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

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UNIVERSITI SAINS MALAYSIA

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By

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بسم الله الرحمن الرحيم

﴿ قُلْ إِنَّ صَلاَتِي وَنُسُكِي وَمَحْيَايَ وَمَمَاتِي لِلهِ رَبِّ الْعَالَمِينَ، لاَ 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

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LIST OF ABREVIATIONS

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_3	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 MENGGUNAKAN 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 (NO_3^-) dan klorida (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 NO_3^- model simulasi adalah 0.996 dan 7% masing-masing. Sementara itu, r dan MAPE bagi model simulasi 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 NO_3^- dan penumpuan Cl^- di GCA bagi tahun 2020 dan 2030. Penilaian air bawah tanah pilihan pengurusan kualiti menunjukkan bahawa min NO_3^- dan kepekatan 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 NO_3^- dan 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 (NO_3^-) and chloride (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 NO_3^- simulation model were 0.996 and 7% respectively. Meanwhile r and MAPE for 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 NO_3^- and Cl^- concentration in GCA for 2020 and 2030. Evaluation of GW quality management scenarios indicated that NO_3^- and 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. 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 Cl^- 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 (Alanbia'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 (NO_3^-) and chloride (Cl^-) are the main dominant water quality problems in GCA (Almasri and Ghabayen, 2008). The average concentration of 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 NO_3^- (Baalousha, 2008). The concentration of Cl^- in many locations of GCA exceeded 2000 mg/l. Furthermore, less than 5% of municipal water wells in GS meet WHO Cl^- standards of 250 mg/l. Overexploitation and lateral flow from adjacent eastern aquifer are the main sources of high 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 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 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 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).

NO_3^- contamination of GW is a serious worldwide problem, where high concentrations of 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 NO_3^- concentration in GW is of a great important especially for public health aspects. Regarding AI-based NO_3^- modelling, none of the earlier studies utilized SVM for estimating 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 NO_3^-; however all the few developed ANNs-based 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 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^- is usually used as a representative of GW salinity problems; and excessive concentration of Cl^- in drinking water is an indicator of the deterioration of its quality (Melloul and Collin, 2000; Abyaneh et al., 2005). Elevated concentration of Cl^- 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^- 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^- 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 NO_3^- and 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.

