $K_h$, stress periods three, five, eight and ten. The dark red colour represents inactive cells.

Figure 49: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (max $K_h$).
The second and third graph compare the evolution at the centre of the Abu Nakhla pond with a cell at a fixed distance in westward, eastward, northward and southward directions. First, it is compared with a cell at a distance of 2 km of the centre of the pond. A similar trend is visible for the cells close to the pond as in the cell in the centre of the pond, however the effect of the changing storage factor is minimal. At the western and southern side, the drop in head is slightly higher than at the northern and eastern side, but each cell reaches constant head after 2391 days (stress period nine).

At a distance of 5 km of the centre of the pond, the changes in heads are lower than at a distance of 2 km. The influence of the change of storage factors is not present at all. Here, the heads also reach a constant value at stress period eight (1558 days).

The fourth graph visualises the head at the centre of the pond in all the layers for each of the ten stress periods. The drop in head between stress period four and five (248 and 406 days) is very noticeable. During the first four stress periods (until 248 days) the head in the top two layers is significantly higher than the heads below model layer three. This difference is due to the large storage factor of the pond which will counteract the drop in head above the Midra Shale Member (model layer three). When the storage factor of the pond is removed, when the pond is completely dry, the head in the upper seven layers becomes the same and the Midra Shale Member does not have any noticeable influence. Layer one becomes dry during stress period six (645 days) and is joined by layer two during stress period eight (1558 days). In the gypsiferous Rus Formation, a major difference can be depicted compared to sub-model four. The heads decrease much slower and due to the major difference in head between the upper aquifer and the first gypsum layers, the top two gypsum layers experiences a larger decrease than at the centre of the gypsum resulting in the large arch in the plots. The Umm er Radhuma Formation shows
no difference in any of the stress periods due to the constant-head boundary present in the bottom layer.

Figure 51: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max Kₚ).

Figure 52: Head (m) versus depth (expressed in layers) of the ten stress periods (max Kₚ). When the head of a cell drops to 0 m, it represents a dry cell.
For the sensitivity analyses with minimum values of $K_h$ for the upper aquifer (min $K_h$), the horizontal and vertical cross-section through the groundwater heads are shown in Figure 53 and Figure 54. It should be kept in mind that the sensitivity factor is smaller compared to the other sensitivity analyses (SenFac is equal to $10^{0.1}$ compared to $10^{0.5}$). At stress periods three and five (144 and 406 days) the shape of the pond is clearly present, at stress periods eight and ten (1558 and 3652 days) the pond is completely gone and only at the northern side, a higher head is still present and continues to lower between the two stress periods.

**Figure 53:** Horizontal cross-section of the groundwater head (m) through layer five with min $K_h$, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.

A vertical cross-section is shown in Figure 54. The presence of the pond is visible in the third and fifth stress period (144 and 406 days) while in stress period eight and ten (1558 and 3652 days), the pond has been desiccated but the influence can still be depicted. Only a small part of layer one has become dry at stress period ten (3652 days), while the rest is still saturated with heads of almost 20 m.
Figure 54: Vertical cross-section of the groundwater head (m) along row 71 with min $K_h$, stress periods three, five, eight and ten. The dark red colour represents inactive cells.

A comparison between the heads in layer one and layer five at the centre of the Abu Nakhla pond is given in Figure 55. A gentle decrease in head is depicted until the head drops below the bottom of the pond in stress period seven (1008 days). It is followed by a steeper slope which indicates a larger drop in head. From stress period nine (2391 days) onwards, the slope stabilises again and this persist into stress period ten (3652 days).
Figure 55: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (min $K_0$).

Figure 56 and Figure 57 visualise the difference between the centre of the pond and at respectively 2 km and 5 km in westward, eastward, northward and southward directions. At a distance of 2 km, the influence of the changing storage factor can be depicted in the western and eastern direction but at different stress periods, respectively stress period seven (1008 days) and stress period five (406 days). In the other two directions no kink can be depicted in the curve. The overall decrease in head is similar with only a difference at the beginning where the drops in head are not similar.

The evolution of the head at 5 km of the centre of the pond is minimal. A general trend of head decrease is present with a maximum drop of less than five meters. A slightly larger drop can be depicted at the western and southern side compared to the northern and eastern side.
RESULTS AND DISCUSSION

Figure 56: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min \( K_h \)).

When plotting the head versus the depth for every stress period (Figure 58), the same trend can be noticed as in the head versus time graphs. Until stress period seven (1008 days) the pond is still present and a higher head due to the influence of the storage factor of the pond in the first two layers is present compared to the layers below the Midra Shale Member while between stress period seven and eight (1008 and 1558 days), the pond becomes completely dry and the difference in head above and below the Midra Shale
Member is gone. A small retardation in head decrease in the gypsiferous Rus Formation can also be depicted and the Umm er Radhuma Formation maintains a constant head.

Figure 58: Head (m) versus depth (expressed in layers) of the ten stress periods (min $K_n$).

8.3.2 Vertical conductivity of the gypsiferous Rus Formation

Figure 59 and Figure 60 visualises the horizontal and vertical cross-section of the groundwater heads when simulating with a maximum value for the vertical conductivity of the gypsiferous Rus Formation (max $K_v$). In the horizontal cross-section, the pond shape is prominently present in the third and fifth stress period (144 and 406 days) while it is completely gone in the eight and tenth stress period (1558 and 3652 days) indicating the pond has completely been desiccated between stress period five and eight (406 and 1558 days). A relatively large change can be depicted between the last two represented stress periods (1558 and 3652 days) where the head in the north drops from over 20 m in stress period eight (1558 days) to just above 15 m in stress period ten (3652 days).

On the vertical cross-section the evolution of the pond is better visible. The increased heads due to the presence of the pond can be noticed in stress period three and five (144 and 406 days). Between stress period five and eight (406 and 1558 days) the pond will completely desiccate and the heads start to decrease rapidly. In stress period ten (3652) only remnants can be depicted of the pond. At stress period eight (1558 days), the desiccation of layer one can be depicted while at stress period ten (3652 days), the desiccation extends until layer three.
Figure 59: Horizontal cross-section of the groundwater head (m) through layer five with max Kv, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.

When looking at the plots of the head versus time of layer one and five (Figure 61) different stages can be depicted. First a gentle drop of the head until it reaches the bottom of the pond. When it drops below the bottom, the storage factor will change and induce a large drop which then stabilises and evolves to a more slowly decreasing head. As seen on the vertical cross-section, layer one desiccates and becomes dry, explaining the decrease in head to 0 m.
Figure 60: Vertical cross-section of the groundwater head (m) along row 71 with max $K_v$, stress periods three, five, eight and ten. The dark red colour represents inactive cells. Continued on the next page.

Figure 61: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (max $K_v$).
Figure 62 and Figure 63 shows the evolution of the head in time at the centre of the pond and at a distance of respectively two and five kilometres in westward, eastward, northward and southward directions in layer five. The decrease in head at a distance of 2 km is as expected, a small influence in the change of the storage factor can be depicted while the general trend of decreasing heads could be described as gentle. In the first seven stress periods (until 1008 days), the decrease in head differs for each of the four directions but at stress period eight (1558 days), the decrease is rather similar.

At five kilometres of the centre of the pond, the evolution is a little different. A maximum decrease in head of just over 5 m can be seen in the western and southern part while a smaller decrease can be depicted in the northern and eastern part. There is an influence present of the pond, which resulted in higher heads, but it is marginal compared to the one at a distance of 2 km. A very gentle evolution is the result of that.

Figure 62: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max Kv).
RESULTS AND DISCUSSION

Figure 63: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max $K_v$).

A comparison of the head versus the depth of each stress period is visualised in Figure 64. The first six stress periods (until 645 days) show a similar trend as previous sensitivity analyses and sub-model four, where the heads above the Midra Shale Member decrease more slowly than below the shale, resulting in a kink in the head evolution with the depth. At stress period seven (1008 days), a larger jump is depicted and the graph straightens out in the upper aquifer resulting in a similar evolution of the head. At stress period nine (2391 days), the first layer falls dry at the centre of the desiccated pond. In the upper layers of the gypsiferous Rus Formation, a retardation in decrease in head can be depicted due to the lower horizontal and vertical conductivity compared to the layers above. The Umm er Radhuma Formation shows no influence due to the constant-head boundary at the bottom layer.
Figure 64: Head (m) versus depth (expressed in layers) of the ten stress periods (max $K_v$). When the head of a cell drops to 0 m, it represents a dry cell.

A horizontal and vertical cross-section of the groundwater heads for the sensitivity analysis with the minimum values of the hydraulic conductivities of the gypsiferous Rus Formation (min $K_v$) is shown in Figure 65 and Figure 66. Similar to the other results, the pond is still present in the third and fifth stress period (144 and 406 days) while it completely dries up between stress period five and eight (406 and 1558 days). In stress period ten (3652 days) only remnants of the pond remain.

The vertical cross-section visualises why the shape of the pond can still be depicted in stress period eight (1558 days) in the horizontal cross-section. The water cannot easily infiltrate in the gypsiferous Rus Formation which results in a slower dissipation of the water in the upper layers of the gypsum. This results in a higher head which is still very well noticeable in stress period ten (3652 days).
8. RESULTS AND DISCUSSION

Figure 65: Horizontal cross-section of the groundwater head (m) through layer five with min $K_v$, stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.

Figure 66: Vertical cross-section of the groundwater head (m) along row 71 with min $K_v$, stress periods three, five, eight and ten. The dark red colour represents inactive cells. Continued on the next page
The same story applies as mentioned above about the graphs with the head versus time or depth (Figure 67, Figure 68, Figure 69 and Figure 70). The same trends in the decreasing head can be seen, where the head in layer one drops to 0 m at the last stress period (3652 days) while the head in layer five decreases slowly. When looked at a distance of two kilometres of the centre of the pond, the change in storage factor can be depicted in all four directions and have an equally large decrease in head resulting in the eastern, northern and southern lines to be parallel. The drop in head is larger in the west resulting in the line crossing the eastern line. It then stabilises and has a similar evolution as the cells in the other directions, starting from stress period eight (1558 days). At five kilometres it is clear that the influence of the pond is a lot less compared to at two kilometres. A decrease can be depicted but it is rather small and uniform in all four directions.

Figure 67: Head (m) vs time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (min Kv).
RESULTS AND DISCUSSION

Figure 68: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min $K_v$).

Figure 69: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min $K_v$).

When looking at the head distribution versus the depth, the first seven stress periods (until 1008 days) show the pattern of higher heads above the Midra Shale Member and lower heads below it while the upper layers of the gypsum show a retardation in the decrease in head. At stress period ten (3652 days), the first layer becomes dry and a relatively large head is still maintained in the gypsum.

96

8. RESULTS AND DISCUSSION
Figure 70: Head (m) versus depth (expressed in layers) of the ten stress periods (min $K_v$). When the head of a cell drops to 0 m, it represents a dry cell.

8.3.3 Storage factors

8.3.3.1 Storage factor near the water table

The horizontal cross-section of layer five of the sensitivity analysis with a maximum storage factor near the water table (max SF[1]) (Figure 71) depicts roughly the same evolution as already discussed multiple times. The shape of the pond can be seen in the third and fifth stress period (144 and 406 days) indicating the pond is not yet dried up. Between stress period five and eight (406 and 1558 days) the pond completely desiccated. In stress period ten (3652 days) only remnants remain of the pond.

The vertical cross-section (Figure 72) visualises the same trend as can be seen in the horizontal cross-section. A prominent higher head due to the pond in the third and fifth stress period (144 and 406 days) and large decrease in head between the fifth and eight stress period (406 and 1558 days). In stress period ten (3652 days), layer one has become partially dry.
Figure 71: Horizontal cross-section of the groundwater head (m) through layer five with max SF[1], stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.

Figure 72: Vertical cross-section of the groundwater head (m) along row 71 with max SF[1], stress periods three, five, eight and ten. The dark red colour represents inactive cells. Continued on the next page.
When looking at the graph showing the head versus the time of layer one and five (Figure 73), it is indeed clear that layer one never falls dry at the centre of the pond. The characteristic kinks are, however, present. The first one being the change in storage factor (stress period six, 645 days) of the pond while the second is from the stabilisation of the drop in head (stress period eight, 1558 days).

Comparing the head in the centre of the pond with cells at two and five kilometres in westward, eastward, northward and southward directions gives the same trend as seen in the other models (Figure 74 and Figure 75). At a distance of 2 km from the pond, the influence of the changing storage factor of the pond can be noticed with a small kink in the curve, while the decrease in head between the last stress periods (from 1558 until 3652 days) is similar. At a distance of 5 km from the pond, no influence of the changing storage factor can be depicted and only a general gentle decrease in head is observed.
Figure 74: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max SF[1]).

Figure 75: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakha pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max SF[1]).

The same story goes for the head versus the depth graph (Figure 76). The first seven stress periods (until 1008 days) show a clear difference in head between the upper two layers above and the four layers of the upper aquifer below the Midra Shale Member. At stress period eight (1558 days), when the pond is completely desiccated, the difference is almost completely gone with only a small difference in head between the top and the bottom of the upper aquifer. On this graph, it is also clear that layer one stays indeed saturated at the centre of the desiccated pond. The gypsiferous Rus Formation shows the
same trend as it has done in each model so far. The head starts equally high, compared with the upper aquifer, but because of the lower conductivity it takes more time to dissipate the water and thus lower the head.

![Graph](image)

**Figure 76**: Head (m) versus depth (expressed in layers) of the ten stress periods (max SF[1]).

For the model with the sensitivity analysis of the minimum value of the storage factor near the water table (min SF[1]), the horizontal and vertical cross-section are displayed on Figure 77 and Figure 78. While the pond is still present in the third and fifth stress period (144 and 406 days), the decrease in head in stress period eight (1558 days) indicates the pond dried up between stress period five and eight (406 and 1558 days). In the tenth stress period (3652 days), only a small band of higher heads in the north remains.

The vertical cross-section shows an interesting feature. The third and fifth stress period (144 and 406 days) differ only in the lateral spread of the high head under the pond, but no major change except the head above 30 m is seen. At the eight stress period (1558 days), the influence of the pond is nearly completely gone and at the western edge of layer one it is already dry. The water of the pond is already dissipated, leaving a general head of around 20 m at the centre and between 15 m and 20 m around the centre. In the upper gypsum layers, a slightly larger head can be depicted. At stress period ten (3652 days), nearly all excess water is dissipated, including in the gypsum, leading to an almost uniform distribution of head with a slightly higher head at the centre of the cross-section. Layer one is completely dry at stress period ten (3652 days).
Figure 77: Horizontal cross-section of the groundwater head (m) through layer five with min SF[1], stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.

