

**DEVELOPMENT OF GROUNDWATER QUALITY  
MANAGEMENT MODELS USING ARTIFICIAL  
INTELLIGENCE (AI) AND STATISTICAL APPROACHES –  
CASE STUDY – KHANYOUNIS GOVERNORATE – GAZA  
STRIP – PALESTINE**

**JAWAD S. I. ALAGHA**

**UNIVERSITI SAINS MALAYSIA**

**2013**

**DEVELOPMENT OF GROUNDWATER QUALITY  
MANAGEMENT MODELS USING ARTIFICIAL  
INTELLIGENCE (AI) AND STATISTICAL APPROACHES –  
CASE STUDY – KHANYOUNIS GOVERNORATE – GAZA  
STRIP - PALESTINE**

**By**

**JAWAD S. I. ALAGHA**

**Thesis submitted in fulfillment of the requirements for the degree of  
Doctor of Philosophy**

**December 2013**

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

﴿ قُلْ إِنَّ صَلَاتِي وَنُسُكِي وَمَحْيَايَ وَمَمَاتِي لِلَّهِ رَبِّ الْعَالَمِينَ، لَا شَرِيكَ لَهُ وَبِذَلِكَ أُمِرْتُ

﴿ وَأَنَا أَوَّلُ الْمُسْلِمِينَ ﴾

سورة الأنعام (162-163)

In the Name of Allah, the Most Beneficent, the Most Merciful

﴿ Say (O Muhammad): "Verily, my prayer, my sacrifice, my living, and my dying are for Allah,

the Lord of the mankind, He has no partner. And of this I have been commanded, and I am the

first of the Muslims ﴾

( Surah Al-An'am (The Cattle), 162-163)

## **DEDICATION**

*To the soul of my father who had dreamt to witness these moments .....*

*To my kind-hearted mother for her unlimited love, tears, sacrifices and prayers .....*

*Jawad*

## ACKNOWLEDGEMENTS

Firstly, all Praises are due to Allah the Almighty, who gave me the ability to accomplish this research and made me overcome all circumstances, Alhamdulillah...

Secondly, the Peace and Blessings of Allah be upon our Prophet Muhammad, and upon His family and companions.

Many great people have contributed towards the successful completion of this work in one way or another. I wish to extend my appreciation, gratitude and sincere thanks to all of them especially:

- **Prof. Dr. Md Azlin Md Said**, the main supervisor of this study, for his guidance, helpful suggestions and continuous support during the period of my study. Thanks are also extended to **Associate Prof. Dr. Yunes Moghier**, my field supervisor in Gaza Strip for his remarkable and basic contribution on this research.
- My beloved wife **Bessan** for her priceless support and patience, and my sons **Saleem** and **Abd Al-Rahman** who inspired me a lot to accomplish my study.
- My dear brothers (**Sameer, Moneer, Bayan, Marwan, and Amad**), my beloved sisters (**Marwa and Maha**) and their families for their unlimited love, prayer, support and encouragement.
- My father, mother, brothers, and sisters in-law, whom I cannot forget their moral support and encouragement.
- People who have given me all kinds of support notably **Dr. Khairy Alagha**, and **Haj Mohamed Kamel Alagha**; may the Almighty Allah grant them health and happiness.

- All my friends for their help, support, encouragement and prayers, especially **Eng. Mohammed Seyam** and **Eng. Ahmed Nassar** for the fruitful discussions we held together.
- The technical staff of water sector related institutions in Gaza, particularly in Khanyounis Municipality, Coastal Municipalities Water Utility, and Ministry of Agriculture for their cordial support.
- All my colleagues in the Ministry of Public Works Housing, and all my Arab brothers and friends at USM.
- Last, but not least, I cannot forget my school PPKA, beloved university USM, and Malaysia, the pearl of Asia.

## TABLE OF CONTENTS

|   |             |
|---|-------------|
| <b>TABLE OF CONTENTS</b> .....                                    | <b>vii</b>  |
| <b>LIST OF FIGURES</b> .....                                      | <b>xii</b>  |
| <b>LIST OF TABLES</b> .....                                       | <b>xvii</b> |
| <b>LIST OF ABBREVIATIONS</b> .....                                | <b>xx</b>   |
| <b>ABSTRAK</b> .....  | <b>xxii</b> |
| <b>ABSTRACT</b> .....   | <b>xxiv</b> |
| <b>CHAPTER 1- INTRODUCTION</b> .....                              | <b>1</b>    |
| 1.1 Preface .....   | 1           |
| 1.2 Problem statement .....                                       | 4           |
| 1.3 Research Objectives .....                                     | 9           |
| 1.4 Scope of the study .....                                      | 9           |
| 1.5 Thesis Organization .....                                     | 10          |
| <b>CHAPTER 2 - LITERATURE REVIEW</b> .....                        | <b>11</b>   |
| 2.1 Introduction .....  | 11          |
| 2.2 Groundwater Quality .....                                     | 11          |
| 2.2.1 Contamination of Groundwater .....                          | 12          |
| 2.2.2 Mechanisms of Groundwater Contamination .....               | 13          |
| 2.2.3 Water Quality in Gaza Coastal Aquifer .....                 | 15          |
| 2.2.3.1 Preface about Gaza Coastal Aquifer .....                  | 15          |
| 2.2.3.2 Gaza Coastal Aquifer Problems .....                       | 18          |
| a. Groundwater Shortage Problem in Gaza Strip .....               | 19          |
| b. Groundwater Quality Problem in Gaza Strip .....                | 19          |
| 2.2.4 Nitrate Contamination of Groundwater .....                  | 22          |
| 2.2.4.1 Introduction .....  | 22          |
| 2.2.4.2 Mechanism of Groundwater Contamination with Nitrate ..... | 24          |
| 2.2.4.3 Nitrate Levels in Gaza Coastal Aquifer .....              | 26          |
| 2.2.5 Chloride Contamination of Groundwater .....                 | 29          |

|  |   |           |
|--|---|-----------|
| 2.2.5.1  | Introduction .....  | 29        |
| 2.2.5.2  | Chloride Levels in Gaza Coastal Aquifer.....                                      | 30        |
| 2.2.6  | The Common Characteristics of Groundwater Quality Problems .                      | 33        |
| 2.3  | Modelling Approaches of Groundwater Quality.....                                  | 34        |
| 2.3.1  | Process Based Approach.....   | 35        |
| 2.3.2  | Statistical Approach.....   | 36        |
| 2.3.3  | Artificial Intelligence (AI) Approach .....                                       | 38        |
| 2.3.3.1  | Artificial Neural Networks (ANNs) .....   | 40        |
| 2.3.3.2  | Support Vector Machine (SVM) .....  | 52        |
| 2.3.3.3  | Comparison between ANNs and SVM.....  | 57        |
| 2.3.3.4  | Limitations of Artificial Intelligence Techniques .....                           | 58        |
| 2.3.4  | Selection of the Suitable Groundwater Modelling Approach.....                     | 59        |
| 2.4  | Groundwater Quality Management .....  | 60        |
| 2.4.1  | Strategies of Groundwater Quality Management .....                                | 60        |
| 2.4.2  | Groundwater Quality Management in Gaza Strip .....                                | 64        |
| 2.5  | Summary of the Previous Groundwater Quality Studies for Gaza Coastal Aquifer..... | 67        |
| 2.6  | Concluding Remarks .....  | 71        |
| <br><b>CHAPTER 3 METHODOLOGY &amp; MODELS DEVELOPMENT.....</b> |   | <b>75</b> |
| 3.1  | Preface about the Study Area .....  | 75        |
| 3.1.1  | Geography and Climate of Gaza Strip.....  | 75        |
| 3.1.2  | Geology and Topography of Gaza Strip .....  | 77        |
| 3.1.3  | Land Use in Gaza Strip.....   | 77        |
| 3.1.4  | Socio-economical Indicators in Gaza Strip .....                                   | 77        |
| 3.2  | Overview about Research Methodology .....   | 78        |
| 3.3  | Data collection and pre-processing .....  | 80        |
| 3.3.1  | Case Study Wells.....   | 82        |
| 3.3.1.1  | Basic Wells Data .....  | 82        |
| 3.3.1.2  | Wells Abstraction Data.....   | 84        |
| 3.3.1.3  | Water Quality Data .....  | 85        |
| 3.3.2  | Land use land cover (LULC) in Khanyounis Governorate .....                        | 86        |
| 3.3.2.1  | LULC Classification of the aerial photos .....                                    | 88        |



|   |  |            |
|---|--|------------|
| 3.3.2.2   | Analysis and Statistics of the Classified Maps .....                                       | 89         |
| 3.3.3   | Data Collection & Calculations of Nitrate Model Input Variables                            | 91         |
| 3.3.3.1   | Groundwater Recharge .....   | 91         |
| 3.3.3.2   | On-ground N-load.....  | 98         |
| 3.3.3.3   | Other Influential Variables Affecting NO <sub>3</sub> <sup>-</sup> in<br>Groundwater ..... | 105        |
| 3.3.4   | Data Collection and Calculations of Cl <sup>-</sup> Model Input Variables .                | 106        |
| 3.3.4.1   | Variables related to well's physical settings .....  | 107        |
| 3.3.4.2   | Variables related to the groundwater recharge .....  | 108        |
| 3.3.4.3   | On-ground Cl-load.....   | 108        |
| 3.4   | Models Development.....  | 111        |
| 3.4.1   | Statistical Analysis.....  | 112        |
| 3.4.2   | Construction Data Matrix for the AI Models .....   | 114        |
| 3.4.2.1   | Selection of the input variables .....   | 114        |
| 3.4.2.2   | Time Distribution Phases of AI Model Data.....   | 115        |
| 3.4.2.3   | Development of Response Matrix of AI Models.....   | 116        |
| 3.4.3   | Developing AI models .....   | 119        |
| <b>CHAPTER 4 - RESULTS AND DISCUSSION .....</b> |  | <b>126</b> |
| 4.1   | Introduction .....   | 126        |
| 4.2   | Result of the Classification of KG Aerial Photos.....                                      | 126        |
| 4.3   | Statistical Analysis of Groundwater Monitoring Data .....                                  | 128        |
| 4.3.1   | Descriptive Statistical Analysis .....   | 128        |
| 4.3.2   | Multivariate Statistical Techniques .....  | 130        |
| 4.3.2.1   | Multivariate Statistical Techniques for Chemical<br>Parameters.....                        | 130        |
| 4.3.2.2   | Multivariate Statistical Techniques for the Case Study<br>Wells                            | 134        |
| 4.3.3   | Trends of Nitrate and Chloride .....   | 138        |
| 4.3.3.4   | Trends of Nitrate.....   | 139        |
| 4.3.3.4   | Trend of Chloride .....  | 143        |
| 4.3.4   | Concluding Remarks Regarding the Statistical Analysis .....                                | 147        |