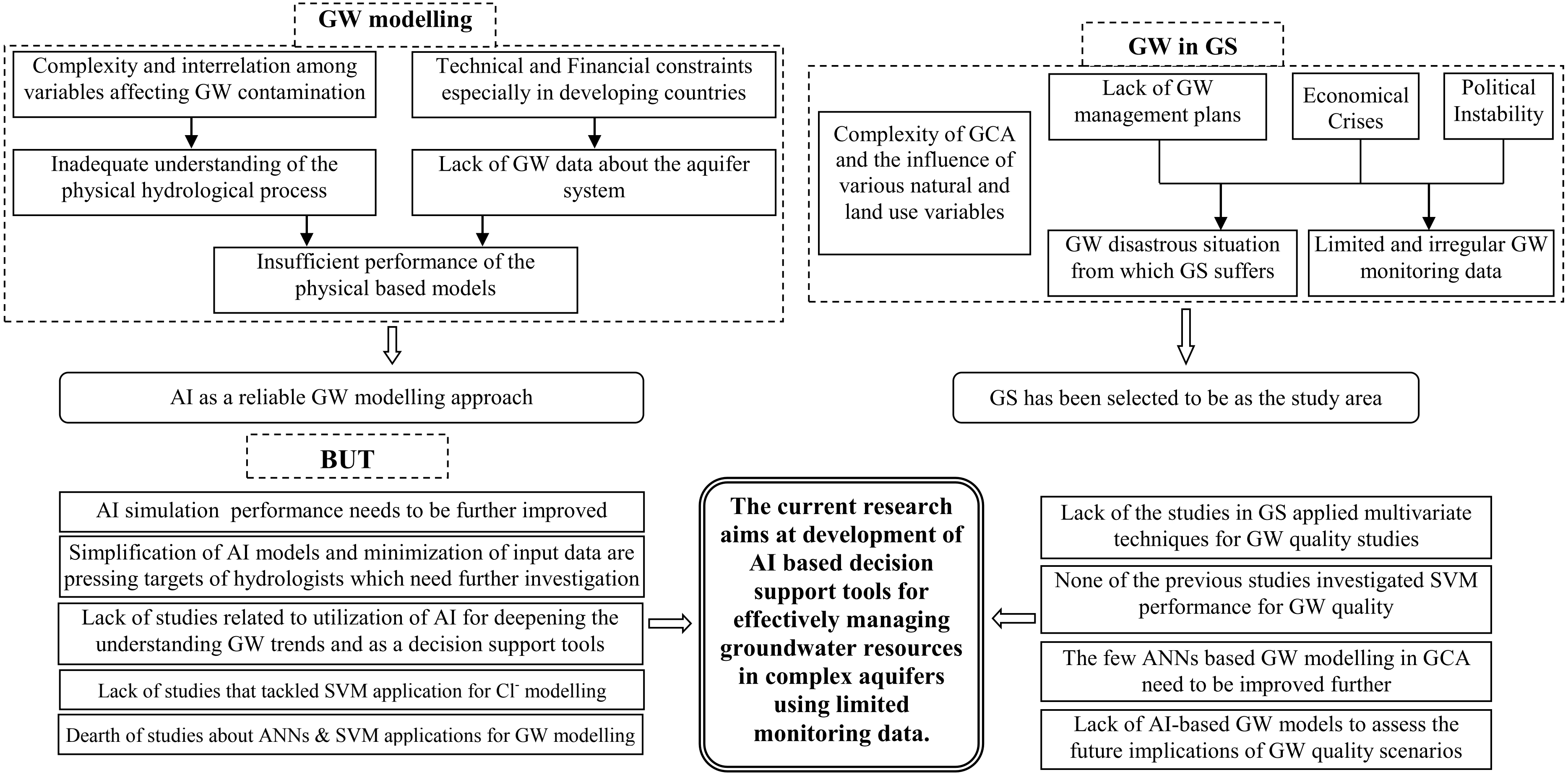

Figure 1.1: Research problem tree

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 NO_3^- and 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 NO_3^- and Cl^-.

1.4 Scope of the study

This study is concerned in modelling the concentration of both NO_3^- and 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^2). 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 NO_3^- and 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 NO_3^- and 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 NO_3^- and 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 (NO_3^-) and chloride (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).