Figure 78: Vertical cross-section of the groundwater head (m) along row 71 with min SF[1], stress periods three, five, eight and ten. The dark red colour represents inactive cells. Continued on the next page.
The decrease in head in time of layer one and five is, as long as layer one is saturated, quite similar (Figure 79). The decrease in head is marginally larger in layer five in the first six stress periods (until 645 days). The change in storage factor of the pond causes a sharp decrease and the heads of layer one and five drops to about the same level. The head keeps decreasing and at the ninth period, layer one falls dry at the centre of the desiccated pond. Layer five experiences a gentle decrease in head.

Comparing layer five at the centre of the pond and at two fixed distances in westward, eastward, northward and southward directions (two and five kilometres) the same trend as before is present (Figure 80 and Figure 81). A larger decrease in head is experienced in the first eight stress periods (until 1558 days) which then stabilises to a more gentle
decrease in head. Again, a clear difference can be noted between cells at two and five kilometres of the centre. At 5 km the decrease in head is lower than at 2 km.

Looking at the head versus the depth for all stress periods (Figure 82), a similar trend as the models before is depicted. The first six stress periods (until 645 days) show a clear distinction in head between the layers above and below the Midra Shale Member. The difference is completely gone at stress period seven (1008 days) and evolves to the first layer to become dry in stress periods nine and ten (2391 and 3652 days). The higher head present in the upper gypsum is visible in all stress periods, though it gets very small in stress period ten (3652 days), where it is nearly completely gone.

Figure 80: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min SF[1]).
8. RESULTS AND DISCUSSION

Figure 81: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min SF[1]).

Figure 82: Head (m) versus depth (expressed in layers) of the ten stress periods (min SF[1]). When the head of a cell drops to 0 m, it represents a dry cell.
8.3.3.2 Storage factor of the aquifer

The horizontal and vertical cross-section of the groundwater heads of the sensitivity analysis with a maximum storage factor of the aquifer for the whole reservoir (max SF[2]) are shown in Figure 83 and Figure 84. In the horizontal cross-section it can be seen that the pond completely desiccated between stress period five and eight (406 and 1558 days). The maximal head in stress period eight (1558 days) is a bit over 25 m meaning it is well under the 32 m bottom elevation of the pond. At stress period ten (3652 days), the shape of the pond cannot be recognised anymore and a zone of heads over 20 m remains in the northern part of the model.

In the vertical cross-section an evolution of the head can be depicted with heads above 25 m present in the upper part of the gypsiferous Rus Formation while the head in the upper aquifer is between 20 m and 25 m in stress period eight (1558 days). The head above 25 m in layer five is situated around row 60 which is near the northern edge of the pond. In stress period ten (3652 days), the higher heads in the upper gypsum layers can still be seen while in the west, layer one falls dry.

Figure 83: Horizontal cross-section of the groundwater head (m) through layer five with max SF[2], stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.
Figure 84: Vertical cross-section of the groundwater head (m) along row 71 with max SF[2], stress periods three, five, eight and ten. The dark red colour represents inactive cells.

In the head versus time graph for a cell in the centre of the pond of layer one and five (Figure 85), two major phases of the evolution of the head are illustrated. In the first phase, a difference between the heads of both layers is present, while in the second phase, their heads are the same.

Figure 86 and Figure 87 illustrate the difference in head evolution between the centre of the Abu Nakhla pond and at two and five kilometres in westward, eastward, northward and southward directions. The evolutions are similar to previous models with less influence on the head at 5 km compared at 2 km.
Figure 85: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (max SF[2]).

Figure 86: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (max SF[2]).
The head evolution in depth (Figure 88) is, as expected, also similar to previous models. In the first seven periods a clear difference in head above and below the Midra Shale Member is present, which disappears completely at stress period eight (1558 days). The water also needs more time to dissipate in the upper gypsum layers, resulting in a relative increasing head compared to the layers of the upper aquifer.

Results of the horizontal and vertical cross-section of the model with minimum values for the storage factor of the aquifer for the whole reservoir (min SF[2]) are shown in Figure 89 and Figure 90. The pond is still present in the fifth stress period (406 days) while the pond...
is completely dried up in stress periods eight and ten (1558 and 3652 days) and only in the north a zone of higher head remains.

In the vertical cross-section the same can be seen. The head of the pond decreases quite rapidly between stress period five and eight (406 and 1558 days) and causes part of layer one to become unsaturated. For the tenth stress period (3652 days), the influence of the pond is nearly invisible as the heads are mostly uniform with only a small gradient remaining. Even in the gypsum no larger remaining head can be depicted.

Figure 89: Horizontal cross-section of the groundwater head (m) through layer five with min SF[2], stress periods three, five, eight and ten (upper left to lower right). The dark red colour in the upper left corners represent inactive cells.
Comparing the head evolution for a cell in the centre of the pond in layer one and layer five (Figure 91), the same two phases discussed in the previous model (with max SF[2]) can be depicted, with the major difference that at stress period nine (2391 days), layer one becomes unsaturated and drops to a head of 0 m. Layer five experience a gentle decrease in head over the course of the last three stress periods (from 1558 until 3652 days).
Figure 91: Head (m) versus time (d) of layer one and five of a cell at the centre of the Abu Nakhla pond (min SF[2]).

Comparing the centre of the pond with cells at a distance of two and five kilometres gives a familiar trend which is present in all previous models (Figure 92 and Figure 93). At 2 km, a larger decrease in head can be depicted compared at a distance of 5 km. After the first eight stress periods (until 1558 days) the decrease in heads stabilise and resulting in parallel lines. At a distance of 5 km, the difference in the drop in heads is smaller compared to the drop in heads in cells at 2 km and a more gentle evolution can be depicted.

Figure 92: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 2 km in westward (green), eastward (red), northward (light blue) and southward (purple) directions (min SF[2]).
Figure 93: Head (m) versus time (d) of layer five of a cell at the centre of the Abu Nakhla pond (dark blue) and of a cell 5 km in westward, eastward northward and southward directions (min SF[2]).

In Figure 94, the head is plotted versus the depth for each stress period. At the first six stress periods (until 645 days), a difference in head above and below the Midra Shale Member is present, while from stress period seven till ten (from 1008 until 3652 days) the difference is gone. The centre of layer one is unsaturated starting at stress period nine (2391 days) but does not have a noticeable influence on the layers below. The higher heads present, which were sometimes present in the upper gypsum layers in previous models, is here only clearly visible in stress period seven (1008 days). For stress period eight to ten (1558 and 3652 days), the difference is small and the heads decrease almost linearly from the upper aquifer to the heads of the Umm er Radhuma Formation.
RESULTS AND DISCUSSION

8.4 Discussion

A comparison is made with a difference figure between the steady state base model and sub-model one, to look at the differences in head distribution induced by the addition of the Abu Nakhla pond (Figure 95). The boundary conditions used in the base model are also used in the sub-models resulting in a 0 m difference between the base model and sub-model one at the boundaries. The south-eastern part maintains similar values showing only a marginal influence by the addition of the Abu Nakhla pond. A general flow towards the northwest and southeast is present in both models, where the watershed from the south-western to the north-eastern corner is best seen in sub-model one. The major differences are seen in the centre of the study area. By adding the pond, with an almost 30 m higher head, circular isolines of the head are obtained.

The base model is also simulated for an unsteady state flow, allowing the first six layers to become unsaturated, which can be compared with the results of sub-model three visualised by a difference figure (Figure 96). The first noticeable difference is the larger amount of inactive cells in the base model compared to sub-model three in layer five. It is visible as an elongated zone below 0 m near the north-western corner (dark blue). This can be ascribed to the pond which induces higher heads in the whole study area causing a smaller part to be unsaturated as seen as the overall higher heads in the difference figure. In the upper four layers, the amount of inactive cells is also larger for the unsteady state base model and can be seen on the vertical cross-sections along row 10 and 71 (Figure 30, Figure 31, Figure 38 and Figure 39). By simulating the base model with the same layer-type, a better understanding is obtained why an increase in head in the northern part of the study area occurs. The increase, noticeable in sub-model three, with heads between 20 m and 25 m shows a spreading in west to east direction but a central
high head, as seen in the base model, is partially masked by the presence of the pond. Looking at the difference figure, an overall 5 m difference in head in the north is present between both models, indicating that a similar head distribution is present with only an overall increase in head due to the pond. The increase can thus be ascribed due to the upper layers becoming unsaturated and the dissipated water infiltrating into the lower lying model layers. While this increase happens over the whole study area, the water is unable to dissipate in the northern part of the study area due to more unsaturated layers present in the north-western part. This blocks the horizontal flow towards the depression cone and the water is unable to be removed vertically through the gypsiferous Rus Formation.

Figure 97 is a visualisation of the difference between the last stress period of sub-model four (3652 days) and the last stress period of the base model (80.92 years). It shows that an influence of the pond is still present, but is reduced significantly. A maximum head difference of slightly above 8 m can be depicted in a very small zone while a more moderate 6 m difference is seen where the pond was situated between the base model and sub-model four. This depicts the drop of over 18 m as visualised in Figure 40. Towards the north-western corner, a small elongated zone of head differences of more than -1 m (dark blue) can be seen. This represents the difference in area of the dry cells between the two models in model layer five.

![Figure 97: Difference figure of the groundwater head (m) through layer five of the last stress period from sub-model one minus the last stress period from the steady state base model.](image-url)
Figure 96: Difference figure of the groundwater head (m) through layer five of the last stress period from sub-model three minus the last stress period from the unsteady state base model.

Figure 97: Difference figure of the groundwater head (m) through layer five of the last stress period from sub-model four minus the last stress period from the unsteady state base model.
In Table 13, the volume difference between sub-model three and the unsteady state base model is represented together with its equivalent water column infiltrated over the area of the pond (5.1 km²). However, the volume is a representation of the difference between those two models when both are in equilibrium with its surroundings. It is not a representation of the total volume of water which has infiltrated through the pond. This is because the boundaries of the study area are constant-head cells which allow excess water to flow out of the model.

Table 13: Volume difference between sub-model three and the unsteady state base model with the corresponding infiltrated water column over the pond area.

<table>
<thead>
<tr>
<th>Volume difference (m³)</th>
<th>Water column infiltrated (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>43,042,266.70</td>
<td>8.44</td>
</tr>
</tbody>
</table>

When comparing the base model without the pond with models with the Abu Nakhla pond, it should be kept in mind that it is assumed that both models are in equilibrium. In other words, both models are in equilibrium with the used estimated hydrogeological parameters. This includes the head of the pond, which is set at 35 m amsl. However, the assumption that the groundwater reservoir is in equilibrium with these input parameters is flawed. The estimated head of the pond is based on a single measurement without taking into account the large fluctuations which occur. To know to which extent the groundwater reservoir is in equilibrium with the pond, a detailed analysis of groundwater reservoir heads is needed. A historical analysis starting at the creation of the pond until the present could help as well. However, both the measurements of the groundwater reservoir heads and the historical analysis is not yet available so in this study it is assumed that the groundwater reservoir is in equilibrium with the pond as it was on the 8th of May 2014.

The sensitivity analyses give a better understanding of how the different hydrogeological parameters influence the dissipation of the Abu Nakhla pond. A comparison of the results of each of these analyses has been made with the results of sub-model four. A graph is plotted of a cell in the centre of the pond (row 71, column 91) in layer five of sub-model four and all the sensitivity analyses to give an overview of the differences (Figure 98). In this overview, a large difference between the head evolution of the max Kₜ and the other sensitivity analyses can be immediately depicted. In following paragraphs, a detailed discussion will be given about the evolutions of the head for each sensitivity analysis compared to sub-model four.
When the horizontal conductivity is increased for the first seven model layers (upper aquifer, max $K_h$), it can be expected that water will be able to dissipate faster. The rapid decrease in head is present throughout the whole study area. The influence of the large storage factor of the pond is larger and the difference in head above and below the Midra Shale Member is also more pronounced. A big contrast exists between the upper aquifer and the gypsiferous Rus Formation. The retardation of the dissipation of the water is much larger compared to sub-model four.

When decreasing the horizontal conductivity (min $K_h$), the decrease in head slows down. Even though the rate of decrease in head is a lot different than sub-model four, it should be kept in mind that the sensitivity factor is smaller compared to the other sensitivity analyses.

When the vertical conductivity of the gypsiferous Rus Formation is increased (max $K_v$), only a relatively small change in decrease rate is obtained. The excess water is able to penetrate more easily into the gypsum, causing the head to be lowered faster. However, the change in decrease rate is rather low compared to the large sensitivity factor used. After the jump in head due to the change of the storage factor of the pond in the upper aquifer, only one stress period is needed to obtain an equilibrium between the head in the upper aquifer and the head in the gypsum. This is much faster than sub-model four where a slight increased head can still be depicted after three stress periods. Another difference is that the heads in the Umm er Radhuma Formation are larger than in sub-model four. In sub-model four it is below ten meters, while with the higher vertical conductivity it is above ten meters. This is because more water is able to flow through the gypsum leading to a higher head in the underlying UER in the steady state flow model (sub-model one). The
bottom layer of the UER is then set as constant-head cells for the unsteady state flow models (sub-model two, three and four) with these higher heads.

When decreasing the vertical conductivity of the gypsum layers (min $K_v$), the effect of the slower dissipation of the water in the gypsum is increased. Besides the larger remaining head in the gypsum layers, the head of the upper aquifer is similar and is only slightly larger than the upper aquifer heads of sub-model four. However, the pond does desiccate slower since the change in storage factor of the pond happens between stress periods seven and eight (1008 and 1558 days), while it happens between stress periods six and seven (645 and 1008 days) in sub-model four.

The storage factor near the water table (SF[1]) and the storage factor of the aquifer (SF[2]) are changed independently. This makes it possible to determine which one has the largest influence on the dissipation of the pond. When increasing the storage factor near the water table (max SF[1]), the drop in head is smaller compared to sub-model four. This is as to be expected because a larger storage factor results in more water able to be stored which is able to counteract the decrease in head more extensively. The decrease in head is indeed smaller and the difference between the head of the upper aquifer and of the gypsum is noticeably smaller than in sub-model four. It is, of course, relative as the heads in the upper aquifer are higher thus reducing the difference.

Lowering the storage factor near the water table (min SF[1]) induces a larger decrease in head compared to sub-model four. A larger drop happens when the storage factor of the pond changes and due to the smaller storage factor, only a small volume of water is able to be released from the storage to counteract this drop. A larger difference in head between the upper aquifer and the gypsum layers when the storage factor is decreased is present.