|  |   |            |
|--|---|------------|
| 4.4  | Application of AI Techniques for Modelling Nitrate and Chloride in GCA.....   | 148        |
| 4.4.1  | Application of AI Techniques for Modelling Nitrate concentration in GCA.....  | 148        |
| 4.4.1.1  | ANNs for Modelling Nitrate Concentration in GCA ....  | 149        |
| 4.4.1.2  | Support Vector Machine for Modelling NO <sub>3</sub> <sup>-</sup> Concentration in GCA .....                            | 153        |
| 4.4.1.3  | Analysis of AI Modelling Results for Nitrate .....  | 161        |
| 4.4.2  | Application of AI Techniques for Modelling Chloride .....   | 164        |
| 4.4.2.1  | ANNs for Modelling Chloride Concentration in GCA .  | 165        |
| 4.4.2.2  | SVM for Modelling Chloride Concentration in GCA...  | 169        |
| 4.4.2.3  | Analysis of AI Modelling Results for Chloride <sup>-</sup> .....  | 175        |
| 4.4.3  | Concluding Remarks Regarding Application of AI Techniques for Modelling Nitrate and Chloride Concentrations in GCA..... | 178        |
| 4.5  | Application of the Developed Models for GW Management .....   | 179        |
| 4.5.1  | Application of the Developed Models for Nitrate Management .  | 181        |
| 4.5.2  | Application of the Developed Models for GW Chloride Management .....  | 192        |
| 4.5.3  | Management of both Chloride and Nitrate in GCA.....   | 201        |
| 4.6  | Summary.....  | 208        |
| <b>CHAPTER 5- CONCLUSIONS AND RECOMMENDATIONS.....</b> |   | <b>210</b> |
| 5.1  | Introduction .....  | 210        |
| 5.2  | Conclusions .....   | 210        |
| 5.2.1  | Understanding of GCA Quality Problems Using Statistical Approach .....  | 210        |
| 5.2.2  | Modelling Nitrate and Chloride Concentration in GW Using ANNs and SVM Techniques .....                                  | 211        |
| 5.2.2.1  | Modelling Nitrate Concentration in GW Using ANNs and SVM Techniques .....   | 211        |
| 5.2.2.2  | Modelling Chloride Concentration in GW Using ANNs and SVM Techniques .....  | 212        |
| 5.2.3  | The Effects of Data Clustering on the Models Performance.....   | 213        |

|                         |   |            |
|-------------------------|---|------------|
| 5.2.4                   | Utilization of the Developed Models for GW Management ..... | 213        |
| 5.2.5                   | The Importance of the Research for the Study Area .....     | 214        |
| 5.2.6                   | Constraints of the Current Research Work .....              | 216        |
| 5.3                     | Recommendations .....                                       | 216        |
| 5.3.1                   | Recommendations Related to GW Management in GCA .....       | 217        |
| 5.3.2                   | GW Modelling and Modelling Requirements for GCA .....       | 218        |
| 5.3.3                   | Future Research Activities .....                            | 219        |
| <b>REFERENCES.....</b>  |   | <b>222</b> |
| <b>APPENDICES .....</b> |   |            |

## LIST OF FIGURES

|   |     |
|---|-----|
| Figure 1.1: Research problem tree   | 8   |
| Figure 2.1: Potential sources of GW contamination   | 13  |
| Figure 2.2 : Layout of Gaza Coastal Aquifer (GCA)   | 16  |
| Figure 2.3: GCA basin and lithology   | 17  |
| Figure 2.4: Typical cross section of GCA at Khanyounis governorate area   | 18  |
| Figure 2.5: Nitrogen cycle and its effect on water resources  | 23  |
| Figure 2.6: Nitrate concentration map in Gaza Strip in 2008.  | 26  |
| Figure 2.7: Chloride concentration maps in GS in (a) 2002; and (b) 2007   | 31  |
| Figure 2.8: ANNs structure with one hidden layer  | 41  |
| Figure 2.9: Basic components of a node  | 42  |
| Figure 2.10: The concept of actual space and feature space in SVM   | 53  |
| Figure 2.11: Suitability of modelling approaches in relation to data and theory richness  | 59  |
| Figure 2.12: Schematic diagram of GW quality management process.  | 64  |
| Figure 3.1: Geographical location of (a): The Palestinian occupied territories; (b): Gaza Strip; (c): Khanyounis Governorate            | 76  |
| Figure 3.2: Flowchart of the research methodology   | 79  |
| Figure 3.3: Location of case study wells  | 82  |
| Figure 3.4: Delineation of Khanyounis governorate wells using Thiessen polygons.  | 87  |
| Figure 3.5: The process of aerial photos classification into LULC categories  | 88  |
| Figure 3.6: Intersection of TP shape file belonging to well # L/43 in 2003 with (a) the raw aerial photo; and (b) the produced LULC map | 89  |
| Figure 3.7: Schematic flowchart of the potential variables affecting $\text{NO}_3^-$ concentration in a well                            | 91  |
| Figure 3.8: The soil recharge coefficients for GS   | 94  |
| Figure 3.9: Schematic flowchart of the potential variables affecting $\text{NO}_3^-$ concentration in a well                            | 99  |
| Figure 3.10: Schematic flowchart of the potential variables affecting Cl- concentration in a well                                       | 106 |
| Figure 3.11: Wells' location with respect to KYC  | 107 |

|  |     |
|--|-----|
| Figure 3.12: Methodology for development of AI models  | 112 |
| Figure 3.13: Schematic example of time intervals used for input variables calculations for Cl- model   | 115 |
| Figure 3.14: Summary of the research methodology and models development  | 125 |
| Figure 4.1: (a) Aerial photo of Khanyounis governorate in 2003; (b) LULC classification map produced by ERDAS IMAGINE 11 for Khanyounis governorate in 2003.       | 127 |
| Figure 4.2: Box & Whisker plot for the selected water quality parameters   | 129 |
| Figure 4.3: Graphical representation of the two PCs.   | 133 |
| Figure 4.4: Clustering dendrogram of water quality parameters  | 134 |
| Figure 4.5: Spatial location of the wells clusters on land use map   | 136 |
| Figure 4.6: The concentrations of both Cl- and NO <sub>3</sub> - in case study wells in 2007 for each well's clusters  | 138 |
| Figure 4.7: The mean concentrations of both Cl- and NO <sub>3</sub> - in case study wells in 2007 compared with WHO standards                                      | 139 |
| Figure 4.8: NO <sub>3</sub> - concentration in case study wells in 2007 compared with WHO standards  | 139 |
| Figure 4.9: Time series of NO <sub>3</sub> - concentrations of selected Wells between 2007 to 2010   | 140 |
| Figure 4.10: Spatial distribution of NO <sub>3</sub> - concentration in GW and built up areas in Khanyounis governorate in the year 2008                           | 142 |
| Figure 4.11: Cl- concentration in the case study wells in 2007 compared with WHO standards   | 143 |
| Figure 4.12: Spatial distribution of Cl- concentration in GW in Khanyounis governorate in the year 2008  | 144 |
| Figure 4.13: Time series of Cl- concentrations of selected Wells between 2006 to 2010  | 145 |
| Figure 4.14: The architecture of the un-clustered ANNs NO <sub>3</sub> - model   | 150 |
| Figure 4.15: RMSE and MAPE for ANNs and SVM aggregated clustered and un-clustered NO <sub>3</sub> - models for the test data set.                                  | 155 |
| Figure 4.16: Observed versus predicted NO <sub>3</sub> - concentrations for ANNs model   | 156 |
| Figure 4.17: Observed versus predicted NO <sub>3</sub> - concentrations for SVM model  | 156 |
| Figure 4.18: Observed versus predicted NO <sub>3</sub> - concentrations for selected wells, (a) L/43 (Cluster I ); (b) L/41 (Cluster II ); (c) L176 (Cluster III ) | 158 |
| Figure 4. 19: Observed versus predicted NO <sub>3</sub> - concentrations in Dec. 2009  | 159 |

|  |     |
|--|-----|
| for, (a) Cluster I; (b) Cluster II; (c) Cluster III, wells   |     |
| Figure 4.20: Observed versus predicted aggregated clustered ANNs NO <sub>3</sub> - results in 2009   | 160 |
| Figure 4.21: Response graphs of AI input variables: (a) NO <sub>3</sub> o- (b) RNBU; (c) ROA; (d) RNAA   | 163 |
| Figure 4.22: The architecture of ANNs un-clustered Cl- model   | 166 |
| Figure 4.23: The observed versus predicted Cl- concentrations by ANNs model  | 170 |
| Figure 4.24: The observed versus predicted Cl- concentrations by SVM model   | 170 |
| Figure 4.25: Observed vs predicted Cl- concentrations in the case study wells in Feb. 2009   | 172 |
| Figure 4.26: The observed versus predicted Cl- concentrations for selected wells from 2005 to 2010, (a) L/127 (Cluster I); (b) L/41 (Cluster II); (c) P146 (Cluster III )                                    | 173 |
| Figure 4.27: RMSE and MAPE for Cl- aggregated clustered and un-clustered ANNs and SVM models based on the test data set.   | 174 |
| Figure 4.28: Response graphs of input variables of ANNs' model. (a) overall recharge & abstraction; (b) Cl <sub>o</sub> ; (c) distance to KYC; (d) bottom screen depth                                       | 177 |
| Figure 4.29: The predicted NO <sub>3</sub> - concentrations for selected wells in 2012 compared with the observed concentrations   | 180 |
| Figure 4.30: The predicted Cl- concentrations for selected wells in 2012 compared with the observed concentrations   | 180 |
| Figure 4.31: The predicted NO <sub>3</sub> - concentration in 2020 based on the 1st scenario compared with the observed concentration in 2010  | 181 |
| Figure 4.32: Khanyounis governorate contour maps for NO <sub>3</sub> - based on (a): the observed data in 2010, (b): the predicted 1st scenario model in 2020, (c): the predicted 1st scenario model in 2030 | 182 |
| Figure 4.33: The predicted NO <sub>3</sub> - concentration in 2020 based on the 2nd scenario compared with the observed concentration in 2010  | 183 |
| Figure 4.34: Khanyounis governorate contour maps of the predicted NO <sub>3</sub> - concentration in 2020 based on the 2nd scenario  | 183 |
| Figure 4.35: The predicted NO <sub>3</sub> - concentration in 2020 based on the 3th scenario compared with the observed concentration in 2010  | 184 |
| Figure 4.36: Khanyounis governorate contour maps of the predicted NO <sub>3</sub> - concentration in 2020 based on the 3rd scenario  | 185 |
| Figure 4.37: The predicted NO <sub>3</sub> - concentration in 2020 based on the 4th scenario (duplication of water recharge) compared with the observed  | 186 |