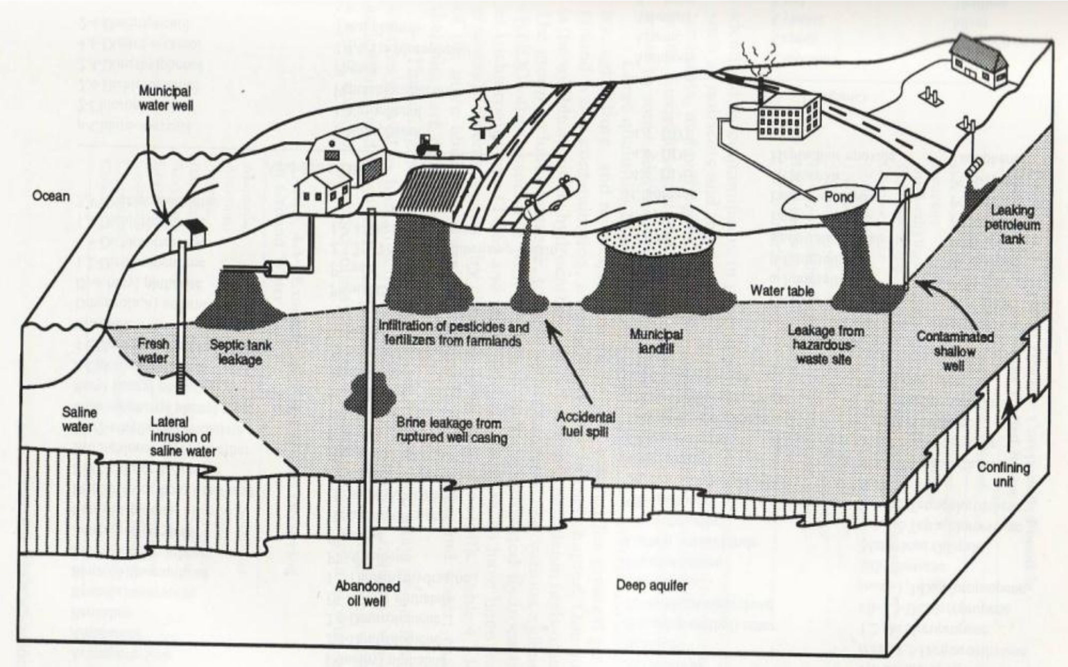

Figure 2.1: Potential sources of GW contamination (Source: Bedient et. al. (1994))

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_2 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).

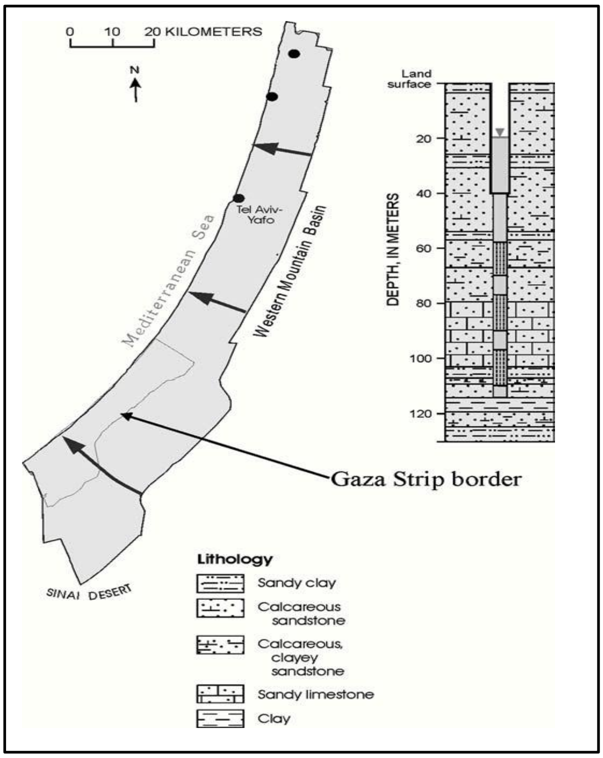

Figure 2.3: GCA basin and lithology
(Source: Baalousha (2006 b))

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.