When the storage factor of the aquifer over the whole reservoir (max SF[2]) is increased, a similar trend is seen as with the increase of the storage factor near the water table. Due to the increase in storage capacity, the head decrease is lower compared with sub-model four due to the larger counteraction against the decrease in head. Looking at cells away from the centre, the decrease in head remains lower and at five kilometres of the centre of the pond, the decrease in head is minimal and stays nearly constant in the northward direction. When the heads versus the depths are compared, a noticeable difference in head distribution between the upper aquifer and the gypsiferous Rus Formation is present. In sub-model four the head difference between the gypsum and the upper aquifer is almost completely gone in the last stress period (3652 days), while it is still clearly present in the model with increased storage factors of the aquifer. This is because the larger storage factor can strongly counteract the decrease in head by releasing large volumes of water and thus a higher head can be maintained.

Lowering the storage factor of the aquifer (min SF[2]) results in a faster decrease in head compared to sub-model four. Even at two and five kilometres of the pond, the difference is quite extensive but, as in the other models, the trend is rather similar. Looking at the head versus depth, the major difference is, again, in the gypsiferous Rus Formation. Only
stress period seven (1008 days) has the characteristic bulging of the head due to the slower dissipation while the other stress periods show no large difference. This is to be expected since only a small amount of water is able to be released from the storage due to the small storage factor, leading to a faster lowering of the heads over the whole study area.

In Table 14, the differences in head (m) between sub-model four and the sensitivity analyses are given of layer five. The difference is also expressed in percentage compared to sub-model four. When comparing the values, it is immediately depicted that larger differences occur when the pond dissipates faster than when it dissipates slower. From the percentages, it is obvious that the horizontal conductivity has the largest influence on the dissipation of the pond. As mentioned before, the sensitivity factor used to calculate the minimum horizontal conductivity is much smaller compared to the sensitivity factor used for the other parameters, and yet the difference is comparable to the changes obtained by the other parameters. This is a good indication that decreasing the horizontal conductivity has the same sensitivity as when it is increased. The least sensitive parameters are the minimum vertical conductivity and the minimum storage factor near the water table. With a maximum difference of 7% they are much lower than the 14% difference seen for the maximum vertical conductivity. This shows that it is not only important to know which parameter has the smallest sensitivity, but more importantly how the sensitivity changes between an increase and decrease of that parameter. It is then possible to understand how a certain parameter will influence the results of the model.

Table 14: On the left: the head (m) of stress period (SP) five to ten of sub-model four and the sensitivity analyses of layer five; On the right: the difference in head of the sensitivity analyses compared to sub-model four expressed as a percentage (%) of stress period (SP) five to ten of layer five.

<table>
<thead>
<tr>
<th>SP</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-model four</td>
<td>32.7</td>
<td>31.54</td>
<td>26.3</td>
<td>21.4</td>
<td>18.5</td>
<td>16.0</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$K_h$ max</td>
<td>21.9</td>
<td>16.6</td>
<td>13.0</td>
<td>10.9</td>
<td>10.5</td>
<td>10.3</td>
<td>67</td>
<td>53</td>
<td>49</td>
<td>51</td>
<td>57</td>
<td>65</td>
</tr>
<tr>
<td>$K_h$ min</td>
<td>33.0</td>
<td>32.3</td>
<td>30.5</td>
<td>24.3</td>
<td>21.3</td>
<td>19.0</td>
<td>101</td>
<td>103</td>
<td>116</td>
<td>114</td>
<td>116</td>
<td>119</td>
</tr>
<tr>
<td>$K_v$ max</td>
<td>32.5</td>
<td>30.7</td>
<td>23.4</td>
<td>19.2</td>
<td>16.1</td>
<td>13.8</td>
<td>99</td>
<td>97</td>
<td>89</td>
<td>90</td>
<td>87</td>
<td>86</td>
</tr>
<tr>
<td>$K_v$ min</td>
<td>32.8</td>
<td>31.7</td>
<td>28.1</td>
<td>22.1</td>
<td>19.2</td>
<td>16.9</td>
<td>100</td>
<td>101</td>
<td>107</td>
<td>103</td>
<td>104</td>
<td>105</td>
</tr>
<tr>
<td>$S_F[1]$ max</td>
<td>32.8</td>
<td>31.9</td>
<td>29.2</td>
<td>24.0</td>
<td>21.0</td>
<td>18.4</td>
<td>100</td>
<td>101</td>
<td>111</td>
<td>112</td>
<td>114</td>
<td>115</td>
</tr>
<tr>
<td>$S_F[1]$ min</td>
<td>32.7</td>
<td>31.3</td>
<td>24.6</td>
<td>20.1</td>
<td>17.2</td>
<td>15.1</td>
<td>100</td>
<td>99</td>
<td>93</td>
<td>94</td>
<td>93</td>
<td>94</td>
</tr>
<tr>
<td>$S_F[2]$ max</td>
<td>32.9</td>
<td>32.0</td>
<td>29.7</td>
<td>24.8</td>
<td>22.1</td>
<td>19.8</td>
<td>101</td>
<td>102</td>
<td>113</td>
<td>116</td>
<td>120</td>
<td>124</td>
</tr>
<tr>
<td>$S_F[2]$ min</td>
<td>32.6</td>
<td>31.0</td>
<td>23.2</td>
<td>18.5</td>
<td>15.6</td>
<td>13.9</td>
<td>100</td>
<td>98</td>
<td>88</td>
<td>87</td>
<td>85</td>
<td>87</td>
</tr>
</tbody>
</table>
In the case of the minimum vertical conductivity of the gypsiferous Rus Formation it can be deducted that the small difference, compared to sub-model four, is because the normal vertical conductivity value is already small. Decreasing this small value results in changing from nearly no water being infiltrated in the gypsum to even less water infiltrating into the gypsum. An increase of this parameter has more influence because more water is able to infiltrate into the gypsum. The gypsum is a thick layer and a large amount of water can suddenly be stored and transported through this gypsum resulting in a much higher sensitivity.

To understand the low sensitivity when lowering the storage factor near the water table, a closer look must be taken to the total storage of the study area. A simplification is made since the concept is more important than the exact calculation. The total storage could then be written as:

\[
\text{Total storage} = S_z D + S_0
\]  

Total storage is the total storage of the reservoir

\(S_z\) (m\(^{-1}\)) is the specific elastic storage (storage coefficient of the aquifer)

\(D\) (m) is the thickness of the reservoir

\(S_0\) (\(\cdot\)) is the storage coefficient near the water table

The storage coefficient near the water table only depends on the change in head of the water table while the elastic storage coefficient is dependent on the change in head over the whole reservoir. The specific elastic storage is multiplying by the thickness of the whole reservoir resulting in the storage factor of the aquifer for the whole reservoir. When the normal values of the storage factors are used, the storage factor of the aquifer is then about two times larger than the storage factor near the water table. When the storage factor near the water table is then divided by the sensitivity factor, the sensitivity will be low because the absolute difference of the total storage is much smaller than when the storage factor near the water table is multiplied by the sensitivity factor. In other words, when the total storage is only slightly smaller, the difference in head, compared with sub-model four, will only be slightly different.
9. CONCLUSION

The influence of the Abu Nakhla pond on the phreatic aquifer was studied by use of numerical models based on the MODFLOW-code. To discuss the model construction and results more easily, the study has been subdivided into two parts: (1) the simulation of the present state and the desiccation and dissipation of the Abu Nakhla pond and (2) the sensitivity analysis to check which hydrogeological parameters have the most influence on the dissipation of the Abu Nakhla pond under the same constant climatic conditions (evaporation and recharge).

To simulate the first part, a base model was created. The horizontal and vertical discretisation comprised of 150 rows, 180 columns and 21 layers. This base model was constructed with all hydraulic parameters which are independent of the Abu Nakhla pond. These hydraulic parameters comprise of the transmissivity, storage factors and the reciprocal value of the hydraulic resistance. The hydraulic parameters, the initial heads and the initial concentrations were estimated based on values found in literature or from field measurements. This base model allowed to evaluate the base input parameters and to have a stable model where the pond can be added later on. The base model represents the head distribution of the groundwater reservoir in equilibrium with the climatic conditions when no pond is present. This equilibrium mainly depends on the estimated hydraulic parameters together with the constant head of the boundaries, estimated from the potentiometric surface map. A watershed running from the south-western corner to the north-eastern corner can be depicted. When allowing cells to become dry (a model-technical option, layer-type), a different head distribution was obtained. A large increase in head in the north-eastern quadrant can be ascribed to the top layers becoming dry and holding the water in place. The Abu Nakhla pond was then added to the stable base model, using the same horizontal and vertical discretisation and boundary conditions. To simulate the desiccation and dissipation of the Abu Nakhla pond, it was assumed that an equilibrium exists between the pond, with a head of 35 m amsl, and the groundwater reservoir. Four sub-models were introduced, each using results obtained from the previous sub-model. These sub-models were: (1) a steady state flow where the pond is introduced, (2) a model mimicking steady state flow but using an unsteady state flow model, (3) a full unsteady state flow model and (4) the simulation of the desiccation and dissipation of the Abu Nakhla pond. The pond was added with constant-head cells with a head equal to 35 m amsl, which was the level measured on the 8th of May 2015. By adding the Abu Nakhla pond into the model, the watershed was expressed more explicit. Similar to the base model, an increase in the north-eastern quadrant can be depicted when allowing cells to become dry. When plotting the head versus time and depth, as the pond was desiccating under constant climatic conditions and was dissipating into the phreatic aquifer, three major features can be depicted. The first and most important feature being the switch between the storage factor of the pond (=1) to the storage factor near the water table (=0.0104). It was associated with a sudden drop of the head because a small storage factor can only release a small volume of water compared to a large storage factor which can release a large
volume of water to counteract a drop in head. In other words, the drop in head will be lower when the volume of water able to be released by the storage factor is larger. A similar trend can be depicted at a distance of 2 km from the centre of the pond but it cannot be depicted at a distance of 5 km, where only a small drop in head is present. The second feature is the difference in head above and below the Midra Shale Member. This can be ascribed to the lower vertical conductivity of the Midra Shale Member, which acts as a flow barrier that the higher heads, due to the influence of the large storage factor of the pond, will not dissipate into the underlying layers. When the storage factor of the pond is removed, the higher heads disappears. The third feature is the slower dissipation of the water in the upper layers of the gypsiferous Rus Formation. When the constant level of the pond is removed, the water in the upper aquifer dissipates quickly, resulting in a fast decrease in head while the dissipation of water in the gypsum is much slower, resulting in a slow decrease in head. The different decrease rates result in a large difference in head between the upper aquifer and the gypsiferous Rus Formation and when the decrease in head stabilises for the upper aquifer, the difference in head will become smaller.

A calculation of the volume difference between the base model and sub-model three was made to illustrate the influence of the pond on the groundwater reservoir in the study area. A volume of 43,042,266.70 m³ was found which corresponds to an infiltrated water column of 8.44 m over the area of the Abu Nakhla pond (5.1 km²). This is, however, not the total amount of water infiltrated but reflects the difference in volume in the study area with the groundwater reservoir in equilibrium without the pond and in equilibrium with a pond with a head of 35 m amsl because excess water will be removed at the constant-head boundaries. A simulation of the historical evolution of the pond would allow to calculate the total infiltrated volume since the creation of the pond.

After the simulation of the base model and the model of the dissipation and desiccation of the pond, it was subjected to a series of sensitivity analyses. A total of four hydraulic parameters were subjected to a sensitivity analysis in which the hydraulic parameters were multiplied and divided by a sensitivity factor of $10^{0.5}$, resulting in a total of eight sensitivity analyses. The hydraulic parameters which were subjected to a sensitivity analysis are: the horizontal conductivity of the upper aquifer, the vertical conductivity of the gypsiferous Rus Formation, the storage factor near the water table and the storage factor of the aquifer (for the whole reservoir). The sensitivity analyses show the same three features as described above, when plotting the head versus the time and depth. Depending on which parameter was subjected to the sensitivity analysis and if it was increased or decreased, one or more feature(s) were more or less pronounced. Comparing the differences in head between the sensitivity analyses and sub-model four reveals which parameters were the most sensitive in terms of the dissipation of the Abu Nakhla pond. The horizontal conductivity of the upper seven layers was by far the most sensitive parameter. Both an increase and decrease of the parameter shows an equal relative increase or decrease of the head, keeping in mind that the sensitivity factor used for decreasing the horizontal conductivity is smaller (factor $10^{0.1}$). The least sensitive parameters were decreasing the vertical conductivity of the
gypsiferous Rus Formation and decreasing the storage factor near the water table. The low sensitivity of the vertical conductivity can be ascribed to the fact that the normal vertical conductivity is already so low that only a very small amount of water will penetrate into the gypsiferous Rus Formation and decreasing this low value will only have a small additional effect. For the decreased storage factor near the water table, the low sensitivity can be ascribed to the large influence of the storage factor of the aquifer. When calculating the total storage, the sum of the storage factor near the water table and the storage factor of the aquifer, the whole reservoir must be taken into account resulting in the normal value for the storage factor of the aquifer of the whole reservoir being roughly two times larger than the storage factor near the water table. When this relatively small value is then lowered, the absolute value of the total storage will only decrease slightly. When increasing the value, the absolute value of the total storage will have a much larger increase compared to the decrease. This is the cause of the non-linear behaviour of the sensitivity.

The aim of this study comprised of modelling present and future scenarios of the Abu Nakhla pond in respect to the influence on the phreatic aquifer and this aim has been achieved. The influence of the pond on the phreatic aquifer can be seen in the volume difference between the base model and sub-model three. It shows the infiltrated volume in the study area due to the presence of the pond when an equilibrium exists between the pond and the groundwater reservoir. The future scenarios comprise of a dissipation of the pond with a set of chosen base parameters and sensitivity analyses which check the influence of the estimated parameters on the dissipation.

It can be concluded that the pond does have a clear influence in the study area, but that the influence rapidly disappears when going beyond 5 km from the centre of the pond. It was also clear that quite some time will pass until the influence of the pond is completely gone and that the rate of the dissipation is mainly influenced by the horizontal conductivity of the upper aquifer.