concentration in 2010

|  |     |
|--|-----|
| Figure 4.38: Khanyounis governorate contour maps of the predicted NO <sub>3</sub> - concentration in 2020 based on the 4th scenario  | 186 |
| Figure 4.39: The predicted NO <sub>3</sub> - concentration in 2020 and 2030 based on the 5th scenario compared with the observed concentration in 2010                                     | 187 |
| Figure 4.40: Khanyounis governorate contour maps of the predicted NO <sub>3</sub> - concentration based on the 5th scenario in (a) 2020; and (b) 2030                                      | 187 |
| Figure 4.41: The predicted NO <sub>3</sub> - concentration in 2020 based on the four management scenarios for (a) Cluster I; (b) Cluster II; (c) Cluster III, wells                        | 189 |
| Figure 4.42: The predicted NO <sub>3</sub> - concentration in 2030 based on the 1st and 5th scenarios  | 191 |
| Figure 4.43: Contour maps of the predicted NO <sub>3</sub> - concentration in 2030 based (a): 5th scenario, and (b): the 1st scenario  | 191 |
| Figure 4.44. Average annual change in NO <sub>3</sub> - concentration in Khanyounis governorate based on (a) the 1st scenario; and (b) the 5th scenario                                    | 192 |
| Figure 4.45: The observed Cl- concentration levels in Khanyounis governorate municipal wells in 2010 and the predicted Cl- concentration levels in 2020 and 2030 based on the 1st scenario | 193 |
| Figure 4.46: Contour maps of the predicted Cl- concentration based on 1st scenario in (a) the year 2020; and (b) the year (2030)   | 194 |
| Figure 4.47: The observed Cl- concentration levels in Khanyounis governorate municipal wells in 2010 and the predicted Cl- concentration levels in 2020 and 2030 based on the 2nd scenario | 195 |
| Figure 4.48: Contour maps of the predicted Cl- concentration based on 2nd scenario in (a) the year 2020; and (b) the year (2030)   | 196 |
| Figure 4.49: The observed Cl- concentration levels in Khanyounis governorate municipal wells in 2010 and the predicted Cl- concentration levels in 2020 and 2030 based on the 3rd scenario | 197 |
| Figure 4.50: The observed Cl- concentration levels in Khanyounis governorate municipal wells in 2010 and the predicted Cl- concentration levels in 2020 and 2030 based on the 4th scenario | 198 |
| Figure 4.51. The predicted Cl- concentration levels in Khanyounis governorate municipal wells based on the 4th scenario in (a) 2020; and (b) in 2030                                       | 198 |
| Figure 4.52: The predicted Cl- concentration in Khanyounis governorate municipal wells in 2030 based on the 1st and 4th scenarios  | 199 |
| Figure 4.53. Contour maps of the Cl- concentration in Khanyounis governorate in 2030 based on (a) the 1st scenario; and (b) the 4th scenario   | 199 |

|  |     |
|--|-----|
| Figure 4.54: Average annual change in Cl <sup>-</sup> concentration in Khanyounis governorate based on (a) the 1st scenario; and (b) the 4th scenario  | 200 |
| Figure 4.55: The concentrations of NO <sub>3</sub> <sup>-</sup> and Cl <sup>-</sup> of the case study wells (a) in 2010 (observed); (b) in 2020 based on the 1st scenario (predicted); and (c) in 2020 based on the best scenarios (predicted) | 202 |
| Figure 4.56: The observed and the predicted concentrations of NO <sub>3</sub> <sup>-</sup> and Cl <sup>-</sup> of the wells in 2010 and 2020 for (a) cluster I; (b) cluster II; and (c) cluster III  | 203 |
| Figure 4.57: The ratio between the predicted NO <sub>3</sub> <sup>-</sup> concentration in 2030 based on the best scenario and WHO standards for NO <sub>3</sub> <sup>-</sup> in Khanyounis governorate aquifer.                               | 205 |
| Figure 4.58: The ratio between the predicted Cl <sup>-</sup> concentration in 2030 based on the best scenario and WHO standards for Cl <sup>-</sup> in Khanyounis governorate aquifer.   | 206 |
| Figure 4.59: Contour map of the observed NCCI in 2010 in Khanyounis governorate aquifer.   | 207 |
| Figure 4.60: Contour map of the predicted NCCI in 2030 in Khanyounis governorate aquifer based on the best scenario  | 207 |
| Figure 5.1: The importance of the present research   | 215 |



## LIST OF TABLES

|  |     |
|--|-----|
| Table 2.1: Water balance of Gaza Coastal Aquifer   | 20  |
| Table 2.2: The average concentrations of the main GCA contaminants and their potential sources                     | 22  |
| Table 2.3: Characteristics of groundwater water quality problems   | 33  |
| Table 2.4: Classification of ANNs in relation to paradigm, architecture, learning algorithm, and task              | 46  |
| Table 2.5: Examples of ANNs applications for GW modelling  | 49  |
| Table 2.6: Examples of SVM's applications for GW modelling   | 56  |
| Table 2.7: Matching between the characteristics of water quality related problems and AI capabilities              | 61  |
| Table 2.8: Summary of the main groundwater quality studies for GCA   | 67  |
| Table 3.1: The main data required for developing the statistical and AI models                                     | 81  |
| Table 3.2: The spatial coordinates and construction years of the case study wells                                  | 83  |
| Table 3.3: Monthly abstraction of the case study wells in 2007   | 85  |
| Table 3.4: The mean concentrations of the available water quality parameters in case study wells from 2007 to 2010 | 84  |
| Table 3.5: The available aerial photos for Khanyounis governorate  | 87  |
| Table 3.6: Rainfall in Khanyounis governorate station for the year 2008  | 93  |
| Table 3.7: Rainfall coefficients of each LULC category   | 93  |
| Table 3.8: Monthly irrigation schedule in GS   | 98  |
| Table 3.9: Annual chemical fertilizers and manures quantities applied on each crop type in GS                      | 101 |
| Table 3.10: The monthly N-load quantities produced by animals and birds  | 103 |
| Table 3.11: Example of input–output response matrix for NO <sub>3</sub> - model of the well L/127 at June 2009     | 116 |
| Table 3.12: Example of input – output response matrix of well (P/154) at May 2010                                  | 118 |
| Table 3.13: Description of nitrate management scenarios  | 123 |
| Table 3.14: Description of Cl- management scenarios  | 124 |
| Table 4.1: The areas of different LULC categories in Khanyounis  | 128 |

governorate

|   |     |
|---|-----|
| Table 4.2: Descriptive statistics of selected groundwater parameters of municipal wells in Khanyounis governorate from 2007 to 2010                       | 129 |
| Table 4.3: Correlations coefficients between NO <sub>3</sub> <sup>-</sup> and Cl <sup>-</sup> with other water quality parameters                         | 130 |
| Table 4.4: PC loading of groundwater samples from the municipal wells in Khanyounis governorate   | 131 |
| Table 4.5: Land use land cover categories in the vicinities of case study wells   | 135 |
| Table 4.6: Correlation coefficients between NO <sub>3</sub> <sup>-</sup> and various explanatory independent variables                                    | 141 |
| Table 4.7: Correlation analysis between Cl <sup>-</sup> and various explanatory independent variables   | 146 |
| Table 4.8: The architecture and training algorithm of un-clustered ANNs nitrate model   | 149 |
| Table 4.9: Performance evaluation indicators of un-clustered ANNs' NO <sub>3</sub> <sup>-</sup> model   | 150 |
| Table 4.10: The architecture and training algorithm of the clustered ANNs NO <sub>3</sub> <sup>-</sup> models   | 151 |
| Table 4.11: Performance evaluation indicators of the aggregated clustered and the three clustered ANNs' NO <sub>3</sub> <sup>-</sup> models               | 151 |
| Table 4.12: Performance evaluation indicators of the ANNs' un-clustered and the aggregated clustered NO <sub>3</sub> <sup>-</sup> models for the test set | 153 |
| Table 4.13: Performance evaluation indicators of SVM un-clustered NO <sub>3</sub> <sup>-</sup> model  | 153 |
| Table 4.14: Performance evaluation indicators of SVM aggregated clustered NO <sub>3</sub> <sup>-</sup> model  | 154 |
| Table 4.15: Ranking of the input variables of un-clustered and clustered nitrate models   | 161 |
| Table 4.16: The architecture and training algorithm of ANNs un-clustered Cl <sup>-</sup> model  | 165 |
| Table 4.17: Performance evaluation indicators of ANNs' un-clustered Cl <sup>-</sup> model   | 166 |
| Table 4.18: The architecture and training algorithm of ANNs aggregated clustered Cl <sup>-</sup> models   | 167 |
| Table 4.19: Performance evaluation indicators for training and test sets of ANNs aggregated clustered Cl <sup>-</sup> model                               | 167 |

|  |     |
|--|-----|
| Table 4.20: Evaluation indicators of both un-clustered and ANNs' aggregated clustered models                                     | 168 |
| Table 4.21: Evaluation of both SVM's un-clustered and aggregated clustered CI- models  | 169 |
| Table 4.22: Ranking of the input variables' for un-clustered and clustered CI- models  | 175 |
| Table 4.23: The average annual change in the concentrations of NO <sub>3</sub> - and Cl- for both the 1st and the best scenarios | 204 |
| Table 5.1: Responsibility matrix for implementing the research recommendations   | 220 |