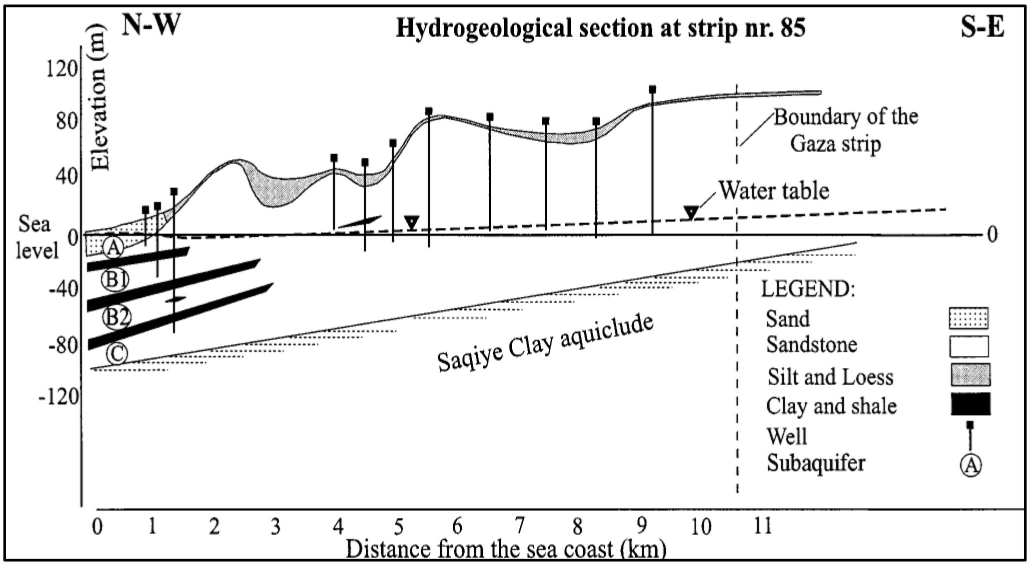

Figure 2.4: Typical cross section of GCA at Khanyounis governorate area (Source: Yakirevich et al. (1998))

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^3 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^3 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 NO_3^- and 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 million m^3**	**Item**	**Annual Quantity million 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		
Total	**110 – 130**	**Total**	**188 - 198**
Deficit	**58 – 88 MCM**		

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 NO_3^- and microbes. Likewise in agricultural areas, the intensive application of manures and fertilizers results in GW contamination with several contaminants notably 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 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_3	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_3^- and Cl^- 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_3^- and Cl^- 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_3^- and Cl^-) 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.

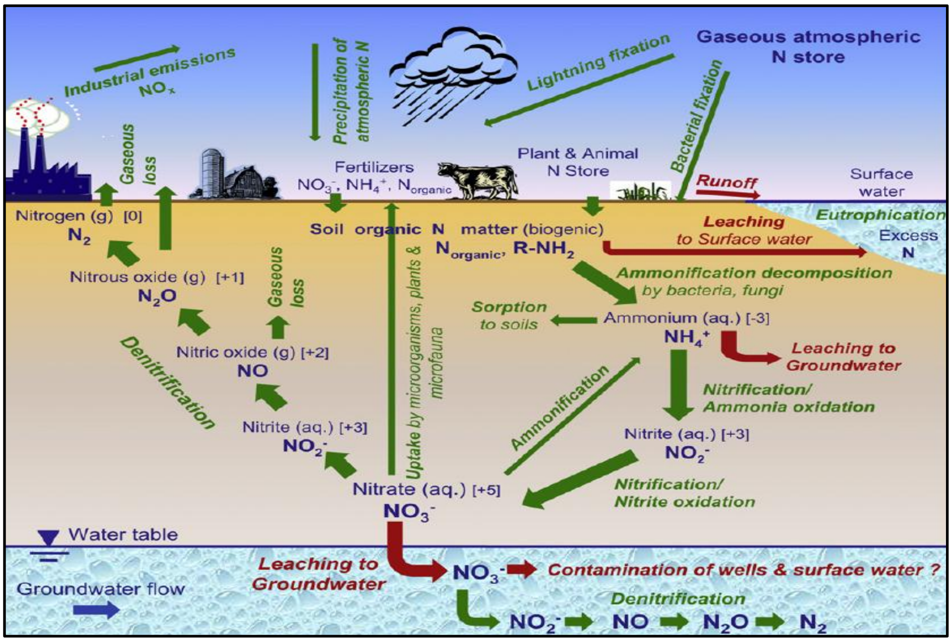

Figure 2.5: Nitrogen cycle and its effect on water resources

(Source: Rivett et al. (2008))

Nitrate (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 (NO_2^-) which in then easily oxidized to NO_3^-. Therefore, NO_3^- is always found in GW under oxidizing conditions. Because of its high mobility and solubility, 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 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). 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

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, NO_3^- concentration in GW exhibits high spatial and temporal variability (Almasri and Kaluarachchi, 2005b; Almasri and Ghabayen, 2008; Kundu and Mandal, 2009).

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 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