Further research could be a simulation of the historical evolution of the pond which, on the one hand, could be used to calculate the effective volume of water which has been infiltrated and on the other hand check if the groundwater reservoir is truly in equilibrium with a pond with a head of 35 m amsl. Measurements of the effective hydraulic parameters present in the study area and adding the injection of the pond water could improve the model so that a clearer understanding of the dissipation of the pond can be made.
Het Abu Nakhla meer is gelegen in Qatar, net buiten de hoofdstad Doha. Het meer is in de jaren ’70 ontstaan uit noodzaak om het overtollige afvalwater, afkomstig van de stad, op te vangen. Het ontvangt behandelde afvalwater afkomstig uit twee afvalwaterzuiveringsinstallaties: Doha West en Doha South. Door de snelle expansie van de stad Doha is er beslist om het meer te laten droogvallen zodanig dat het gebied ook kan aangewend worden voor bouwprojecten. Deze studie heeft als doel om een numeriek grondwater stromingsmodel op te stellen die de huidige toestand (8 mei 2014) modelleert, waarbij uitgegaan wordt van de veronderstelling dat het meer in evenwicht is met het grondwaterreservoir, om daarna de uitdroging en de verspreiding van het water in het grondwaterreservoir van het meer te modelleren. Daarnaast is er ook een gevoeligheidsanalyse uitgevoerd, waarbij onderzocht werd welke hydrogeologische parameters de grootste invloed uitoefenen op deze verspreiding van het water in het grondwaterreservoir.

Het schiereiland Qatar heeft een lengte van 189 km in noord-zuid richting en een breedte die schommelt tussen de 55 km en 85 km in oost-west richting. De totale oppervlakte van het land bedraagt 11 586 km² en wordt gekenmerkt door zijn woestijn karakter. Het reliëf is relatief vlak met een maximale hoogte tot 103 m. De economie bestaat voornamelijk uit de ontginning van hun natuurlijk gas en olie en de visvangst.

Het Abu Nakhla meer is ongeveer 3,1 km in oost-west richting en ongeveer 2,5 km in noord-zuid richting en heeft een oppervlak van 5,1 km². Een volume van ongeveer 50 000 m³ tot 100 000 m³ wordt dagelijks gelooosd in het Abu Nakhla meer. Het meer kan een totaal volume van ongeveer 20 miljoen m³ aan water bevatten. De gemiddelde dagelijkse infiltratie en evaporatie bedraagt samen ongeveer 50 000 m³.

Om de numerieke modellen van het grondwaterreservoir op te stellen is een gedetailleerde studie nodig van de ondergrond. De aanwezige structurele geologie van Qatar bestaat uit een grote anticline die van noord naar zuid loopt doorheen het midden van Qatar. Deze wordt de Qatar Arch genoemd en heeft een declinatie in de noordelijke richting. Verscheidene kleinere longitudinale plooien liggen boven op deze anticline: de Simsima Dome/Arch in het noordoosten en de Dukhan anticline in het westen. Rondom deze Dukhan anticline liggen verscheidene anticlinale en synclinale structuren. Aan het oppervlak dagzoomt voornamelijk de Dammam Formatie. Deze representeert ongeveer 80% van de totale landoppervlakte. De Midden-Eocene Rus Formatie dagzoomt ongeveer op 10% van het landoppervlak en is verspreid in kleinere zones. Kijkende naar de stratigrafie, dan zijn er drie belangrijke formaties die van belang zijn voor deze studie: de Umm er Radhuma Formatie (UER), de Rus Formatie en de Dammam Formatie.

De UER is de oudste formatie van het vroeg-Eoceen. De UER heeft een dikte tussen de 270 m en 370 m en de lithologie is gedomineerd door een carbonaat facies met dolomiet.
en kalksteen. Op 20 m onder de top is een silicieuze kalksteenlaag aanwezig die de hydraulische connectiviteit tussen de bovenste UER en onderste UER beperkt.

De Rus Formatie ligt bovenop de UER en is gedateerd als Ieperiaan. De formatie is onderverdeeld in twee leden: het Traina lid en het Al-Khor lid. De totale dikte van de Rus Formatie bedraagt ongeveer 128 m en de lithologie is voornamelijk (dolomitische) kalksteen. De formatie kan onderverdeeld worden in twee provincies: de noordelijke provincie, gekenmerkt door de aanwezigheid van een depositioneel carbonaat facies en een residueel sulfaat facies, en de zuidelijke provincie, gekenmerkt door de aanwezigheid van een depositioneel sulfaat facies. Het studiegebied ligt in de zuidelijke provincie en het depositioneel sulfaat facies gedraagt zich als aquitard.

De Dammam Formatie is van midden-Eoceen ouderdom en is onderverdeeld in vier leden, van oud naar jong: het Midra Shale lid, het Dukhan lid, het Umm Bab lid en het Abaruq lid. De dikte van de formatie varieert tussen de 30 m en 52 m. De lithologie bestaat voornamelijk uit (dolomitische) kalksteen behalve voor het Midra Shale lid dat een schalie is.

Naast de geologie is ook de hydrogeologie van belang bij het opstellen van het model. Hierbij worden er twee aquifers beschouwd en één aquitard. De aquifers bestaan uit de “upper aquifer” en de “lower” aquifer. De upper aquifer is een combinatie van de Dammam Formatie het bovenste gedeelte van en Rus Formatie. De lower aquifer bestaat uit de Umm er Radhuma Formatie. Deze bovenste Rus Formatie bestaat uit een carbonaat facies. Het Midra Shale lid is ook aanwezig in deze upper aquifer en acteert als een dunne ondoorlatende laag binnenin de upper aquifer, maar zal door zijn geringe dikte eerder weinig invloed uitoefenen. De aquitard, die uit de “upper” van de “lower” aquifer scheidt, bestaat uit de onderste Rus Formatie. Deze is opgebouwd uit het depositioneel sulfaat facies en bevat verschordene dikke gipspakketten. Onder deze aquitard ligt de UER aquifer waarbij, zoals eerder vermeld, het bovenste gedeelte van de aquifer van het onderste gedeelte gescheiden wordt door de aanwezigheid van een silicieuze kalksteenlaag.

De stijghoogte distributie zoals deze teruggevonden wordt in de literatuur geeft een algemeen beeld voor zowel de UER, Rus en Dammam formaties. De stijghoogte distributie van de UER is aanwezig op regionale schaal over het Arabische schiereiland. In Qatar, een daling in de UER van 6 m boven het zeeniveau in het zuiden tot 3 m boven het zeeniveau in het noorden is aanwezig. De stijghoogte distributie van de Rus Formatie wordt aan de grenzen van Qatar door de zee beïnvloed wat leidt tot een daling tot 0 m. Een verschil tussen de noordelijke en de zuidelijke provincie is aanwezig worden waarbij in de noordelijke provincie de stijghoogtes hoger zijn dan de stijghoogtes van de onderliggende UER en dit is niet het geval in de zuidelijke provincie. Voornamelijk in het centrale noordelijk deel is er een neerwaartse grondwaterstroming aanwezig, waarbij er een heropvulling van de “lower” aquifer plaatsvindt. Langs de kustvlakte is deze relatie omgekeerd waarbij de UER stijghoogtes hoger zijn dan deze in de bovenliggende Rus
Formatie. De Dammam Formatie toont een gelijkwaardige trend als de Rus Formatie. Meer recentere metingen van het potentiometrisch oppervlak tonen een grote depressie aan de noordgrens van het modelgebied. Daar wordt vermoedelijk dicht bij grondwater opgepompt. Een hogere stijghoogte is aanwezig waar het Abu Nakhla meer is gelegen.

Gegevens over de hydrogeologische parameters van de verschillende hydrogeologische lagen is schaars in de literatuur. Dit komt door de grote variatie van de parameters, daar deze vaak door de secundaire porositeit worden bepaald. Zo zijn er waarden voor de transmissiviteit in de UER teruggevonden tussen de 6,05 m²/d en 53 568 m²/d. Dit komt omdat deze transmissiviteit bepaald wordt door de aanwezige karst en dolomitisatie, resulterend in deze grote verschillen. Voor de Rus Formatie zijn er geen metingen van de hydraulische conductiviteiten voor het depositioneel sulfaat facies beschikbaar in de literatuur. Een inschatting gebaseerd op waarden gevonden voor gelijkwaardige anhydrietlagen levert waarden op tussen de 3,456 * 10⁻⁸ m/d tot 1,728 * 10⁻³ m/d. Ook voor de Dammam Formatie bestaan er geen gemeten waarden en deze worden geschat aan de hand van gelijkwaardige waarden voor dolomitische kalksteen met karst, die tussen de 1 m/d en 8.64 m/d variëren.

Qatar wordt gekenmerkt door een woestijnklimaat. De gemiddelde jaarlijkse neerslag bedraagt 80 mm/jaar en de gemiddelde evaporatie bedraagt 2200 mm/jaar. Van deze neerslag zal maar een klein deel effectief infiltreren in de bodem en zo de aquifers heropvullen. Uit de literatuur blijkt dat ongeveer 6% van de totale jaarlijkse neerslag zal infiltreren.

De software die gebruikt wordt om het numerieke grondwatermodel te simuleren is MOCDENS3D. Deze code is gebaseerd op MODFLOW, met als additie de mogelijkheid om dichtelijksafhankelijke stroming te simuleren in 3D. De input bestaat uit tekstbestanden waarin alle hydraulische parameters verwerkt zijn, evenals de initiële stijghoogtes en concentraties. De output bestaat eveneens uit tekstbestanden die geanalyseerd kunnen worden met de postprocessor VisualMOCDENS3D, om zo de resultaten ook visueel te kunnen weergeven.

Om het eerste deel van de studie, de uitdroging en verspreiding van het water van het Abu Nakhla meer, te simuleren werd er eerst een basis model opgebouwd dat de huidige situatie van het grondwaterreservoir simuleert zonder dat het meer reeds aanwezig is. Het bevat dus alle hydraulische parameters die onafhankelijk zijn van het meer en geeft in feite de toestand van het grondwaterreservoir weer indien het meer niet aanwezig zou geweest zijn. Het modelgebied werd zo gekozen dat het een gebied van 18 km in west-oost richting en 15 km in noord-zuid richting beslaat. Het bestaat uit cellen van 100 m x 100 m en een grid van 180 x 150 cellen is verkregen. De verticale discretisatie is gebaseerd op lithologische boorbeschrijvingen die in de onmiddellijke omgeving van het meer werden opgesteld (ondiepe geologie). Voor de diepere verticale discretisatie werd gesteund op gegevens beschikbaar in de literatuur. Op basis hiervan is het model onderverdeeld in 21 lagen met een uniforme dikte van 5 m. Drie hydrogeologische parameters die

10. NEDERLANDSTALIGE SAMENVATTING
onafhankelijk zijn van het meer zijn: de transmissiviteit, het omgekeerde van de hydraulische weerstand en de bergingsfactoren (zowel de bergingsfactor nabij de watertafel en de bergingsfactor van de aquifer). Een overzicht van de waarden voor deze parameters is gegeven in Table 4. De vier randen van het studiegebied zijn gedefinieerd als constante stijghoogte cellen en de waarde voor de stijghoogte is afgeleid uit de potentiometrische oppervlaktekaart, waarbij telkens een gemiddelde waarde voor tien cellen gekozen werd. De zout-zout distributie is afgeleid uit de literatuur waarbij iedere hydrogeologische eenheid (upper aquifer, Rus aquitard, lower aquifer) verondersteld werd een unifoerme waarde te hebben over het volledige interval van de eenheid, uitgedrukt in ppm. Ook de heropvulling en evapotranspiratie is toegevoegd aan dit basis model en deze klimatologische factoren blijven constant in ieder volgend gesimuleerd model.

Nadat een stabiel basis model verkregen werd, kon het meer aan het numerieke model worden toegevoegd. Om de uitdroging en verspreiding van het water te modelleren werden vier sub-modellen opgesteld. Deze zijn: (1) een permanente grondwaterstroming met aanwezigheid van het meer, (2) het nabootsen van permanente stroming aan de hand van een niet-permanent stromingsmodel, (3) een model met volledig niet-permanente stroming en (4) de uitdroging en verspreiding van het water van het meer. Ieder model gebruikt hierbij de resultaten van het voorgaande sub-model. In sub-model 1 wordt het meer toegevoegd aan het model aan de hand van constante stijghoogte cellen met een stijghoogte van 35 m, dit is de stijghoogte zoals deze op 8 Mei 2014 werd opgemeten. Door middel van een lineaire interpolatie tussen het centrum van het pond en de randen werd een initiële inschatting de stijghoogten voor de overige cellen berekend. Omdat verschillende laag-types nodig zijn om de verspreiding van het water van het Abu Nakhla meer te simuleren, werden deze reeds geïntroduceerd in sub-model 2. Om een vlotte overgang mogelijk te maken tussen het permanente en niet-permanente stromingsmodel wordt er, door gebruik te maken van 100 keer kleinere bergingsfactoren, een permanente stroming gesimuleerd aan de hand van een niet-permanent model, waarbij voor de bovenste zes lagen een aangepast laag-type werd ingevoerd. Sub-model 3 is analoog aan sub-model 2, maar gebruikt normale bergingsfactoren. Enkel numerieke dispersies worden verwacht tussen deze twee modellen. Sub-model 4 simuleert de uitdroging en het verspreiden van het water van het meer. Hierbij worden de cellen van het meer omgezet naar variabele stijghoogte cellen. Om de volledige saturatie van de cellen (100% gevuld met water) te bekomen, werden deze ingevoerd met een bergingsfactor gelijk aan 1, zo wordt een open watervlakte gecreëerd. Eenmaal het peil van het meer onder de bodem daalt, dan valt de bergingsfactor voor deze respectievelijke cel terug naar zijn normale waarde.

Het tweede deel van het onderzoek bestaat uit een gevoeligheidsanalyse van het eerder opgestelde model. Vier hydraulische parameters werden onderworpen aan deze gevoeligheidsanalyse: (1) de horizontale conductiviteit van de upper aquifer, (2) de verticale conductiviteit van de Rus aquitard, (3) de bergingsfactor nabij de watertafel en (4) de bergingsfactor van de aquifer. Deze parameters zijn allen vermenigvuldigd en
gedeeld door een sensitiviteitsfactor van $10^{0.5}$, zo wordt een totaal van acht gevoeligheidsanalyses bekomen.

De resultaten van het basis model maken duidelijk dat het veranderen van het laag-type een verandering teweeg brengt in de distributie van de stijghoogte. Door deze te vergelijken met de resultaten van de sub-modellen kan de invloed van dit laag-type duidelijk gezien worden in beide modellen.

Wanneer het volume verschil wordt berekend tussen het model zonder meer (het basismodel) en het model met het Abu Nakhla meer erin, dan wordt een volume van ongeveer 43 miljoen m³ berekent. Omgerekend naar een hoogte van een waterkolom komt dit neer op een hoogte van 8,44 m over het oppervlakte van het meer. Dit is niet noodzakelijker wijs het totaal volume geïnfiltreerd water maar is het verschil tussen de situatie in evenwicht zonder meer en het evenwicht met het meer die een stijghoogte van 35 m heeft.