## LIST OF ABBREVIATIONS

|        |  |
|--------|--|
| AI     | Artificial Intelligence                  |
| ANNs   | Artificial neural Networks               |
| BP     | Back-propagation                         |
| BSD    | Bottom Screen Depth                      |
| CA     | Cluster analysis                         |
| Cl     | Chloride                                 |
| CM     | Correlation Matrix                       |
| CMWU   | Coastal Municipalities Water Utility     |
| CV     | Coefficient of Variation                 |
| DKYC   | Distance to Khanyounis Center            |
| GCA    | Gaza Coastal Aquifer                     |
| GIS    | Geographical Information Systems         |
| GS     | Gaza Strip                               |
| GW     | Groundwater                              |
| KYM    | Khanyounis Municipality                  |
| LM     | Levenberg-Marquardt                      |
| LULC   | Land Use Land Cover                      |
| LULCRC | Land Use Land Cover Recharge Coefficient |
| MA     | Municipal Abstraction                    |
| MAPE   | Mean Average Percentage Error            |
| MLP    | Multi-layer Perceptron                   |
| MOA    | Ministry of Agriculture                  |
| MOH    | Ministry of Health                       |
| MOLG   | Ministry of Local Government             |
| MOP    | Ministry of Planning                     |
| NAA    | On-ground N-load in Agricultural Areas   |

|                 |   |
|-----------------|---|
| NBU             | On-ground N-load in Built Up Areas                  |
| NCCI            | Nitrate – Chloride Contamination Index              |
| NGO's           | Non-Governmental Organizations                      |
| NO <sub>3</sub> | Nitrate   |
| NSE             | Nash-Sutcliffe Efficiency                           |
| ONA             | Overall On-ground N-load                            |
| OR              | Overall Recharge                                    |
| PCA             | Principal Component Analysis                        |
| PCBS            | Palestinian Central Bureau of Statistics            |
| PLA             | Palestinian Land Authority                          |
| PWA             | Palestinian Water Authority                         |
| r               | Correlation Coefficient                             |
| RAA             | Recharge from Agricultural Areas                    |
| RBA             | Recharge from Built Up Areas                        |
| RBF             | Radial Basis Function                               |
| RMSE            | Root mean Square Error                              |
| RNAA            | Recharge and On-ground N-load in Agricultural Areas |
| RNBU            | Recharge and On-ground N-load in Built Up Areas     |
| ROA             | Recharge from Open Area                             |
| SLT             | Statistical Learning Theory                         |
| SRC             | Soil Recharge Coefficient                           |
| SRM             | Structural Risk Minimization                        |
| SVM             | Support Vector Machine                              |
| TP              | Thiessen Polygon                                    |
| WHO             | World Health Organization                           |

**PEMBANGUNAN MODEL-MODEL PENGURUSAN KUALITI AIR BUMI  
MENGUNAKAN KAEDAH KECERDASAN BUATAN (AI): KAJIAN KES  
KHANYOUNIS GOVERNORATE, GAZA, PALESTINE**

**ABSTRAK**

Air bawah tanah merupakan sumber air yang unik untuk lebih daripada satu pertiga daripada penduduk dunia. Kualiti air bawah tanah adalah di bawah ancaman serius kerana urbanisasi dan perindustrian yang pesat dewasa ini. Pencemaran air bawah tanah dipengaruhi oleh pelbagai pembolehubah bergerakbalas, yang membawa kepada kesukaran yang tinggi untuk proses pemodelan kualiti air bawah tanah. Kaedah statistik dan kecerdasan buatan (AI) telah menjadi alat pemodelan air bawah tanah yang biasa disebabkan oleh prestasi yang tinggi. Dalam kajian ini, sistem hibrid terdiri daripada dua teknik AI iaitu rangkaian neural tiruan (ANNs) dan mesin penyokong vektor (SVM) disamping teknik statistik multivariat pelbagai telah digunakan untuk mensimulasikan dua parameter kualiti air bawah tanah terutamanya nitrat ( $\text{NO}_3^-$ ) dan klorida ( $\text{Cl}^-$ ) dalam akuifer kompleks. Model telah dilatih menggunakan data pemantauan terhad dan tidak teratur daripada 22 telaga perbandaran 1998-2010 di Pantai Gaza Akuifer (GCA) yang merupakan akuifer yang kompleks dan sangat heterogen. Keputusan analisis statistik pembolehubah GCA yang mendalam menunjukkan kebolehpercayaan teknik statistik dalam menangkap gambaran yang ringkas namun menyeluruh tentang trend kualiti air bawah tanah. Kedua-dua ANNs dan teknik SVM menunjukkan simulasi prestasi yang sangat memuaskan dengan keputusan yang setanding. Pekali korelasi ( $r$ ) dan bermakna peratusan ralat purata (MAPE) bagi  $\text{NO}_3^-$  model simulasi adalah 0.996 dan 7% masing-masing. Sementara itu,  $r$  dan MAPE bagi model simulasi  $\text{Cl}^-$  adalah 0.998 dan 3.7% masing-masing. Keputusan menunjukkan merit melakukan pengelompokan data input kepada kelompok yang konsisten sebelum permohonan yang berasingan teknik AI bagi setiap kluster. Memandangkan prestasi yang tinggi dan kesederhanaan, model simulasi yang dibangunkan telah digunakan dengan berkesan sebagai air bawah tanah pengurusan kualiti alat sokongan keputusan dengan menilai kesan pilihan pengurusan pelbagai  $\text{NO}_3^-$  dan penumpuan  $\text{Cl}^-$  di GCA bagi tahun 2020 dan 2030. Penilaian air bawah tanah pilihan pengurusan kualiti menunjukkan bahawa min  $\text{NO}_3^-$  dan kepekatan  $\text{Cl}^-$  dalam telaga perbandaran kawasan kajian setiap tahun akan meningkat sebanyak 7 mg/l dan 21 mg/l masing-masing jika keadaan kekal

tanpa sebarang campur tangan segera. Sebaliknya, penggunaan kombinasi pilihan pengurusan tunggal yang sangat akan meningkatkan tahap  $\text{NO}_3^-$  dan  $\text{Cl}^-$  dalam telaga. Kajian menunjukkan keupayaan teknik AI untuk digunakan sebagai alat kualiti pengurusan air bawah tanah terutama di negara-negara membangun mengalami kekurangan dan ketidakteraturan data pemantauan air bawah tanah.

**DEVELOPMENT OF GROUNDWATER QUALITY MANAGEMENT  
MODELS USING ARTIFICIAL INTELLIGENCE (AI) APPROACH – CASE  
STUDY – KHANYOUNIS GOVERNORATE – GAZA STRIP – PALESTINE**

**ABSTRACT**

Groundwater (GW) is the unique water source for more than one third of the world's populations. GW quality is under serious threat due to the recent rapid urbanization and industrialization. GW contamination is influenced by various interrelated variables, leading to high complexity in the GW quality modelling process. Statistical and artificial intelligence (AI) techniques have recently become common GW modelling tools due to their high performance. In this research, hybrid systems composed of two AI techniques namely artificial neural networks (ANNs) and support vector machine (SVM) in addition to various multivariate statistical techniques, were utilized to simulate the concentrations of two GW quality parameters particularly nitrate ( $\text{NO}_3^-$ ) and chloride ( $\text{Cl}^-$ ) in complex aquifers. The models were trained using limited and irregular monitoring data from 22 municipal wells from 1998 to 2010 in Gaza Coastal Aquifer (GCA) which is a complex and highly heterogeneous aquifer. Results of the statistical analyses deepened the understanding of the GCA influencing variables and GW quality trends. Both ANNs and SVM techniques showed very satisfactory simulation performance with comparable results. The correlation coefficient ( $r$ ) and mean average percentage error (MAPE) for  $\text{NO}_3^-$  simulation model were 0.996 and 7% respectively. Meanwhile  $r$  and MAPE for  $\text{Cl}^-$  simulation model were 0.998 and 3.7% respectively. The results demonstrated also the merit of performing clustering of input data into consistent clusters prior to separate application of AI techniques for each cluster. Given their high performance and simplicity, the developed models were effectively utilized as GW quality management decision support tools by assessing the effects of various management scenarios on  $\text{NO}_3^-$  and  $\text{Cl}^-$  concentration in GCA for 2020 and 2030. Evaluation of GW quality management scenarios indicated that  $\text{NO}_3^-$  and  $\text{Cl}^-$  concentrations in the study area municipal wells would noticeably increase if the situation remained without any immediate intervention. On the other hand, GW quality levels in most study area wells would be highly improved if a combination of management scenarios was adopted.  $\text{NO}_3^-$  management scenarios included completion of the wastewater collection system in the study area, reduction of



manure and fertilizers used in agricultural activities by 50%, duplication of GW recharge. While CI management scenarios included reduction of GW abstractions by 50% and duplication of GW recharge. The study showed the ability of AI-based hybrid techniques to be used as a GW quality management tools especially in developing countries suffering from lack and irregularity of GW monitoring data.

# CHAPTER 1

## INTRODUCTION

*"We made from water every living thing. Will they not then believe?"*

*Holly Quran (Alambia'a 30)*

### 1.1 Preface

Noble prize winner Albert Szent-Gyorgyi summarized the priceless value of water stating that "*Water is life's mater and matrix, mother and medium. There is no life without water*" (Beattie, 2011). However, the ecosystem including water resources is horribly deteriorated as a result of the rapid population growth associated with urbanization and diversity of human activities (Chofqi et al., 2004)

Groundwater (GW) is the unique water source for more than one third of world's population (Morris et al., 2003). GW is an important source for sustainable economic growth in any community specially in arid and semi-arid regions (Sheng, 2013). This valuable source is not completely isolated from the surrounding environment. It is affected by both natural and anthropogenic contamination sources. Therefore an assessment of GW quality is of great importance for society and particularly for public health aspects (Ramakrishnaiah et al., 2009; Sener et al., 2009). Nevertheless, GW contamination is a complicated process that is influenced by various interrelated physical, chemical, and biological variables, resulting in high spatial and temporal variability (ASCE, 2000). These characteristics add more complexity to GW modelling process that requires considering all potential variables and integrating different disciplines and fields of knowledge.

During recent years, various artificial intelligence (AI) techniques such as artificial neural networks (ANNs) and support vector machine (SVM) have been utilized for hydrological modelling purposes using relatively less cost, effort and data (Almasri and Kaluarachchi, 2005a; Chau, 2006). These techniques have exhibited a satisfactory simulation performance notably when the hydrological process is difficult to be accurately described and / or when the available data are insufficient for applying numerical and physical models which is the case for many GW problems (Trichakis et al., 2009).

ANNs have been successfully applied for different GW applications such as forecasting GW level and modelling GW quality (Nourani et al., 2008; Banerjee et al., 2011; Seyam and Mogheir, 2011; Trichakis et al., 2011; Yesilnacar and Sahinkaya, 2012). Likewise, the application of SVM has attracted higher attention during recent years for modelling both surface water and GW processes. For example, SVM has been utilized for stream flow predictions (Asefa et al., 2006), river flow discharge (Wang et al., 2009), GW level forecasting (Behzad et al., 2010; Yoon et al., 2010), and GW quality assessment (Dixon, 2009).