Bij het verdwijnen van het meer kunnen drie zaken opgemerkt worden. Het eerste treedt op bij de omzetting van de bergingsfactor van het meer naar de bergingsfactor nabij de watertafel als de stijghoogte van het meer onder de bodem van het meer daalt. Dit kan gezien worden door een sterke daling in stijghoogte, doordat een groot volume water plots niet meer kan geborgen worden in de kleinere bergingsfactor nabij de watertafel. Het tweede kenmerk is het verschil in stijghoogte boven en onder het Midra Shale lid. Dit komt doordat deze laag als een kleine aquitard werkt en er dus minder invloed is van de grote bergingsfactor van het meer onder deze laag. Het derde is de relatief trage verspreiding van het water in de bovenste lagen van de onderste Rus Formatie waardoor een relatief groot verschil ontstaat met de upper aquifer. Verder werd opgemerkt dat er op 2 km afstand van het midden van het meer nog een relatief grote invloed aanwezig is op de stijghoogte maar dat deze bijna volledig weg is bij 5 km van het midden van het meer.

Bij de gevoeligheidsanalyses komen deze zelfde drie kenmerken terug, maar afhankelijk van welke parameter is aangepast, zal het ene kenmerk er meer uitspringen dan de andere. Wanneer deze gevoeligheidsanalyses worden vergeleken met het model van de uitdroging en verspreiding van het water en de andere gevoeligheidsanalyses, dan vallen enkele zaken op. Zo is de horizontale conductiviteit van de bovenste zeven lagen duidelijk de meest gevoelige parameter. Indien deze wordt vergroot is er een versnelling in daling te zien en als deze wordt verkleind dan gebeurt het omgekeerde. De minst gevoelige parameters zijn de minimale waarde voor de verticale conductiviteit en de verlaging van de bergingsfactor nabij de watertafel. Voor de verticale conductiviteit komt dit doordat de normale waarde reeds zo klein is, zodat er bijna geen water meer zal infiltreren. Een verlaging van deze waarde zal dan ook weinig effect hebben. Voor de bergingsfactor nabij de watertafel kan dit toegeschreven worden aan het absoluut verschil in totale berging (berging nabij de watertafel + berging van het volledige grondwaterreservoir). De berging van het volledige grondwaterreservoir is bij de normale waarden al ongeveer 2 maal zo groot. Wanneer de relatief kleinere berging nabij de watertafel verkleind wordt, zal dit maar
een klein verschil geven in totale berging ten opzichte van een vergroting van deze waarde.

Het doel van deze studie, het modelleren van de huidige toestand en mogelijke toekomstige scenario’s, is behaald. Er kan geconcludeerd worden dat de invloed van het meer niet veel verder reikt dan 5 km ten opzichte van het midden van het meer en dat de snelheid van de verspreiding van het water voornamelijk afhangt van de horizontale conductiviteit van de upper aquifer.

Verder onderzoek zou een meer gedetailleerde berekening kunnen inhouden van het effectief geïnfiltreerd volume water, door de modellering van de volledige historiek van het meer. Ook is er nood aan meer gedetailleerde informatie omtrent de hydraulische parameters rondom het Abu Nakhla meer.
11. REFERENCES


ASHGAL, sd:sn


ESC Archives, sd *Environmental Study Centre Archives of the Qatar University.* sl:sn


### APPENDIX A: BOREHOLE LOGS

**Symbols for Soil & Rock**

<table>
<thead>
<tr>
<th>Soil</th>
<th>Sedimentary</th>
<th>Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobble &amp; Boulder</td>
<td>Chalk</td>
<td>Granite / Gabbro</td>
</tr>
<tr>
<td>Gravel</td>
<td>Limestone</td>
<td>Diorite / Andesite</td>
</tr>
<tr>
<td>Sand</td>
<td>Phosphate</td>
<td>Basalt / Rhyolite</td>
</tr>
<tr>
<td>Silt</td>
<td>Coral</td>
<td>Metamorphic (Foliated)</td>
</tr>
<tr>
<td>Clay</td>
<td>Chert</td>
<td>(C) Gneiss</td>
</tr>
<tr>
<td></td>
<td>Conglomerate</td>
<td>(M) Schist</td>
</tr>
<tr>
<td>Others</td>
<td>Breccia</td>
<td>(F) Slate</td>
</tr>
<tr>
<td>Made Ground / Fill</td>
<td>Sandstone</td>
<td>Metamorphic (Non Foliated)</td>
</tr>
<tr>
<td>Peat / Topsoil</td>
<td>Siltstone</td>
<td>(C) Metaconglomerate</td>
</tr>
<tr>
<td>Concrete</td>
<td>Mudstone / Claystone</td>
<td>(M) Marble</td>
</tr>
<tr>
<td>Asphalt</td>
<td>Shale</td>
<td>(F) Hornfels</td>
</tr>
<tr>
<td>Landslide / Debris Flow</td>
<td>Marlstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gypsum / Rocksalt</td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- Composite Soil types will be signed by combined symbols, e.g. *Sandy Silt*.

**Abbreviations:**
- (C): Coarse Grained.
- (M): Medium Grained.
- (F): Fine Grained.
Soil & Rock - Consistency, Strength and Relative Density

Coarse Soils - Relative Density & Strength

<table>
<thead>
<tr>
<th>SPT N Value</th>
<th>Relative Density</th>
<th>Density Index ( I_d ) (%)</th>
<th>Angle of Internal Friction, ( \phi' ) (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 4</td>
<td>Very Loose</td>
<td>0 to 15</td>
<td>&lt; 29</td>
</tr>
<tr>
<td>4 - 10</td>
<td>Loose</td>
<td>15 to 35</td>
<td>29 to 30</td>
</tr>
<tr>
<td>10 - 30</td>
<td>Medium Dense</td>
<td>35 to 65</td>
<td>30 to 40</td>
</tr>
<tr>
<td>30 - 50</td>
<td>Dense</td>
<td>65 to 85</td>
<td>36 to 41</td>
</tr>
<tr>
<td>&gt;50</td>
<td>Very Dense</td>
<td>85 to 100</td>
<td>&gt; 41</td>
</tr>
</tbody>
</table>


Fine Soils - Consistency

<table>
<thead>
<tr>
<th>Consistency</th>
<th>Consistency Description</th>
<th>Consistency Index ( I_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Soft</td>
<td>Finger easily pushed in up to 33mm: Inclines between fingers</td>
<td>&lt; 0.25</td>
</tr>
<tr>
<td>Soft</td>
<td>Finger pushed in up to 33mm: Made in light fling pressure</td>
<td>0.25 to 0.50</td>
</tr>
<tr>
<td>Firm</td>
<td>Thumb makes impression easily. Cannot be moulded by fingers, rolls in the hand to a semi-moist shape without breaking or crumbling</td>
<td>0.50 to 0.75</td>
</tr>
<tr>
<td>Stiff</td>
<td>Can be indented slightly by thumb. Cannot be moulded by fingers, or hardened under pressure</td>
<td>0.75 to 1.00</td>
</tr>
<tr>
<td>Very Stiff</td>
<td>Can be indented slightly by thumb. Cannot be moulded by fingers, or hardened under pressure</td>
<td>&gt; 1.00</td>
</tr>
<tr>
<td>Hard</td>
<td>Can be scratched by thumb.</td>
<td></td>
</tr>
</tbody>
</table>

Fine Soils - Undrained Shear Strength

<table>
<thead>
<tr>
<th>Undrained Shear Strength of Clays</th>
<th>Undrained Shear Strength ( C_u ) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely Low</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Very Low</td>
<td>10 to 20</td>
</tr>
<tr>
<td>Low</td>
<td>20 to 40</td>
</tr>
<tr>
<td>Medium</td>
<td>40 to 75</td>
</tr>
<tr>
<td>High</td>
<td>75 to 150</td>
</tr>
<tr>
<td>Very High</td>
<td>150 to 200</td>
</tr>
<tr>
<td>Extremely High</td>
<td>&gt; 300</td>
</tr>
</tbody>
</table>

Rock Strength

<table>
<thead>
<tr>
<th>Description</th>
<th>Field Definition</th>
<th>Unconfined Compressive Strength, UOS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely Weak</td>
<td>Can be indented by thumb. Gravel sized lump. Crush between fingers and thumb.</td>
<td>0.5 - 1.5</td>
</tr>
<tr>
<td>Very Weak</td>
<td>Gravel sized lump. Can be peeled with pocket knife.</td>
<td>1.0 - 5.0</td>
</tr>
<tr>
<td>Weak</td>
<td>Can be peeled with a pocket knife.</td>
<td>5.0 - 25.0</td>
</tr>
<tr>
<td>Medium Strong</td>
<td>Can be scraped with pocket knife.</td>
<td>25.0 - 50.0</td>
</tr>
<tr>
<td>Strong</td>
<td>Requires more than one blow of geological hammer to fracture.</td>
<td>50.0 - 100.0</td>
</tr>
<tr>
<td>Very Strong</td>
<td>Requires many blows of geological hammer to fracture.</td>
<td>100.0 - 250.0</td>
</tr>
<tr>
<td>Extremely Strong</td>
<td>Can only be stripped with geological hammer.</td>
<td>&gt; 250.0</td>
</tr>
</tbody>
</table>

Definitions

- SPT - Standard Penetration Test (N): Number of blows to drive the sampler to final 300mm of the total 450mm driving distance.
- TCR - Total Core Recovery (%): Ratio of length of core recovered to length drilled.
- SCR - Solid Core Recovery (%): Ratio of length of core recovered as solid core pieces to length drilled.
- RQD - Rock Quality Designation (%): Ratio of length of core recovered in lengths greater than 100mm to length drilled.
- FI - Fracture Index: Number of fractures to length of core run per linear meter.
- \( I_d \) - Density Index: Ratio of difference between maximum void ratio and natural void ratio to difference between maximum and minimum void ratios.
- \( I_c \) - Consistency Index: Ratio of difference between liquid limit and natural water content to plasticity index.
### APPENDIX A: BOREHOLE LOGS

**Borehole No. L1-BH-1**

**Sheet 1 of 3**

- **Total Depth (m):** 23
- **Ground Level (m):** 35.24
- **Boring Started:** 04-Jan-15
- **Boring Completed:** 08-Jan-15
- **Rig:** TOHO III
- **Driller:** A. Abd Alhamid
- **Drilling Method:** ROTARY CORE
- **Drilling Medium:** Boring Dia. (mm): 125
- **Core Dia. (mm):** 84
- **Casing Dia. (mm):** 150
- **Casing Depth (m):** 0.6
- **Water Depth (m):** 4.48

<table>
<thead>
<tr>
<th>Scale (m)</th>
<th>Samples Type and Number</th>
<th>Field Records</th>
<th>Core Recovery</th>
<th>Description of Strata</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1.5</td>
<td>B</td>
<td>60</td>
<td>0</td>
<td>Fill Materials Light brown to brown, fine to coarse grained, silty SAND mixed with sub-rounded gravels and cobbles of limestone with pieces of asphalt.</td>
</tr>
<tr>
<td>1.5 - 3</td>
<td>B</td>
<td>90</td>
<td>10</td>
<td>Simaiza Limestone Member weak to strong, off-white to light gray, micritic limestone with occasional light green to reddish pink, atollitic clay with crystalline quartz and calcaceous silty limestone. Partially to distinctly weathered (P-D). Fractures are very closely spaced.</td>
</tr>
<tr>
<td>3 - 3.5</td>
<td>B</td>
<td>50</td>
<td>50</td>
<td><strong>Legend</strong></td>
</tr>
<tr>
<td>3.5 - 4</td>
<td>CS</td>
<td>100</td>
<td>85</td>
<td>Ni</td>
</tr>
<tr>
<td>4 - 5.5</td>
<td>CS</td>
<td>100</td>
<td>65</td>
<td>Ni</td>
</tr>
<tr>
<td>5.5 - 7</td>
<td>CS</td>
<td>100</td>
<td>85</td>
<td>Ni</td>
</tr>
<tr>
<td>7 - 8.5</td>
<td>CS</td>
<td>100</td>
<td>95</td>
<td>Ni</td>
</tr>
<tr>
<td>8.5 - 10</td>
<td>CS</td>
<td>100</td>
<td>95</td>
<td>Ni</td>
</tr>
</tbody>
</table>

#### Undisturbed Sample Key
- CS: Core Sample
- DB: Drive Barrel
- SH: Shelby Tube

#### Disturbed Sample Key
- P: Percussion
- SPT: Standard Penetration Test
- B: Bulk Sample

#### Abbreviations
- Ground Water Table
- TCR: Total Core Recovery
- SCR: Solid Core Recovery
- ROD: Rock Quality Designation
- Fl: Fracture Index
- Ni: Non-Intact
- RX: Refusal

#### Remarks
- * The samples were described in accordance with appropriate standards (BS 5930, ASTM D2487).
### Borehole No. L1-BH-1

**Drilling Method:** ROTARY CORE  
**Drilling Medium:** Core Dia. (mm): 125  
**Boring Started:** 04-Jan-15  
**Boring Completed:** 08-Jan-15  
**Rig:** TOHO III  
**Driller:** Alaa Abd Alhamid  
**Water Depth (m):** 4.48  
**Casing Dia. (mm):** 150  
**Casing Depth (m):** 0.8

<table>
<thead>
<tr>
<th>Samples</th>
<th>Depth (m)</th>
<th>Field Records</th>
<th>SPT Records</th>
<th>Core Recovery</th>
<th>Description of Strata</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>G′</td>
<td>N Stns (m)</td>
<td>SCR (%)</td>
<td>ROD (%)</td>
</tr>
<tr>
<td>CS</td>
<td>10 - 11.5</td>
<td>95</td>
<td>85</td>
<td>75</td>
<td>5</td>
</tr>
<tr>
<td>CS</td>
<td>11.5 - 12</td>
<td>95</td>
<td>85</td>
<td>85</td>
<td>3</td>
</tr>
<tr>
<td>CS</td>
<td>13 - 14.5</td>
<td>100</td>
<td>90</td>
<td>90</td>
<td>3</td>
</tr>
<tr>
<td>CS</td>
<td>14.5 - 15</td>
<td>95</td>
<td>85</td>
<td>85</td>
<td>5</td>
</tr>
<tr>
<td>CS</td>
<td>16 - 17.5</td>
<td>95</td>
<td>70</td>
<td>65</td>
<td>5</td>
</tr>
<tr>
<td>CS</td>
<td>17.5 - 19</td>
<td>90</td>
<td>70</td>
<td>65</td>
<td>5</td>
</tr>
<tr>
<td>CS</td>
<td>19 - 20.5</td>
<td>100</td>
<td>95</td>
<td>90</td>
<td>5</td>
</tr>
</tbody>
</table>

**Undisturbed Sample Key:** CS: Core Sample  
**Disturbed Sample Key:** DB: Drive Barrel  
**SH:** Shelby Tube  
**P:** Percussion  
**B:** Bulk Sample

**Abbreviations:**  
- G′: Ground Water Table  
- TCR: Total Core Recovery  
- SCR: Solid Core Recovery  
- ROD: Rock Quality Designation  
- FI: Fracture Index  
- N: Non Intact  
- RX: Refusal

**Remarks:** The samples were described in accordance with appropriate standards (BS 5130, ASTM D2968).

Logged By: Emmanuel  
Checked By: A.O.
## APPENDIX A: BOREHOLE LOGS

### Borehole No. L1-BH-1

**Drilling Method:** ROTARY CORE  
**Drilling Medium:**  
- Core Dia. (mm): 125  
- Casing Dia. (mm): 150  
- Casing Depth (m): 0.6  
- Water Depth (m): 4.48

**Coordinates:**  
- N: 379,003.01  
- E: 215,551.72

**Drilling Dates:**  
- Boring Started: 04-Jan-16  
- Boring Completed: 08-Jan-16

**Rig:** TOHO III  
**Driller:** Ali Al Ali Al Hamid

### Logs

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Description of Strata</th>
</tr>
</thead>
</table>
| 20.6 - 22 | Simulated Limestone Member  
Medium strong to strong, off-white to light gray, doleritic and micaceous LIMESTONE, occasionally varied (10-30mm) infilled with clayey sandy materials with inclinations of some light green to reddish brown, alternating clay and calcareous clay materials. Partially weathered (B). Fractures are closely to widely spaced. |
| 22 - 23  | Middle Shale Member  
Very weak to weak, yellowish brown to greenish gray SHALE with a finely bedded, medium strong, effusive to light brown limestone and carbonates silt materials. Partially to distinctly weathered (B-C). Fractures are very closely to matrix spaced. |

### SPT Records

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Field Records</th>
<th>Core Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.6 - 22</td>
<td>65 90 75 4</td>
<td></td>
</tr>
<tr>
<td>22 - 23</td>
<td>85 75 65 4</td>
<td></td>
</tr>
</tbody>
</table>

### Undisturbed Sample Key

- **CS**: Core Sample  
- **DB**: Drive Barrel  
- **SH**: Shelby Tube  
- **PB**: Percussion  
- **SPT**: Standard Penetration Test  
- **B**: Bulk Sample

### Disturbed Sample Key

- **P**: Percussion  
- **W**: Water Table  
- **SC**: Solid Core Recovery  
- **RC**: Rock Quality Designation  
- **F**: Fracture Index  
- **NL**: Non Intact  
- **RX**: Refusal

### Abbreviations

- **GW**: Ground Water Table  
- **TCR**: Total Core Recovery  
- **SC**: Solid Core Recovery  
- **RQD**: Rock Quality Designation  
- **FI**: Fracture Index  
- **NI**: Non Intact  
- **RX**: Refusal

### Remarks

* The samples were described in accordance with appropriate standards (IS 6933, ASTM D2488).
## Appendix A: Borehole Logs

**Borehole No. L2-BH-1**

- **Project**: Drilling of Wells Around
- **Project Ref. No.**: S140000266
- **Location**: Abu Nakhla, Qatar
- **Client**: Qatar University
- **Contractor**: 
- **Consultant**: 

### General Information
- **Total Depth (m)**: 24.5
- **Ground Level (m)**: 33.601
- **Coordinates**: N = 377,788.96, E = 219,418.91
- **Boring Started**: 17-Dec-14
- **Boring Completed**: 23-Dec-14
- **Rig**: TOHO III
- **Driller**: Ali Abd Alhamid
- **Drilling Method**: ROTARY CORE
- **Drilling Medium**: 
  - **Boring Dia. (mm)**: 125
  - **Core Dia. (mm)**: 84
  - **Casing Dia. (mm)**: 150
  - **Casing Depth (m)**: 0.8
  - **Water Depth (m)**: 4.42

### Description of Strata

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type and Number</th>
<th>Depth (%)</th>
<th>Field Records</th>
<th>Core Recovery</th>
<th>Description of Strata</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0 - 1</td>
<td>70</td>
<td>35</td>
<td>28 Ni</td>
<td>Simaena Limestone Member</td>
</tr>
<tr>
<td>CS</td>
<td>1 - 1.5</td>
<td>90</td>
<td>20</td>
<td>0 Ni</td>
<td>Medium strong to strong, off-white to light grey, clastic dolomite and micro-crystalline LIMESTONE, voided (5-35%v/v) with occasional light green, fibrous calcite, and carbonate clasts. Distinctly weathered (C). Fractures are very closely to medium spaced.</td>
</tr>
<tr>
<td>CS</td>
<td>1.5 - 2</td>
<td>100</td>
<td>90</td>
<td>30 Ni</td>
<td>Medium strong to strong, off-white to light grey, clastic dolomite and micro-crystalline LIMESTONE, voided (5-35%v/v) with occasional light green, fibrous calcite, and carbonate clasts. Distinctly weathered (C). Fractures are very closely to medium spaced.</td>
</tr>
<tr>
<td>CS</td>
<td>2 - 3</td>
<td>95</td>
<td>80</td>
<td>25 Ni</td>
<td>Medium strong to strong, off-white to light grey, clastic dolomite and micro-crystalline LIMESTONE, voided (5-35%v/v) with occasional light green, fibrous calcite, and carbonate clasts. Distinctly weathered (C). Fractures are very closely to medium spaced.</td>
</tr>
<tr>
<td>CS</td>
<td>3 - 4</td>
<td>95</td>
<td>65</td>
<td>35 Ni</td>
<td>Medium strong to strong, off-white to light grey, clastic dolomite and micro-crystalline LIMESTONE, voided (5-35%v/v) with occasional light green, fibrous calcite, and carbonate clasts. Distinctly weathered (C). Fractures are very closely to medium spaced.</td>
</tr>
<tr>
<td>CS</td>
<td>4 - 5.5</td>
<td>95</td>
<td>70</td>
<td>50 Ni</td>
<td>Medium strong to strong, off-white to light grey, clastic dolomite and micro-crystalline LIMESTONE, voided (5-35%v/v) with occasional light green, fibrous calcite, and carbonate clasts. Distinctly weathered (C). Fractures are very closely to medium spaced.</td>
</tr>
<tr>
<td>CS</td>
<td>5.5 - 7</td>
<td>100</td>
<td>75</td>
<td>75 Ni</td>
<td>Medium strong to strong, off-white to light grey, clastic dolomite and micro-crystalline LIMESTONE, voided (5-35%v/v) with occasional light green, fibrous calcite, and carbonate clasts. Distinctly weathered (C). Fractures are very closely to medium spaced.</td>
</tr>
<tr>
<td>CS</td>
<td>7 - 8.5</td>
<td>100</td>
<td>90</td>
<td>90 Ni</td>
<td>Medium strong to strong, off-white to light grey, clastic dolomite and micro-crystalline LIMESTONE, voided (5-35%v/v) with occasional light green, fibrous calcite, and carbonate clasts. Distinctly weathered (C). Fractures are very closely to medium spaced.</td>
</tr>
<tr>
<td>CS</td>
<td>8.5 - 10</td>
<td>95</td>
<td>85</td>
<td>83 Ni</td>
<td>Medium strong to strong, off-white to light grey, clastic dolomite and micro-crystalline LIMESTONE, voided (5-35%v/v) with occasional light green, fibrous calcite, and carbonate clasts. Distinctly weathered (C). Fractures are very closely to medium spaced.</td>
</tr>
</tbody>
</table>

### Undisturbed Sample Key
- CS: Core Sample
- DB: Drive Barrel
- SH: Shelby Tube

### Disturbed Sample Key
- P: Percussion
- SPT: Standard Penetration Test
- B: Bulk Sample

### Abbreviations:
- GWT: Ground Water Table
- TCR: Total Core Recovery
- SCR: Solid Core Recovery
- RQD: Rock Quality Designation
- FI: Fracture Index
- NI: Non-Intact

### Remarks:
- * The samples were described in accordance with appropriate standards (IS 5600; ASTM D4969).
### Borehole No. L2-BH-1

**Total Depth (m):** 24.5  
**Ground Level (m):** 33.501  
**Coordinates:** N = 377,788.98  
**E = 216,418.91**  
**Rig:** TOHO III  
**Driller:** Alan A. Al Madi

**Drilling Method:** ROTARY CORE  
**Boring Started:** 17-Dec-14  
**Boring Completed:** 23-Dec-14  
**Drilling Medium:**  
- Core Dia. (mm): 125  
- Casing Dia. (mm): 150  
- Casing Depth (m): 0.8  
- Water Depth (m): 4.42

### Samples and SPT Records

<table>
<thead>
<tr>
<th>Samples</th>
<th>Type and Number</th>
<th>Depth (m)</th>
<th>Field Records</th>
<th>N Blows</th>
<th>Core Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>10.0 - 11.5</td>
<td>95</td>
<td>95</td>
<td>90</td>
<td>4</td>
</tr>
<tr>
<td>CS</td>
<td>11.5 - 13</td>
<td>95</td>
<td>70</td>
<td>70</td>
<td>Ni</td>
</tr>
<tr>
<td>CS</td>
<td>12.0 - 14.5</td>
<td>95</td>
<td>80</td>
<td>75</td>
<td>5</td>
</tr>
<tr>
<td>CS</td>
<td>14.5 - 16</td>
<td>100</td>
<td>75</td>
<td>75</td>
<td>5</td>
</tr>
<tr>
<td>CS</td>
<td>16.0 - 17.5</td>
<td>100</td>
<td>85</td>
<td>75</td>
<td>3</td>
</tr>
<tr>
<td>CS</td>
<td>17.5 - 19</td>
<td>95</td>
<td>85</td>
<td>85</td>
<td>2</td>
</tr>
<tr>
<td>CS</td>
<td>19.0 - 20.5</td>
<td>95</td>
<td>85</td>
<td>85</td>
<td>3</td>
</tr>
</tbody>
</table>

**Description of Strata**

- **Salmama Limestone Member:**  
  - Medium to strong, off-white to light grey, cherty, dolomitic and more crystalline LIMESTONE with abundant inclusions of some light green in red-brown clasts. Limestones are close to medium spaced.  
  - Fractures and clay are likely sheared and somewhat cut-off.  
  - *15.56-15.62 and 17.55-17.61: Littoral fractures*

**Undisturbed Sample Key**  
- CS: Core Sample
- DB: Drive Barrel
- SH: Shelby Tube
- B: Bulk Sample

**Disturbed Sample Key**
- P: Percussion
- SPT: Standard Penetration Test

**Abbreviations:**
- TCR: Total Core Recovery
- SCR: Solid Core Recovery
- RQD: Rock Quality Designation
- FI: Fracture Index
- NI: Non-Intact
- RX: Refusal

**Remarks:**  
*The samples were described in accordance with appropriate standards (BS 5930, ASTM D4268).*

**Logged By:** Emmanuel  
**Checked By:** A.O
**APPENDIX A: BOREHOLE LOGS**

**Borehole No. L2-BH-1**

<table>
<thead>
<tr>
<th>Scale (m)</th>
<th>Type and Number</th>
<th>Depth (m)</th>
<th>Field Records</th>
<th>SPT Records</th>
<th>Core Recovery</th>
<th>Description of Strata</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>N Blows</td>
<td>TCR (%)</td>
<td>SCR (%)</td>
<td>ROP (%)</td>
</tr>
<tr>
<td>21</td>
<td>CS</td>
<td>20.5 - 22</td>
<td>100</td>
<td>95</td>
<td>95</td>
<td>2</td>
</tr>
<tr>
<td>22</td>
<td>CS</td>
<td>22 - 23.5</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>4</td>
</tr>
<tr>
<td>23</td>
<td>CS</td>
<td>23.5 - 24.5</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>95</td>
<td>95</td>
<td>2</td>
</tr>
</tbody>
</table>

**Undamaged Sample Key:**
- CS: Core Sample
- PB: Percussion
- DB: Drive Barrel
- SH: Shelby Tube

**Disturbed Sample Key:**
- SPT: Standard Penetration Test

**Abbreviations:**
- TCR: Total Core Recovery
- SCR: Solid Core Recovery
- RQD: Rock Quality Designation
- FI: Fracture Index
- NLI: Non Intact
- RFI: Refusal

**Remarks:**
- The samples were described in accordance with appropriate standards (BS 5930, ASTM D2488).

Logged By: Emmanuel

Checked By: A.Q.
**APPENDIX A: BOREHOLE LOGS**

---

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type and Number</th>
<th>Depth (m)</th>
<th>Field Records</th>
<th>Core Recovery</th>
<th>Description of Strata</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0 - 1</td>
<td></td>
<td>80</td>
<td>15</td>
<td>0 N</td>
</tr>
<tr>
<td>CS</td>
<td>1 - 1.6</td>
<td></td>
<td>90</td>
<td>60</td>
<td>20 8</td>
</tr>
<tr>
<td>CS</td>
<td>1.5 - 2</td>
<td></td>
<td>100</td>
<td>80</td>
<td>60 8</td>
</tr>
<tr>
<td>CS</td>
<td>2 - 3</td>
<td></td>
<td>100</td>
<td>80</td>
<td>60 8</td>
</tr>
<tr>
<td>CS</td>
<td>3 - 4</td>
<td></td>
<td>100</td>
<td>75</td>
<td>65 9</td>
</tr>
<tr>
<td>CS</td>
<td>4 - 5.6</td>
<td></td>
<td>100</td>
<td>95</td>
<td>65 3</td>
</tr>
<tr>
<td>CS</td>
<td>5.5 - 7</td>
<td></td>
<td>95</td>
<td>75</td>
<td>75 N</td>
</tr>
<tr>
<td>CS</td>
<td>7 - 8.5</td>
<td></td>
<td>100</td>
<td>75</td>
<td>75 5</td>
</tr>
<tr>
<td>CS</td>
<td>8.5 - 10</td>
<td></td>
<td>100</td>
<td>85</td>
<td>85 3</td>
</tr>
</tbody>
</table>

**Undisturbed Sample Key:**
- CS: Core Sample
- DB: Drive Barrel
- SH: Shelby Tube

**Disturbed Sample Key:**
- P: Percussion
- SPT: Standard Penetration Test
- B: Bulk Sample

**Abbreviations:**
- N: Non-Intact
- RI: Rock Index
- GWT: Ground Water Table
- TCR: Total Core Recovery
- SCR: Solid Core Recovery
- ROD: Rock Quality Designation
- F: Fracture Index