Statistical techniques have also been widely used in GW studies due to their suitability in dealing with the nature of GW monitoring data (Sorichetta et al., 2013). Among different statistical techniques, multivariate techniques such as correlation matrix (CM), cluster analysis (CA), and principal component analysis (PCA), have widely been utilized in GW studies to help in exploring the hidden relationships among different parameters especially at cases of difficulties in the integration, interpretation and representation of the available data (Chen et al., 2007; Prasanna et al., 2010).

In a recent report entitled "Gaza in 2020 A liveable place?", UNCT (2012) expected that, based on the current water and sanitation situation, the GW in Gaza Strip (GS) could become unusable as early as 2016; moreover the damage of the GW in GS would be irreversible by 2020. This study also mentioned that 90% of the GW in GS is currently not safe for drinking purposes without adequate treatment. Being the only source of water in GS population of more than 1.6 million (PCBS, 2012), Gaza coastal aquifer (GCA) is in a disastrous quality situation (Qahman and Larabi, 2006). Increased concentrations of nitrate ( $\text{NO}_3^-$ ) and chloride ( $\text{Cl}^-$ ) are the main dominant water quality problems in GCA (Almasri and Ghabayen, 2008). The average concentration of  $\text{NO}_3^-$  in GS domestic wells is 128 mg/l compared with the World Health Organization (WHO) standards of 50 mg/l (Shomar et al., 2008; WHO, 2008). Untreated wastewater and agricultural activities are the main sources  $\text{NO}_3^-$  (Baalousha, 2008). The concentration of  $\text{Cl}^-$  in many locations of GCA exceeded 2000 mg/l. Furthermore, less than 5% of municipal water wells in GS meet WHO  $\text{Cl}^-$  standards of 250 mg/l. Overexploitation and lateral flow from adjacent eastern aquifer are the main sources of high  $\text{Cl}^-$  concentrations in GCA (Al-Khatib and Arafat, 2009; Shomar et al., 2010). What worsens the problem is the political situation along with the difficult economical conditions that delay almost all actions to de-stress GCA and find reliable and sustainable solutions (Shomar, 2011).

Khanyounis governorate has the largest area among the five GS governorates. The water quality situation in Khanyounis governorate is the worst among GS governorates. According to Shomar et. al. (2008), the average  $\text{NO}_3^-$  concentration in Khanyounis governorate in 2007 was 191 mg/l. Work done by Almasri and Ghabayen (2008) related such high concentrations to the fact that most of Khanyounis governorate inhabitants are still using cesspits for disposing their

wastewater. The highest  $\text{Cl}^-$  concentration in GS was also recorded to be 2652 mg/l in one of Khanyounis governorate wells in 2008; i.e. 10 times more than WHO standards for  $\text{Cl}^-$ ; this high concentration is due to seawater intrusion and lateral flow from adjacent eastern aquifer (Yakirevich et al., 1998; Shomar et al., 2010).

## **1.2 Problem statement**

Despite the wide strides and the increasing trends during the recent years regarding the utilization of AI techniques for GW quality modelling, there remain some areas that need further investigation. For example, the literature review reveals that there are very limited studies on the assessment of the performance of SVM technique in modelling GW contamination compared with ANNs and compared with surface water applications. Additionally, the comparison between the performance of ANNs and SVM for different hydrological processes is an attractive field that requires a lot of further research (Behzad et al., 2010; Yoon et al., 2010).

Simplicity, accuracy, and cost effectiveness are the main characteristics of the efficient and feasible GW quality modelling and management processes (Bierkens, 2006; Ammar et al., 2009; Harou et al., 2009). Therefore the recent trends in the field of hydrological modelling are related to proposing techniques for improving modelling prediction ability without the need for extra data and effort. Thus, AI-based hybrid models that combine AI with other techniques are considered to be one of the promising research areas in the field of GW quality modelling (Nourani, 2012). The hybrid models are characterized by their improved accuracy, and are developed using minimum data, time and effort. These targeted models are effectively and reliably utilized to support management decisions related to GW quality especially in complex heterogeneous aquifers (Chau, 2006; Li et al., 2013).

Reviewing the literature showed that most of the previous modelling studies on GW quality using AI techniques were more concerned with optimization of the models performance by investigating the model's parameters and architecture that achieve the highest performance. On the other hand, lack of studies are concerned with utilization of AI-based GW quality models for future prediction of GW quality situations under various management scenarios. (Yesilnacar et al., 2008; Trichakis et al., 2011).

$\text{NO}_3^-$  contamination of GW is a serious worldwide problem, where high concentrations of  $\text{NO}_3^-$  in water can cause blood disorder called methemoglobinemia, commonly known as blue baby syndrome, which at severe cases can result in brain damage and death especially for infants below six months of age (Cissé and Mao, 2008). Therefore modelling of  $\text{NO}_3^-$  concentration in GW is of a great important especially for public health aspects. Regarding AI-based  $\text{NO}_3^-$  modelling, none of the earlier studies utilized SVM for estimating  $\text{NO}_3^-$  concentration in GW based on the potential influencing variables. Furthermore, there is a dearth of studies that is related to ANNs based models for  $\text{NO}_3^-$ ; however all the few developed ANNs-based  $\text{NO}_3^-$  simulation models could be categorized into three categories; (1) Models that required a lot of input data and used sophisticated methods for input calculations such as the study conducted by Almasri and Kaluarachchi (2005a) in an agriculture dominated area. Though their accuracy, the applicability of these models is limited due to the detailed and accurate data required. (2) Models that predicted  $\text{NO}_3^-$  levels in the GW using the concentration of other variables (Yesilnacar et al., 2008). The main shortcoming of these types of models is that these models could not be used for future GW management because the absence of the physical meaning of contamination process. (3) Relatively simple models with less input dimensionality

but their accuracy needed to be further improved, as found in the model developed by Al-Mahallawi et al. (2012).

Cl<sup>-</sup> is usually used as a representative of GW salinity problems; and excessive concentration of Cl<sup>-</sup> in drinking water is an indicator of the deterioration of its quality (Melloul and Collin, 2000; Abyaneh et al., 2005). Elevated concentration of Cl<sup>-</sup> in drinking water has negative effects on human health especially to persons who have kidney or heart problems (Versari et al., 2002; Aichele, 2004; Virkutyte and Sillanpää, 2006). As for AI-based modelling of Cl<sup>-</sup> in GW using explanatory input variables, only one study has been found using ANNs (Seyam and Mogheir, 2011), however, the accuracy of their model was relatively low due to neglecting many influencing variables; therefore their model needs further improvement. Additionally, none of the previous studies utilized SVM to model Cl<sup>-</sup> concentration in GW.

Gaza Strip, the study area, is an extreme model on how unstable political environment, disastrous economic situation, decaying environmental conditions and unplanned human activities are combined together to further deteriorate the GW quality (Shomar, 2011). Therefore, understanding of GW trends and modelling the most sensitive and dominant GW quality parameters using cost-effective techniques depending on few monitoring data can be considered to be very much advantageous point not only in GS but also in all developing countries that suffer from lack of financial and technical capabilities.

The present research attempts to form a comprehensive view about GW situation in complex aquifers by investigating the most influencing variables using a hybrid system composed of two AI techniques namely ANNs and SVM along with various multivariate statistical techniques (CM, PCA and CA). Almost all potential

influencing variables on GW quality are investigated including land use activities and aquifer physical settings. The most significant variables are selected as input variables in the final models for modelling both  $\text{NO}_3^-$  and  $\text{Cl}^-$  using the available limited monitoring data. Furthermore an improvement technique is proposed that positively affects the modelling efficiency. Moreover the developed models are used for assessing the implications of various GW quality management scenarios on the future GW quality in 2020 and 2030. The applicability of the developed models was validated using data from GCA which is an extremely complex hydro-geological system with deteriorated conditions. Figure 1.1 summarizes the problem statement mentioned above and illustrates the driving forces of conducting the current research.