**Remarks:**
- The samples were described in accordance with appropriate standards (BS 5900; ASTM D2488).

---

**Checked By:** A.Q
# APPENDIX A: BOREHOLE LOGS

**Borehole No. L3-BH-1**

**Drilling Method:** ROTARY CORE

**Drilling Medium:**
- Boring Dia. (mm): 125
- Core Dia. (mm): 84
- Casing Dia. (mm): 150
- Casing Depth (m): 0.66
- Water Depth (m): 10.1

**Total Depth (m):** 31
**Ground Level (m):** 32.928
**Coordinates:** N= 377,035.26, E= 215,270.42

## Samples

<table>
<thead>
<tr>
<th>Scale (m)</th>
<th>Type and Number</th>
<th>Description of Strata</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0 - 10.5</td>
<td>CS</td>
<td>Ditto as from (0.0m=10.0m).</td>
</tr>
<tr>
<td>11.5 - 12</td>
<td>CS</td>
<td>Ditto as from (0.0m=10.0m).</td>
</tr>
<tr>
<td>13 - 14.5</td>
<td>CS</td>
<td>Ditto as from (0.0m=10.0m).</td>
</tr>
<tr>
<td>14.5 - 16</td>
<td>CS</td>
<td>Ditto as from (0.0m=10.0m).</td>
</tr>
<tr>
<td>16 - 17.5</td>
<td>CS</td>
<td>Ditto as from (0.0m=10.0m).</td>
</tr>
<tr>
<td>17.5 - 19</td>
<td>CS</td>
<td>Ditto as from (0.0m=10.0m).</td>
</tr>
</tbody>
</table>

## SPT Records

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Field Records</th>
<th>Core Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 1.5</td>
<td>100</td>
<td>65</td>
</tr>
<tr>
<td>0.0 - 2.0</td>
<td>95</td>
<td>70</td>
</tr>
<tr>
<td>0.0 - 3.0</td>
<td>95</td>
<td>70</td>
</tr>
<tr>
<td>0.0 - 4.0</td>
<td>95</td>
<td>65</td>
</tr>
<tr>
<td>0.0 - 5.0</td>
<td>95</td>
<td>50</td>
</tr>
</tbody>
</table>

## Undisturbed Sample Key

- **CS:** Core Sample
- **DB:** Drive Barrel
- **P:** Percussion
- **SPT:** Standard Penetration Test
- **ST:** Shelby Tube
- **F:** Fracture Index
- **N:** Non-Intact
- **RX:** Refusal

## Disturbed Sample Key

- **P:** Percussion

## Abbreviations:
- **GWT:** Ground Water Table
- **TCC:** Total Core Recovery
- **SCC:** Solid Core Recovery
- **RQD:** Rock Quality Designation
- **FI:** Fracture Index
- **NI:** Non-Intact
- **RX:** Refusal

## Remarks:
- The samples were described in accordance with appropriate standards (BS 5930; ASTM D2488).

Logged By: Emmanuel
Checked By: A.O.
## Appendix A: Borehole Logs

**Borehole No. L3-BH-1**

### Drilling Method: ROTARY CORE
- **Drilling Medium:** Boring Dia. (mm): 125, Core Dia. (mm): 84
- **Core Recovery:** Casing Dia. (mm): 150, Casing Depth (m): 0.56
- **Water Depth (m):** 10.1

### Logs Details

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type and Number</th>
<th>Depth (m)</th>
<th>Field Records</th>
<th>Core Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>N Stones</td>
<td>TCR (%)</td>
</tr>
<tr>
<td>CS</td>
<td>26.5 - 22</td>
<td>95</td>
<td>75 65 7</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>22 - 23.5</td>
<td>100</td>
<td>95 75 7</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>23.5 - 25</td>
<td>95</td>
<td>85 88 Ni</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>25 - 26.5</td>
<td>100</td>
<td>75 75 7</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>26.6 - 28</td>
<td>100</td>
<td>15 95 75 Ni</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>28 - 29.5</td>
<td>95</td>
<td>30 25 Ni</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>29.6 - 30</td>
<td>70</td>
<td>10 9 Ni</td>
<td></td>
</tr>
</tbody>
</table>

### Undisturbed Sample Key
- CS: Core Sample
- DB: Drive Barrel
- SH: Shelby Tube

### Disturbed Sample Key
- P: Percussion
- SPT: Standard Penetration Test

### Abbreviations:
- GWT: Ground Water Table
- TCR: Total Core Recovery
- SCR: Solid Core Recovery
- RQD: Rock Quality Designation
- FI: Fracture Index
- NI: Non Intact
- RX: Refusal

### Remarks
- The samples were described in accordance with appropriate standards (GSI 69/30: ASTM D4584).

Logged By: Emmanuel
Checked By: A.O.
<table>
<thead>
<tr>
<th>Samples</th>
<th>SPT Records</th>
<th>Core Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Field Records</td>
<td></td>
</tr>
<tr>
<td>GS</td>
<td>30 - 31</td>
<td>85 45 35 N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Description of Strata:**

**End of Boring (21.03m)**

**Remarks:**

*The samples were described in accordance with appropriate standards (35 5930, ASTM D2487).*

**Abbreviations:**

- G: Ground Water Table
- TCR: Total Core Recovery
- SCR: Solid Core Recovery
- RQD: Rock Quality Designation
- F: Fracture Index
- NI: Non Intact
- RX: Refusal

**Logged By:** Emmanuel

**Checked By:** A.G
## Borehole Log

**Borehole No. L4-BH-1**

**Total Depth (m):** 22  
**Ground Level (m):** 34.913  
**Coordinates:** N 378,017.97, E 214,904.11

**Drilling Method:** ROTARY CORE  
**Drilling Medium:** Core Dia. (mm): 125  
**Boring Dia. (mm):** 125  
**Boring Completed:** 01-Jan-15  
**Casing Dia. (mm):** 150  
**Rig:** TOHO III  
**Casing Depth (m):** 0.63  
**Driller:** Alaa Abd Alhamid  
**Water Depth (m):** 4.29

### Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type and Number</th>
<th>Depth (m)</th>
<th>Field Records</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td></td>
<td>0 - 0.5</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td></td>
<td>0.5 - 1</td>
<td>70 0 0 NI</td>
</tr>
<tr>
<td>CS</td>
<td></td>
<td>1 - 2</td>
<td>100 55 46 NI</td>
</tr>
<tr>
<td>CS</td>
<td></td>
<td>2 - 3</td>
<td>95 35 30 NI</td>
</tr>
<tr>
<td>CE</td>
<td></td>
<td>3 - 4</td>
<td>100 95 60 NI</td>
</tr>
<tr>
<td>CS</td>
<td></td>
<td>4 - 5.5</td>
<td>100 75 70 7</td>
</tr>
<tr>
<td>CS</td>
<td></td>
<td>5.5 - 7</td>
<td>100 75 70 8</td>
</tr>
<tr>
<td>CS</td>
<td></td>
<td>7 - 8.5</td>
<td>95 75 85 7</td>
</tr>
<tr>
<td>CS</td>
<td></td>
<td>8.5 - 10</td>
<td>95 60 45 NI</td>
</tr>
</tbody>
</table>

### SPT Records

<table>
<thead>
<tr>
<th>N Blows</th>
<th>TCR (%</th>
<th>SCR (%)</th>
<th>ROC (%)</th>
<th>FI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Core Recovery

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Reduced Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Description of Strata

- **Residual Soil**
  - Brown, fine to coarse grained, silty SAND
  - Medium strength, undisturbed and well rounded grains of limestone

- **Sedimentary Limestone Member**
  - Medium strong to strong, off-white to light grey and reddish powdery and micro-crystalline LIMESTONE with infusions of occasionally light grey, attapulgite clay and carbonaceous silty materials. Patches to distinctly weathered (S-6). Fractures are very close to medium spaced.

**Undisturbed Sample Key**

- CS: Core Sample
- DB: Drive Barrel
- SH: Shelby Tube

**Disturbed Sample Key**

- P: Percussion
- SPT: Standard Penetration Test
- B: Bulk Sample

**Abbreviations:**

- G: Ground Water Table
- TCR: Total Core Recovery
- SCR: Solid Core Recovery
- ROC: Rock Quality Designation
- FI: Fracture Index
- NI: Non-Intact
- RX: Refusal

**Checked By:** A.O

*These samples were described in accordance with appropriate standards (IS 59330, ASTM D2483).*
## APPENDIX A: BOREHOLE LOGS

### Borehole No. L4-BH-1

<table>
<thead>
<tr>
<th>Samples</th>
<th>SPT Records</th>
<th>Core Recovery</th>
<th>Description of Strata</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>Type and Member</td>
<td>Depth (m)</td>
<td>Field Records</td>
</tr>
<tr>
<td>------</td>
<td>----------------</td>
<td>----------</td>
<td>---------------</td>
</tr>
<tr>
<td>11</td>
<td>CS 10 - 11.5</td>
<td>95</td>
<td>35</td>
</tr>
<tr>
<td>12</td>
<td>CS 11.5 - 12</td>
<td>95</td>
<td>35</td>
</tr>
<tr>
<td>13</td>
<td>CS 13 - 14.5</td>
<td>95</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>CS 14.5 - 15</td>
<td>95</td>
<td>55</td>
</tr>
<tr>
<td>15</td>
<td>CS 15 - 17.5</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>16</td>
<td>CS 17.5 - 19</td>
<td>95</td>
<td>70</td>
</tr>
<tr>
<td>19</td>
<td>CS 19 - 20.5</td>
<td>100</td>
<td>95</td>
</tr>
</tbody>
</table>

**Undisturbed Sample Key:**
- CS: Core Sample
- DB: Drive Barrel
- SH: Shelby Tube

**Disturbed Sample Key:**
- P: Percussion
- SPT: Standard Penetration Test
- B: Bulk Sample

**Abbreviations:**
- TCR: Total Core Recovery
- SCR: Solid Core Recovery
- RQD: Rock Quality Designation
- FI: Fracture Index
- NI: Non Intact
- RX: Refusal

**Remarks:**
- The samples were described in accordance with appropriate standards (BS 5930; ASTM D2488).

Logged By: Emmanuel

Checked By: A.Q.
**Borehole No. L4-BH-1**

**Project:** Drilling of Wells Around Location: Abu Nakhla, Qatar

**Client:** Qatar University

**Contractor:** -

**Consultant:** -

**Total Depth (m):** 22

**Ground Level (m):** 34.913

**Coordinates:** N = 378,017.97

**E = 214,004.11**

**Drilling Method:** ROTARY CORE

**Drilling Medium:** Boring Dia. (mm): 125

**Core Dia. (mm):** 84

**Casing Dia. (mm):** 150

**Casing Depth (m):** 0.63

**Water Depth (m):** 4.20

**Rig:** TOTO III

**Driller:** Ala Ab Alhamid

### SPT Records

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Type of Sample</th>
<th>Depth (m)</th>
<th>Field Records</th>
<th>Core Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>CS</td>
<td>20.5 - 22</td>
<td>100 85 75 7</td>
<td></td>
</tr>
</tbody>
</table>

**Description of Strata**

- **Mid Shale Member:**
  - Very weak to weak, yellowish brown to greenish grey SHALE with medium to very fine, medium to very coarse grained sandstone, calcareous and carbonaceous clays. Partially weathered (P). Fractures are closed to medium sized.

**End of Boring (22.00m)**

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Reduced Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>12.91</td>
</tr>
</tbody>
</table>

### Remarks

- The samples were described in accordance with appropriate standards (BS 6993: ASTM D2488).

**Abbreviations:**

- CS: Core Sample
- DB: Drive Barrel
- SH: Shelby Tube
- P: Percussion
- SPT: Standard Penetration Test
- B: Bulk Sample

**Checked By:** A.O

**Logged By:** Emmanuel
### APPENDIX A: BOREHOLE LOGS

**Borehole No. L5-BH-1**

<table>
<thead>
<tr>
<th>Samples</th>
<th>Type and Number</th>
<th>Depth (m)</th>
<th>Field Records</th>
<th>N Blows</th>
<th>TCR (%)</th>
<th>SCR (%)</th>
<th>RQD (%)</th>
<th>FI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0 - 1</td>
<td></td>
<td></td>
<td>100</td>
<td>75</td>
<td>35</td>
<td>Ni</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>1 - 2</td>
<td></td>
<td></td>
<td>100</td>
<td>85</td>
<td>65</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>2 - 3</td>
<td></td>
<td></td>
<td>85</td>
<td>60</td>
<td>40</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>3 - 4</td>
<td></td>
<td></td>
<td>100</td>
<td>90</td>
<td>65</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>4 - 5</td>
<td></td>
<td></td>
<td>90</td>
<td>80</td>
<td>40</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>5 - 6</td>
<td></td>
<td></td>
<td>100</td>
<td>65</td>
<td>40</td>
<td>Ni</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>6 - 7</td>
<td></td>
<td></td>
<td>100</td>
<td>60</td>
<td>40</td>
<td>Ni</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>7 - 8</td>
<td></td>
<td></td>
<td>95</td>
<td>60</td>
<td>50</td>
<td>Ni</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>8 - 9</td>
<td></td>
<td></td>
<td>100</td>
<td>60</td>
<td>60</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>9 - 10</td>
<td></td>
<td></td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

**Description of Strata**

**Silesian Limestone Member**

Medium strong to strong, off-white to light grey dolomitic and micro-crystalline LIMESTONE, veined (10-30mm) with inclusions of some light green to reddish pink, arkosic clay with crystalline gypsum and dolomitic clay materials. Partly to distinctly weathered (B-Q). Fractures are very closely to medium spaced.

* 2.17-3.34, 3.0-3.17, 5.60-5.75, 6.0-4.20 and 7.5-7.16m: Non-Intact.