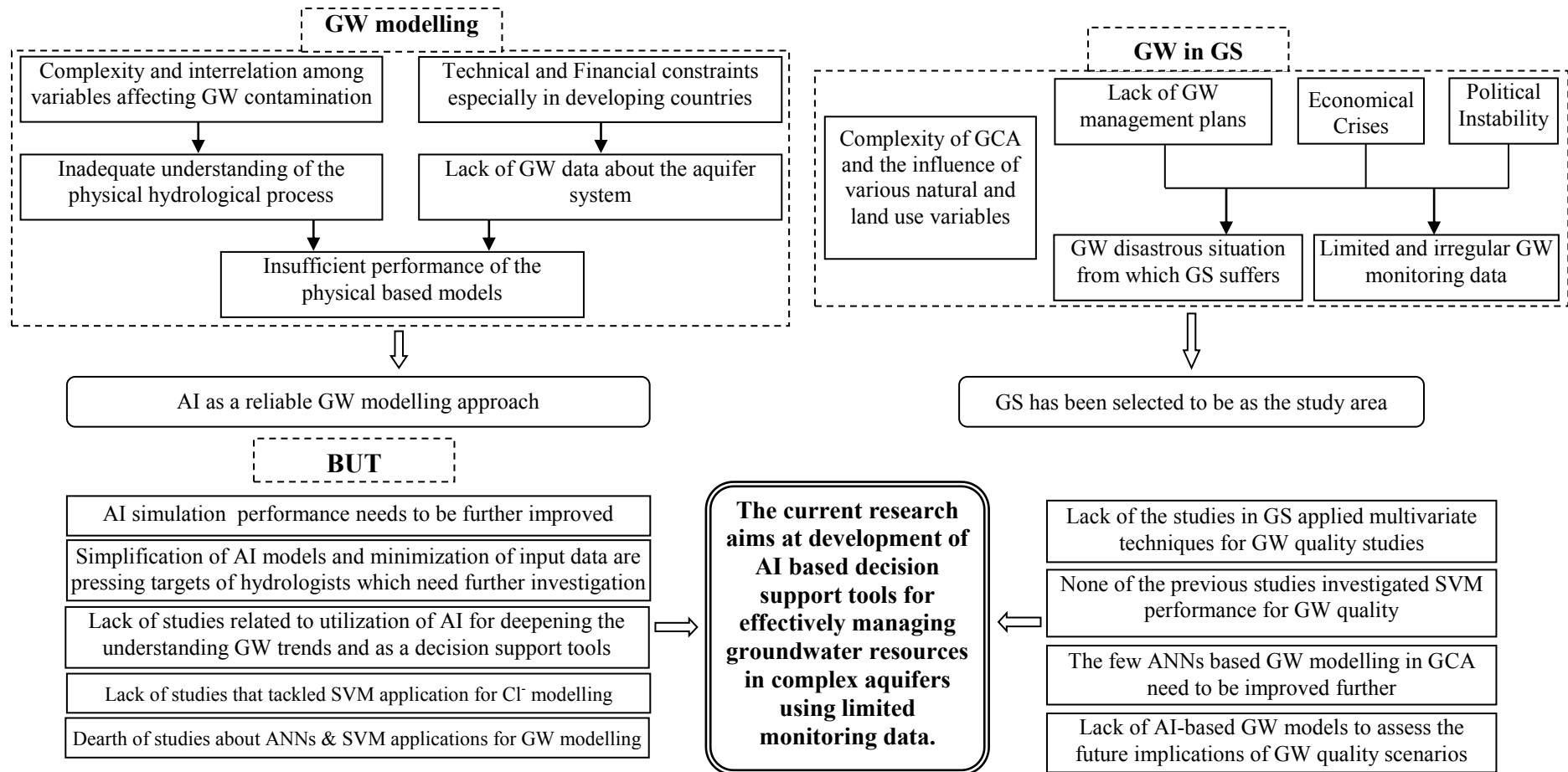


Figure 1.1: Research problem tree

### **1.3 Research Objectives**

This research is designed and carried out to develop an artificial intelligence based hybrid models to be used as a decision support tools for effectively managing groundwater quality using limited monitoring data in Khanyounis governorate as a case study. To be more specific, the research is intended to achieve the following objectives:

1. To investigate the performance of multivariate statistical techniques for capturing a simple and general view about GW system in complex aquifers,
2. To develop reliable and simple AI-based models for simulating the concentrations of  $\text{NO}_3^-$  and  $\text{Cl}^-$  in complex aquifer systems by ANNs and SVM,
3. To evaluate the effect of clustering the input data on the simulation performance of the developed AI models, and
4. To predict the implications of various proposed GW quality management scenarios on the future concentrations of  $\text{NO}_3^-$  and  $\text{Cl}^-$ .

### **1.4 Scope of the study**

This study is concerned in modelling the concentration of both  $\text{NO}_3^-$  and  $\text{Cl}^-$  in GW using ANNs and SVM as AI techniques. Several statistical techniques (i.e. CM, PCA, CA), geographical information systems (GIS), and classification of aerial photos into and different land use land cover (LULC) categories are integrated with AI to achieve best models' accuracy.

The study area of the present research is Khanyounis governorate which is the largest governorate in GS in terms of area (110 km<sup>2</sup>). The available data for

developing GW quality models are obtained from 22 municipal wells from 1998 to 2010 with a lot of missing records. Such missing records are due to irregularity of GW quality monitoring, in addition to financial and technical constraints in the area.

## 1.5 Thesis Organization

The thesis consists of 5 chapters as follows; **Chapter One** is the introduction which gives a preface about the research topic and the study area. Identification of research problem, objectives, and scope are also included in this chapter. **Chapter Two** describes the literature review; where several topics are reviewed, including GW quality issues with a focus on  $\text{NO}_3^-$  and  $\text{Cl}^-$ , GW quality modelling approaches and GW quality management practices. The latest research efforts pertaining AI applications for GW quality modelling are also reviewed. Additionally this chapter describes GW quality problems and the management prospects in GS and Khanyounis governorate as the study area. **Chapter Three** contains detailed description about the study area, data collection, data pre-processing, calculations of models' input variables for both  $\text{NO}_3^-$  and  $\text{Cl}^-$ ; as well as the steps for carrying out the statistical analyses and AI models. **Chapter Four** presents the results and discussion of the application of the statistical analyses and AI simulation models for  $\text{NO}_3^-$  and  $\text{Cl}^-$ . The chapter also illustrates the results and discussion of application of the developed AI based hybrid models for GW quality management in the study area. Finally **Chapter Five** contains conclusions related to GCA status, AI modelling techniques, research importance and constraints. In this chapter, various recommendations derived from the research results are presented including recommendations related to GW management in GS, GW modelling process as well as proposed future research works.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1 Introduction**

This chapter presents a general overview about various GW quality aspects concentrating on the two water quality contaminants namely, nitrate ( $\text{NO}_3^-$ ) and chloride ( $\text{Cl}^-$ ). Sources, characteristics, modelling, and management of these contaminants are also tackled. Theoretical background of artificial intelligence (AI) techniques along with their applications in hydrology is provided as well. Furthermore, the characteristics of Gaza Coastal Aquifer (GCA) as the study area and its conditions in terms of quality situation are described.

#### **2.2 Groundwater Quality**

Water constitutes one of the basic components of nation's development. Rapid population growth coupled with the increasing diversity of human activities are inseparable to such development, which consequently lead to increase water demand (de Andrade et al., 2008; Sinan and Razack, 2009).

GW is considered as the most important natural resource that mankind is challenged to manage, since it constitutes about 89% of the freshwater on the earth (Koundouri, 2004). In many regions of the world, GW is the unique source of drinking water, especially in the cases of limited or contaminated surface water resources (Schmoll, 2006; Sener et al., 2009). It is estimated that more than one third of world's population completely depend on GW to satisfy their water needs (Morris et al., 2003). Compared with surface water, GW has generally lower vulnerability to

contamination (Zhang et al., 2009). Therefore GW plays an important role in meeting the continuously increasing water demand.

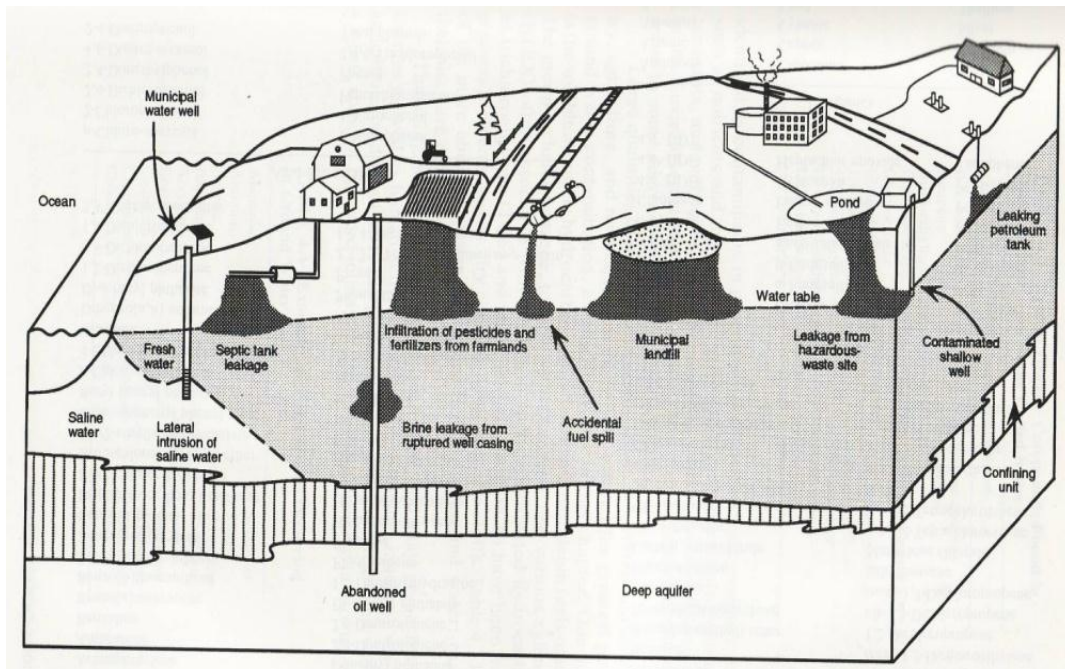
### **2.2.1 Contamination of Groundwater**

GW is not completely detached from the ground surface. Therefore, almost every human activity such as rapid urbanization has the potential to directly or indirectly affect the aquifer system to a certain extent (Harter and Walker, 2001; Chofqi et al., 2004; Kresic, 2009). During the last decades, it has been noticed that the GW availability and its quality have been negatively affected by over-abstraction in addition to various land use activities such as improper disposal of human solid wastes and wastewater, and intensive agricultural activities (Ramakrishnaiah et al., 2009). For instance, the extensive use of fertilizers coupled with utilization of new agricultural equipment aiming at increasing the crops' yield in many areas of the world, have highly deteriorated the GW quality in these areas (de Andrade et al., 2008)

In addition to the anthropogenic factors resulted from human activities, natural factors have also considerable effects on GW quality; these factors are related to the characteristics of aquifer's media and unsaturated zone, climate and topography (Helena et al., 2000; Wu and Huang, 2009). The effects of both anthropogenic and natural contaminations sources on GW quality are noticeably appeared in many regions of the world (Draoui et al., 2008; Sener et al., 2009). But as a general fact, the anthropogenic contaminants usually have much greater negative impacts on GW quality than the natural contaminants (Kresic, 2009).

As depicted from Figure 2.1, many sources can be considered as potential GW contamination sources; these include septic tanks, agricultural activities, saltwater intrusion, landfills, accidental spills, underground storage tanks and pipelines

(Bedient et al., 1994). If contaminants released from the aforementioned sources reach the aquifer, the GW quality is altered and deteriorated. Such GW alteration and deterioration definitely constrains its usage, and may make it unreliable for domestic and other usages (Kumar and Alappat, 2005; Zhang et al., 2009).



**Figure 2.1: Potential sources of GW contamination**  
(Source: Bedient et. al. (1994))

### 2.2.2 Mechanisms of Groundwater Contamination

When contaminants are released from their sources, percolate through the unsaturated zone, and finally reach the GW and contaminate it (Mirbagheri, 2004), these contaminant are mixed with GW contaminants forming a plume that spread with GW system based on the characteristics of GW flow (Javadi and Al-Najjar, 2007; Vasanthi et al., 2008). Many variables can influence the potential of a contaminant to impact the underlying GW quality. These variables can be classified into three categories: (1) environmental variables; (2) contamination source related variables; and (3) pathway related variables.

Environmental variables mainly include climate related parameters such as precipitation and humidity (Mato, 2002). Contamination source related variables include the location of contamination source, contaminants load and quantity, in addition to contaminant characteristics such as its resistance to degradation (Mato, 2002). Pathway related variables are referred to the course taken by contaminants while being transported from the source to aquifers, and is described by various characteristics of unsaturated and saturated zones that govern contaminant transport processes (Islam and Singhal, 2004).

Complex interactions usually occur between contaminants and transport media; moreover contaminants themselves may react with each other adding further complexity to transport process (Ferguson et al., 1998). Therefore, once a contaminant gets released out from its source, its chemical, biochemical and physical characteristics may be altered (Islam and Singhal, 2004). For example, many contaminants experience natural attenuation (purification) by natural processes leading to reduce their concentration to acceptable level (Bagchi, 1990). This process is highly dependent on the interaction between the source related characteristics (chemical parameters of the contaminant) and the pathway related hydro-geological characteristics (Harter and Walker, 2001; Park et al., 2008). Therefore, understanding the behavior of contaminants through these zones is essential in predicting the potential for GW contamination by these contaminants (Islam and Singhal, 2004; Park et al., 2008).

The main transport processes of concern in GW include advection, diffusion, dispersion, adsorption, and biodegradation. The following is a brief description of these processes (McBean et al., 1995; Javadi and Al-Najjar, 2007):

- **Advection:** is the transport of contaminants caused by the net flow of the fluid in which the contaminant is suspended.
- **Diffusion:** is a molecular mass-transport process in which contaminants move from areas of higher concentration to areas of lower concentration.
- **Dispersion:** is a mixing process caused by velocity variations in the porous media.
- **Adsorption:** refers to adherence of chemical species (contaminants) primarily on the surface of the porous matrix.
- **Biodegradation:** represents the transformation of certain organic materials to simple CO<sub>2</sub> and water in the presence of microbes.

Such complex processes result in high nonlinearity and high degree of spatial and temporal variability of contaminants in GW. Moreover uncertainties in hydrological variables' estimates are one of the main features of GW contamination process (ASCE, 2000). Therefore, GW contamination is a complex dynamic process that is difficult to be sufficiently understood due to its dependency on the characteristics of the contaminant, pathway media as well as the surrounding environmental conditions leading to difficulty in GW quality modelling process (Daliakopoulos et al., 2005)

### **2.2.3 Water Quality in Gaza Coastal Aquifer**

#### **2.2.3.1 Preface about Gaza Coastal Aquifer**

Gaza Coastal Aquifer (GCA) is a highly heterogeneous hydro-geological system (Yakirevich et al., 1998). It is the only natural source of water in GS where water is pumped from the aquifer by more than 4000 municipal and agricultural



wells (UNEP, 2009; ANERA, 2012); among them more than 1000 wells exist in Khanyounis governorate (Qahman and Larabi, 2006). GCA is a part of the coastal aquifer that extends from GS in the south to Carmel Mountains in the north along the Mediterranean coast line (about 120 km) as shown in Figure 2.2 that illustrates the layout of GCA and the adjacent aquifers (UNEP, 2003). The width of GCA varies from 3-10 km in the north to about 20 km in the south (Yakirevich et al., 1998; Almasri, 2008). GCA thickness varies from about 120 m in the west (at the shoreline) to few meters in the east (Baalousha, 2006b). Meanwhile, the depth of water level of GCA ranges from about 60 m below ground surface in the east to few meters near the coastline in the west (UNEP, 2003).

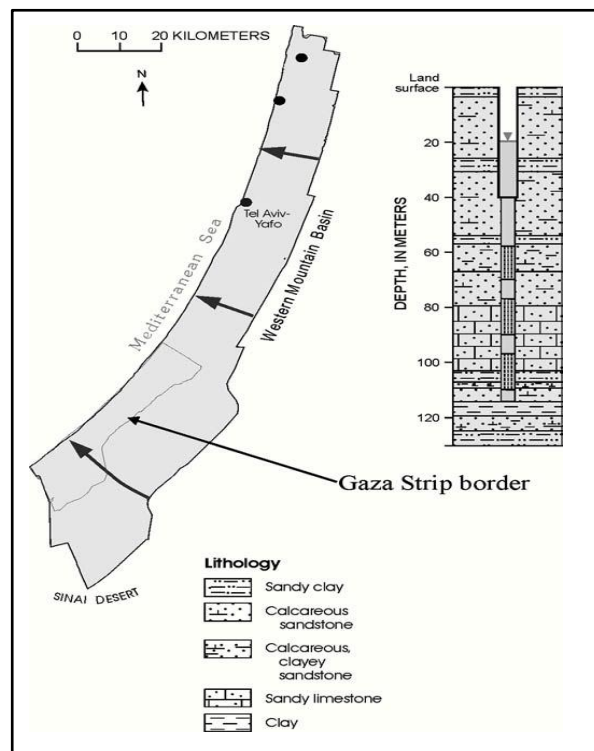


**Figure 2.2 : Layout of Gaza Coastal Aquifer (GCA)**

**(Source: UNEP (2003))**

Geologically, GCA is a Pleistocene-age granular phreatic hydro-geological system. It is composed of layers of dune sand, sandstone, calcareous sandstone, and

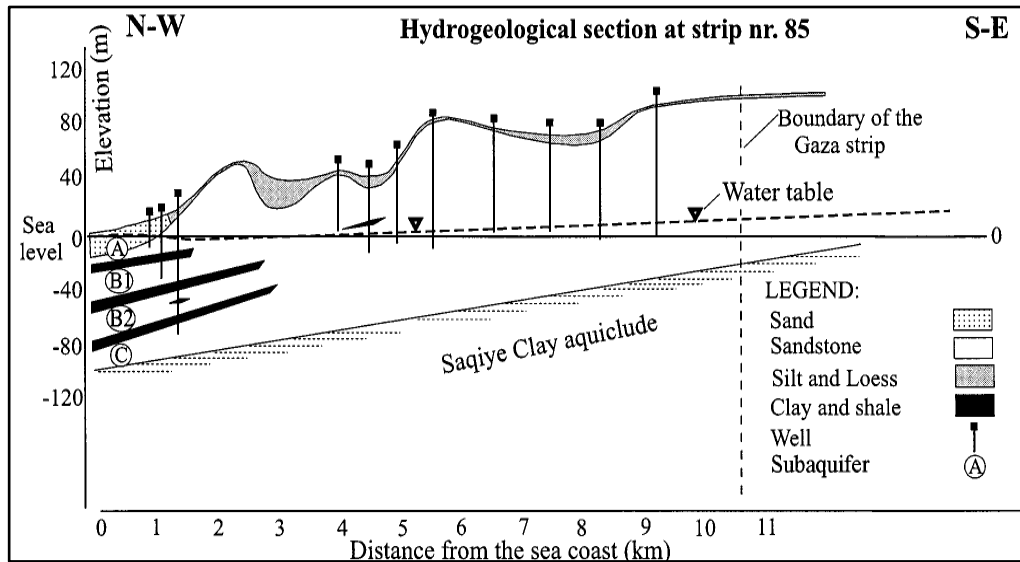
silt as shown in Figure 2.3. It also contains several silty-clayey impermeable layers which partially intercalate and subdivide it into sub-aquifers (Yakirevich et al., 1998; Melloul and Collin, 2000; Baalousha, 2006b). GCA is considered as unconfined in the east, while, in the west it becomes confined / unconfined multi-aquifer. In this area sub-aquifer A is phreatic, whereas sub-aquifers B and C (Figure 2.4) become increasingly confined towards the coastline in the west, (Qahman and Larabi, 2006). Many municipal wells in GS have been constructed and screened across more than one sub aquifer, each of which has specific characteristics, and few data are known about hydraulic properties of each sub aquifer (Shomar, 2011).



**Figure 2.3: GCA basin and lithology**  
**(Source: Baalousha (2006 b))**

GCA materials are underlain by a very thick impermeable clay layer called “Saqiya Formation” which acts as the aquifer bed. Saqiya Formation is an aquiclude layer consisting of about 100 m of black shale of Pliocene age (Al-Agha and El-

Nakhal, 2004). There is a connection between GCA and the Eocene aquifer which is located in the east. This connection leads to increase GCA salinity in the eastern part (Yakirevich et al., 1998). Typical cross section (sec. A-A in Figure 2.2) of GCA at Khanyounis governorate area is depicted in Figure 2.4.



**Figure 2.4: Typical cross section of GCA at Khanyounis governorate area (Source: Yakirevich et al. (1998))**

GW flow in GCA as whole is generally from the southeast to the northwest. However, flow direction may change due to high abstraction rates from some wells (Al-Agha and El-Nakhal, 2004; Weinthal et al., 2005; Almasri and Ghabayen, 2008). Hajhamad and Almasri (2009) reported that the hydraulic conductivity of GCA is in the range of 20–80 m/d.

### 2.2.3.2 Gaza Coastal Aquifer Problems

GCA is considered as the most precious and valuable natural resource in GS area, where it is extensively utilized to meet the various water demands (Ghabayen et al., 2006; Shomar et al., 2010). This utilization makes GCA under increasing

problematic conditions in terms of quantity and quality (Shomar, 2011). Where, the rapid increase in GS population coupled with the growth of urban and agricultural activities have resulted in increasing GW demand and horrible decline in GW quality (Al-Agha and El-Nakhal, 2004).

#### **a. Groundwater Shortage Problem in Gaza Strip**

GCA is a dynamic system that exhibits a continuous variation in the inflow and outflow conditions (Qahman and Larabi, 2006). The main sources of GCA recharge are precipitation, inflow from the adjacent eastern aquifer through the connection between the two aquifers, irrigation return flow, leakage from water distribution and wastewater collection networks, and discharge from wastewater facilities (Baalousha, 2008). Baalousha (2006b) reported that about 30% to 40% of the annual precipitation percolated to the aquifer. Hajhamad and Almasri (2009) estimated that about 15% of water used for irrigation was considered as a return flow that recharged into the GCA. It is clear from water balance of GCA presented in Table 2.1 that the current abstraction rates from GCA are unsustainable leading to annual deficit of at least 58 million m<sup>3</sup> implying lowering of the GW table, reduction in availability of fresh GW and increased seawater and deep brines intrusion (UNEP, 2003). For the near future, Baalousha (2006a) estimated that with increasing water demand for different uses, the annual water deficit in GS would exceed 100 million m<sup>3</sup> in 2020.