**Undisturbed Sample Key**

| CS: Core Sample | P: Percussion | DB: Drive Barrel | SH: Shelby Tube | SPT: Standard Penetration Test |

**Disturbed Sample Key**

- Ground Water Table
- TGR: Total Core Recovery
- SCR: Solid Core Recovery
- RQD: Rock Quality Designation
- FI: Fracture Index
- NI: Non-Intact
- RX: Refusal

**Remarks**

* The samples were described in accordance with appropriate standards (BS 5930, ASTM D3085).
APPENDIX A: BOREHOLE LOGS

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>CS</th>
<th>Depth (m)</th>
<th>CS</th>
<th>Depth (m)</th>
<th>CS</th>
<th>Depth (m)</th>
<th>CS</th>
<th>Depth (m)</th>
<th>CS</th>
<th>Depth (m)</th>
<th>CS</th>
<th>Depth (m)</th>
<th>CS</th>
<th>Depth (m)</th>
<th>CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 - 11</td>
<td>CS</td>
<td>10 - 11</td>
<td>CS</td>
<td>11 - 12</td>
<td>CS</td>
<td>12 - 13</td>
<td>CS</td>
<td>13 - 14</td>
<td>CS</td>
<td>14 - 15</td>
<td>CS</td>
<td>15 - 16</td>
<td>CS</td>
<td>16 - 17</td>
<td>CS</td>
</tr>
<tr>
<td>11 - 12</td>
<td>CS</td>
<td>11 - 12</td>
<td>CS</td>
<td>11 - 12</td>
<td>CS</td>
<td>12 - 13</td>
<td>CS</td>
<td>13 - 14</td>
<td>CS</td>
<td>14 - 15</td>
<td>CS</td>
<td>15 - 16</td>
<td>CS</td>
<td>16 - 17</td>
<td>CS</td>
</tr>
<tr>
<td>12 - 13</td>
<td>CS</td>
<td>12 - 13</td>
<td>CS</td>
<td>12 - 13</td>
<td>CS</td>
<td>12 - 13</td>
<td>CS</td>
<td>13 - 14</td>
<td>CS</td>
<td>14 - 15</td>
<td>CS</td>
<td>15 - 16</td>
<td>CS</td>
<td>16 - 17</td>
<td>CS</td>
</tr>
<tr>
<td>13 - 14</td>
<td>CS</td>
<td>13 - 14</td>
<td>CS</td>
<td>13 - 14</td>
<td>CS</td>
<td>13 - 14</td>
<td>CS</td>
<td>13 - 14</td>
<td>CS</td>
<td>14 - 15</td>
<td>CS</td>
<td>15 - 16</td>
<td>CS</td>
<td>16 - 17</td>
<td>CS</td>
</tr>
<tr>
<td>16 - 17</td>
<td>CS</td>
<td>16 - 17</td>
<td>CS</td>
<td>16 - 17</td>
<td>CS</td>
<td>16 - 17</td>
<td>CS</td>
<td>16 - 17</td>
<td>CS</td>
<td>17 - 18</td>
<td>CS</td>
<td>18 - 19</td>
<td>CS</td>
<td>19 - 20</td>
<td>CS</td>
</tr>
<tr>
<td>17 - 18</td>
<td>CS</td>
<td>17 - 18</td>
<td>CS</td>
<td>17 - 18</td>
<td>CS</td>
<td>17 - 18</td>
<td>CS</td>
<td>17 - 18</td>
<td>CS</td>
<td>18 - 19</td>
<td>CS</td>
<td>19 - 20</td>
<td>CS</td>
<td>20 - 21</td>
<td>CS</td>
</tr>
<tr>
<td>18 - 19</td>
<td>CS</td>
<td>18 - 19</td>
<td>CS</td>
<td>18 - 19</td>
<td>CS</td>
<td>18 - 19</td>
<td>CS</td>
<td>18 - 19</td>
<td>CS</td>
<td>19 - 20</td>
<td>CS</td>
<td>20 - 21</td>
<td>CS</td>
<td>21 - 22</td>
<td>CS</td>
</tr>
<tr>
<td>19 - 20</td>
<td>CS</td>
<td>19 - 20</td>
<td>CS</td>
<td>19 - 20</td>
<td>CS</td>
<td>19 - 20</td>
<td>CS</td>
<td>19 - 20</td>
<td>CS</td>
<td>20 - 21</td>
<td>CS</td>
<td>21 - 22</td>
<td>CS</td>
<td>22 - 23</td>
<td>CS</td>
</tr>
</tbody>
</table>

**Description of Strata**

**Sinmites Limestone Member**
- Medium to strong, off-white to light grey, compact and massive dolomite and marly-dolomite LIMESTONE, weathered (10-60mm) with inclusions of occasional light grey to reddish-brown, tight, truebreast and calcareous silt.<br>- Partially weathered (II). Fractures are close to medium spaced.
- 15.20-15.28m: Lateral fracture.<br>- 15.45-15.55 and 12.6-12.08m: Non-Intact

**Sinmites Limestone Member**
- Medium strong to strong, off-white to light grey, compact and massive dolomite LIMESTONE, weathered (10-60mm) with inclusions of occasional light grey to reddish-brown, tight, truebreast and calcareous silt.<br>- Partially weathered (II). Fractures are close to medium spaced.
APPENDIX B: TIME DISCRETISATION

Table 15: The duration of each of the fifteen stress periods in days with their cumulative duration expressed in days and years.

<table>
<thead>
<tr>
<th>Stress period</th>
<th>Duration (d)</th>
<th>Cumulative (d)</th>
<th>Cumulative (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>30</td>
<td>0.08</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>75</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>69</td>
<td>144</td>
<td>0.40</td>
</tr>
<tr>
<td>4</td>
<td>104</td>
<td>248</td>
<td>0.68</td>
</tr>
<tr>
<td>5</td>
<td>158</td>
<td>406</td>
<td>1.11</td>
</tr>
<tr>
<td>6</td>
<td>239</td>
<td>645</td>
<td>1.77</td>
</tr>
<tr>
<td>7</td>
<td>363</td>
<td>1008</td>
<td>2.76</td>
</tr>
<tr>
<td>8</td>
<td>550</td>
<td>1558</td>
<td>4.27</td>
</tr>
<tr>
<td>9</td>
<td>833</td>
<td>2391</td>
<td>6.55</td>
</tr>
<tr>
<td>10</td>
<td>1261</td>
<td>3652</td>
<td>10.00</td>
</tr>
<tr>
<td>11</td>
<td>1911</td>
<td>5563</td>
<td>15.23</td>
</tr>
<tr>
<td>12</td>
<td>2895</td>
<td>8458</td>
<td>23.16</td>
</tr>
<tr>
<td>13</td>
<td>4386</td>
<td>12844</td>
<td>35.17</td>
</tr>
<tr>
<td>14</td>
<td>6645</td>
<td>19489</td>
<td>53.36</td>
</tr>
<tr>
<td>15</td>
<td>10067</td>
<td>29556</td>
<td>80.92</td>
</tr>
</tbody>
</table>
Table 16: The incrementally increasing time steps (d) of the fifteen stress periods used in sub-model two and three. Sub-model four only uses ten of the fifteen stress periods while sub-model two uses the same values but 100 times smaller.

<table>
<thead>
<tr>
<th>Stress period</th>
<th>t1</th>
<th>t2</th>
<th>t3</th>
<th>t4</th>
<th>t5</th>
<th>t6</th>
<th>t7</th>
<th>t8</th>
<th>t9</th>
<th>t10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t11</td>
<td>t12</td>
<td>t13</td>
<td>t14</td>
<td>t15</td>
<td>t16</td>
<td>t17</td>
<td>t18</td>
<td>t19</td>
<td>t20</td>
</tr>
<tr>
<td>1</td>
<td>1.22</td>
<td>1.25</td>
<td>1.27</td>
<td>1.30</td>
<td>1.33</td>
<td>1.36</td>
<td>1.38</td>
<td>1.41</td>
<td>1.44</td>
<td>1.47</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>1.54</td>
<td>1.57</td>
<td>1.60</td>
<td>1.64</td>
<td>1.67</td>
<td>1.70</td>
<td>1.74</td>
<td>1.78</td>
<td>1.81</td>
</tr>
<tr>
<td>2</td>
<td>1.85</td>
<td>1.89</td>
<td>1.93</td>
<td>1.97</td>
<td>2.01</td>
<td>2.05</td>
<td>2.10</td>
<td>2.14</td>
<td>2.19</td>
<td>2.23</td>
</tr>
<tr>
<td></td>
<td>2.28</td>
<td>2.33</td>
<td>2.38</td>
<td>2.43</td>
<td>2.48</td>
<td>2.53</td>
<td>2.58</td>
<td>2.64</td>
<td>2.69</td>
<td>2.75</td>
</tr>
<tr>
<td>3</td>
<td>2.81</td>
<td>2.87</td>
<td>2.93</td>
<td>2.99</td>
<td>3.05</td>
<td>3.11</td>
<td>3.18</td>
<td>3.25</td>
<td>3.31</td>
<td>3.38</td>
</tr>
<tr>
<td></td>
<td>3.45</td>
<td>3.53</td>
<td>3.60</td>
<td>3.68</td>
<td>3.75</td>
<td>3.83</td>
<td>3.91</td>
<td>3.99</td>
<td>4.08</td>
<td>4.16</td>
</tr>
<tr>
<td>4</td>
<td>4.25</td>
<td>4.34</td>
<td>4.43</td>
<td>4.52</td>
<td>4.62</td>
<td>4.72</td>
<td>4.82</td>
<td>4.92</td>
<td>5.02</td>
<td>5.13</td>
</tr>
<tr>
<td></td>
<td>5.23</td>
<td>5.34</td>
<td>5.45</td>
<td>5.57</td>
<td>5.69</td>
<td>5.81</td>
<td>5.93</td>
<td>6.05</td>
<td>6.18</td>
<td>6.31</td>
</tr>
<tr>
<td>5</td>
<td>6.44</td>
<td>6.58</td>
<td>6.71</td>
<td>6.85</td>
<td>7.00</td>
<td>7.15</td>
<td>7.30</td>
<td>7.45</td>
<td>7.61</td>
<td>7.76</td>
</tr>
<tr>
<td>6</td>
<td>9.76</td>
<td>9.96</td>
<td>10.17</td>
<td>10.39</td>
<td>10.60</td>
<td>10.83</td>
<td>11.05</td>
<td>11.28</td>
<td>11.52</td>
<td>11.76</td>
</tr>
<tr>
<td></td>
<td>10.01</td>
<td>12.26</td>
<td>12.52</td>
<td>12.78</td>
<td>13.05</td>
<td>13.32</td>
<td>13.60</td>
<td>13.89</td>
<td>14.18</td>
<td>14.48</td>
</tr>
<tr>
<td>7</td>
<td>14.78</td>
<td>15.09</td>
<td>15.41</td>
<td>15.73</td>
<td>16.06</td>
<td>16.40</td>
<td>16.74</td>
<td>17.10</td>
<td>17.46</td>
<td>17.82</td>
</tr>
<tr>
<td>8</td>
<td>22.40</td>
<td>22.87</td>
<td>23.35</td>
<td>23.84</td>
<td>24.34</td>
<td>24.85</td>
<td>25.37</td>
<td>25.90</td>
<td>26.44</td>
<td>27.00</td>
</tr>
<tr>
<td></td>
<td>27.57</td>
<td>28.14</td>
<td>28.74</td>
<td>29.34</td>
<td>29.95</td>
<td>30.58</td>
<td>31.23</td>
<td>31.88</td>
<td>32.55</td>
<td>33.23</td>
</tr>
<tr>
<td>9</td>
<td>33.93</td>
<td>34.64</td>
<td>35.37</td>
<td>36.11</td>
<td>36.87</td>
<td>37.64</td>
<td>38.43</td>
<td>39.24</td>
<td>40.06</td>
<td>40.90</td>
</tr>
<tr>
<td></td>
<td>41.76</td>
<td>42.64</td>
<td>43.53</td>
<td>44.45</td>
<td>45.38</td>
<td>46.33</td>
<td>47.31</td>
<td>48.30</td>
<td>49.31</td>
<td>50.35</td>
</tr>
<tr>
<td>10</td>
<td>51.40</td>
<td>52.48</td>
<td>53.58</td>
<td>54.71</td>
<td>55.84</td>
<td>57.03</td>
<td>58.23</td>
<td>59.45</td>
<td>60.70</td>
<td>61.97</td>
</tr>
<tr>
<td></td>
<td>63.27</td>
<td>64.60</td>
<td>65.95</td>
<td>67.34</td>
<td>68.75</td>
<td>70.20</td>
<td>71.67</td>
<td>73.17</td>
<td>74.71</td>
<td>76.28</td>
</tr>
<tr>
<td>11</td>
<td>77.88</td>
<td>79.51</td>
<td>81.18</td>
<td>82.88</td>
<td>84.62</td>
<td>86.40</td>
<td>88.21</td>
<td>90.06</td>
<td>91.96</td>
<td>93.89</td>
</tr>
<tr>
<td></td>
<td>95.86</td>
<td>97.87</td>
<td>99.92</td>
<td>102.02</td>
<td>104.16</td>
<td>106.35</td>
<td>108.58</td>
<td>110.86</td>
<td>113.18</td>
<td>115.56</td>
</tr>
<tr>
<td>12</td>
<td>117.98</td>
<td>120.46</td>
<td>122.99</td>
<td>125.57</td>
<td>128.21</td>
<td>130.90</td>
<td>133.64</td>
<td>136.45</td>
<td>139.31</td>
<td>142.24</td>
</tr>
<tr>
<td></td>
<td>145.22</td>
<td>148.27</td>
<td>151.38</td>
<td>154.56</td>
<td>157.80</td>
<td>161.11</td>
<td>164.50</td>
<td>167.95</td>
<td>171.47</td>
<td>175.07</td>
</tr>
<tr>
<td>13</td>
<td>178.75</td>
<td>182.50</td>
<td>186.33</td>
<td>190.24</td>
<td>194.23</td>
<td>198.31</td>
<td>202.47</td>
<td>206.72</td>
<td>211.06</td>
<td>215.49</td>
</tr>
<tr>
<td></td>
<td>220.01</td>
<td>224.63</td>
<td>229.34</td>
<td>234.16</td>
<td>239.07</td>
<td>244.09</td>
<td>249.21</td>
<td>254.44</td>
<td>259.78</td>
<td>265.23</td>
</tr>
<tr>
<td>14</td>
<td>270.80</td>
<td>276.48</td>
<td>282.29</td>
<td>288.21</td>
<td>294.26</td>
<td>300.44</td>
<td>306.74</td>
<td>313.18</td>
<td>319.75</td>
<td>326.46</td>
</tr>
<tr>
<td></td>
<td>333.32</td>
<td>340.31</td>
<td>347.45</td>
<td>354.75</td>
<td>362.79</td>
<td>369.79</td>
<td>377.55</td>
<td>385.48</td>
<td>393.57</td>
<td>401.83</td>
</tr>
<tr>
<td>15</td>
<td>410.26</td>
<td>418.87</td>
<td>427.66</td>
<td>436.64</td>
<td>445.80</td>
<td>455.16</td>
<td>464.71</td>
<td>474.47</td>
<td>484.43</td>
<td>494.59</td>
</tr>
<tr>
<td></td>
<td>504.97</td>
<td>515.57</td>
<td>526.39</td>
<td>537.44</td>
<td>548.72</td>
<td>560.24</td>
<td>571.99</td>
<td>584.00</td>
<td>596.26</td>
<td>608.77</td>
</tr>
</tbody>
</table>

APPENDIX B: TIME DISCRETISATION 155