#### **b. Groundwater Quality Problem in Gaza Strip**

GCA is considered as a characteristic case of highly contaminated aquifer due to hydrological stresses in addition to insufficient water resources management (Zoller et al., 1998). Recent studies reported that no GW in GS meets all WHO

drinking water standards; additionally more than 90% of GW in GS is not suitable for drinking due to the elevated concentrations of many chemical parameters particularly  $\text{NO}_3^-$  and  $\text{Cl}^-$  in addition to microbiological contamination which exists in many locations within GS (Shomar et al., 2008; Shomar et al., 2010; UNCT, 2012; Abbas et al., 2013). On the other hand, and due to the economical problems, only 3% of GS populations uses the imported bottled-water, and around 25% has home water filters (Shomar, 2011).

**Table 2.1: Water balance of Gaza Coastal Aquifer  
(Source: MOA (2010))**

| Inflow  |   | Outflow                      |   |
|---|---|------------------------------|---|
| Item  | Annual Quantity<br>million $\text{m}^3$ | Item                         | Annual Quantity<br>million $\text{m}^3$ |
| Recharge from rainfall                          | 40 – 50                                 | Municipal Abstraction        | 90                                      |
| Return flow from irrigation                     | 15 – 30                                 | Agricultural abstraction     | 80 - 90                                 |
| Return flow from wastewater collection networks | 15 – 25                                 | Industrial abstraction       | 10                                      |
| Return flow from water distribution networks    | 25 – 30                                 | Natural discharge to the sea | 8                                       |
| Lateral flow from adjacent eastern aquifer      | 15 – 25                                 |                              |   |
| <b>Total</b>                                    | <b>110 – 130</b>                        | <b>Total</b>                 | <b>188 - 198</b>                        |
| <b>Deficit</b>                                  | <b>58 – 88 MCM</b>                      |                              |   |

In general, GCA is susceptible to contamination sources applied to ground surface (Shomar et al., 2008). Contamination sources in GS include cesspools, seawater intrusion, agricultural activities, and inadequate waste management (UNEP, 2003; Ghabayen et al., 2006). These sources produce a “cocktail” of contaminants that have the potential to highly deteriorate GCA (Al-Agha and El-Nakhal, 2004). GW quality is influenced by many variables including land use activities, soil/water

interaction in the unsaturated zone, rainfall, return flows, sea water intrusion, effect of deep brines, and disposal of municipal and industrial wastes into the aquifer (Abbas et al., 2013).

In GS, land use is one of the main influencing variables that govern the concentration of chemical parameters in GW (Almasri and Ghabayen, 2008). For instance, many urban areas in GS are not connected to wastewater collection systems; in these areas, people still use cesspools for disposing their wastewater. Considerable quantities of such sewage percolate through unsaturated zone to the aquifer, and the remaining sewage in these cesspools is collected by vacuum vehicles; then the collected sewage is discharged to open fields without any treatment (Baalousha, 2008). This in turn results in elevated concentrations of many contaminants such as  $\text{NO}_3^-$  and microbes. Likewise in agricultural areas, the intensive application of manures and fertilizers results in GW contamination with several contaminants notably  $\text{NO}_3^-$  (UNEP, 2003).

Consequently, the concentrations of many water quality parameters in GCA exceed the maximum contaminant level set by various related agencies such as WHO guidelines (Almasri and Ghabayen, 2008; Shomar, 2011). This obviously indicates the deterioration and disastrous conditions of GCA as seen in Table 2.2 that summarizes the main contaminants in GCA, and their potential sources. It is noticed that over-pumping resulted from rapid population growth leading to seawater intrusion along with low GW recharge due to low rainfall and urbanization are the main sources of most GW quality parameters notably EC, TDS, Cl, Ca, Mg and total hardness. Whereas untreated wastewater, uncontrolled agricultural activities and improper solid waste disposal are the main sources of  $\text{NO}_3^-$ .

**Table 2.2: The average concentrations of the main GCA contaminants and their potential sources  
(Source: Shomar (2011))**

| Parameter       | Average concentration in GCA | WHO guidelines | Potential contamination sources                          |
|-----------------|------------------------------|----------------|--|
| EC              | 3308                         | 2000           | Over-pumping, Low recharge, Seawater intrusion           |
| TDS             | 2045                         | 500            | Over-pumping, Low recharge, Seawater intrusion           |
| NO <sub>3</sub> | 170                          | 50             | Wastewater, fertilizers, solid waste leachate            |
| Cl              | 779                          | 250            | Over-pumping, Low recharge, Seawater intrusion           |
| Ca              | 91                           | 50             | Natural, Over-pumping, Low recharge, Seawater intrusion  |
| Mg              | 72                           | 30             | Natural, Over-pumping, Low recharge, Seawater intrusion  |
| T. Hardness     | 553                          | 200            | Natural , Over-pumping, Low recharge, Seawater intrusion |

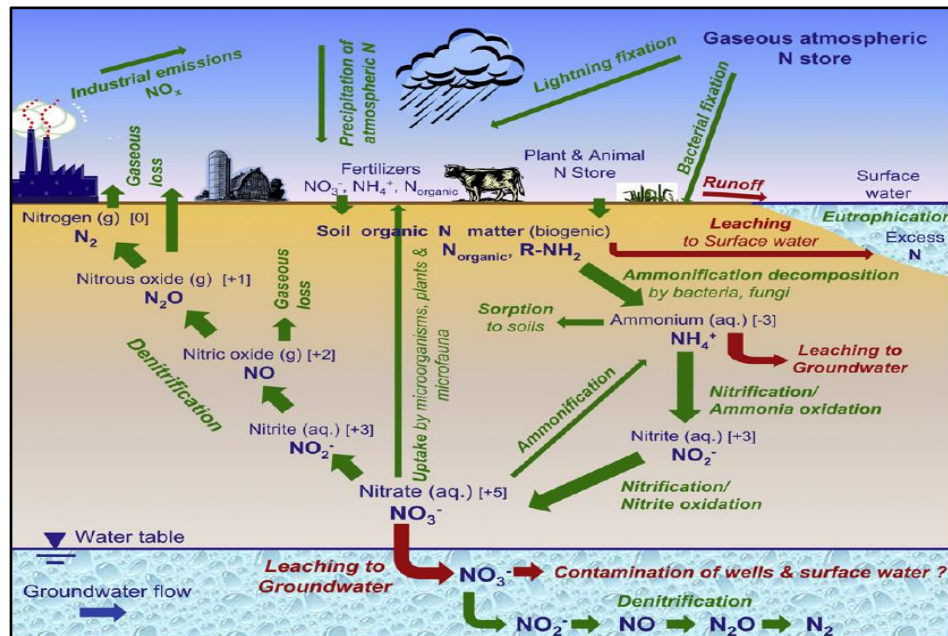
Basically, GCA suffers from two main GW quality problems, NO<sub>3</sub><sup>-</sup> and Cl<sup>-</sup> contamination (Hamdan and Jaber, 2001; Al-Mahallawi, 2005). Among GS five governorates, particularly, Khanyounis governorate has the most serious situation in relation to GW quality problems; where the highest concentrations of both NO<sub>3</sub><sup>-</sup> and Cl<sup>-</sup> were recorded in Khanyounis governorate (Baalousha, 2006a; Shomar et al., 2008; Shomar et al., 2010). Brief theoretical background about these two main GW quality parameters (NO<sub>3</sub><sup>-</sup> and Cl<sup>-</sup>) will be described in the following sections highlighting the dimension of the problems in the study area.

## **2.2.4 Nitrate Contamination of Groundwater**

### **2.2.4.1 Introduction**

Nitrogen (N) is one of the basic components for the production of a number of complex organic matters such as proteins, amino and nucleic acids that are essential elements for humans and animals (Pidwirny, 2006). It is also an important nutrient element that enhances growth rates of crops and plants (Almasri and Kaluarachchi, 2005b). N is converted from one form to another when it is subjected to a series of

biological and chemical processes during its cycle in the environment in which bacteria play major roles (Harrison, 2003). Figure 2.5 illustrates the nitrogen cycle in the environment and its effects on water quality.



**Figure 2.5: Nitrogen cycle and its effect on water resources**  
(Source: Rivett et al. (2008))

Nitrate ( $\text{NO}_3^-$ ) is a part of the nitrogen cycle. It is formed when bacteria decompose wastes containing organic nitrogen forming ammonia. Afterward ammonia is oxidized into nitrite ( $\text{NO}_2^-$ ) which in then easily oxidized to  $\text{NO}_3^-$ . Therefore,  $\text{NO}_3^-$  is always found in GW under oxidizing conditions. Because of its high mobility and solubility,  $\text{NO}_3^-$  is easily carried by water percolating through soil (Ramasamy et al., 2003; Almasri and Ghabayen, 2008; Majumder et al., 2008; Shomar et al., 2008).

GW contamination with  $\text{NO}_3^-$  is a worldwide problem and it is considered as the most frequent and common GW contaminant (McLay et al., 2001; Leone et al., 2009; Huang et al., 2011).  $\text{NO}_3^-$  is usually used as a GW contamination index (or



quality indicator) in various GW studies due to being the main contaminant associated with human activities (Panagopoulos et al., 2006).

#### **2.2.4.2 Mechanism of Groundwater Contamination with Nitrate**

$\text{NO}_3^-$  concentration at a specific location of the aquifer is a function of many interrelated and complicated variables and processes that occur on the ground surface as well as in both unsaturated and saturated zones. These variables include on-ground nitrogen loading (N-load) which is related to the quantity of nitrogen associated with each nitrogen source which is dependent on land use practice. Other influencing variables include soil characteristics, soil nitrogen dynamics, aquifer characteristics, GW recharge, as well as bacterial effects. Therefore,  $\text{NO}_3^-$  concentration in GW exhibits high spatial and temporal variability (Almasri and Kaluarachchi, 2005b; Almasri and Ghabayen, 2008; Kundu and Mandal, 2009).

$\text{NO}_3^-$  concentration in GW is affected by various variables that could be divided into three categories: (a) variables related to the on-ground nitrogen load (N-load), and its spatial distribution; (b) variables related to the unsaturated zone that govern soil nitrogen transformations; and (c) variables related to the aquifer itself and the processes occur through transport of  $\text{NO}_3^-$  with GW system (Almasri and Kaluarachchi, 2005a).

Estimation of the on-ground N-load is not an easy task, since it is characterized by both spatial and temporal variability (Almasri and Kaluarachchi, 2005a). The spatial variability is due to the changeability of land use categories from location to another, which consequently leads to different on-ground N-load. The temporal variability is related to the changeability of N-load over the time, such as variability of fertilizers and manures applications, and variability of precipitation and