An-Najah National University
Faculty of Graduate Studies

MANAGEMENT OF NITRATE CONTAMINATION OF GROUNDWATER USING LUMPED PARAMETER MODELS

Prepared by
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Submitted in Partial Fulfillment of the Requirements for the Degree of Master in Water and Environmental Engineering, Faculty of Graduate studies, at An-Najah National University, Nablus, Palestine

2007

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Dedicated to

My Parents
My husband Sameer Al-Sheeb
My Kids: Yazan, Zeina, and Rama
My Brothers and Sisters.

Acknowledgments

First of all, praise be to Allah for helping me in making this thesis possible. I would like to express my sincere gratitude to Dr. Mohammad N. Almasri for his supervision, guidance and constructive advice. Special thanks also go to my defense committee.

Thanks go also to those who helped in providing the data used in this research, mainly Water and Environmental Studies Institute (WESI). Special thanks go to Dr. Said Ghabayen from Gaza municipality for producing of many data used in this study.

Thanks to my dear husband Sameer and my children for their love, patience and support.

My parents, brothers and sisters, thank you for being a great source of support and encouragement. All my fellow graduate students, thank you.

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Abstract

Many regions all over the world depend entirely on groundwater resources for various uses. Nitrate contamination of ground water can cause methemoglobinemia. Evidence indicates that nitrate levels routinely exceeded the maximum contamination level (MCL) of 10 mg/L NO_3-N in 90 percent of the water supply wells in the Gaza costal aquifer (GCA). In addition, elevated nitrate concentrations are encountered in Gaza city and Jabalia camp (GCJC). In order to simulate the occurrences of nitrate contamination in GCJC area, a single-cell model was developed. This model was employed to study different management options and to determine their efficiency in decreasing the nitrate contamination in the study area for a specified time horizon. Main findings of the research showed that there is an emerging need to manage the nitrate contamination problem in the groundwater of the study area and single management options are not effective when considered individually. As such, the combination of management options ought to be considered if nitrate concentration to drop below the MCL.

CHAPTER 1

INTRODUCTION

1.1 General

Many regions all over the world depend entirely on groundwater resources for various uses (Babiker et al., 2003). Population growth and the increase in demand for water and food supplies place an increasing stress on the groundwater quality and quantity (Joosten et al., 1998). Over-abstraction of freshwater depletes the available quantity of groundwater. In addition, the increase in demand for food supplies may lead to groundwater contamination by nitrate since the major contributor to nitrate contamination in groundwater is the use of fertilizers associated with cropping activities (Konkow and Person 1985; Shamrukh et al., 2001). Gaza Coastal Aquifer (GCA) witnesses both quantity and quality problems due respectively to the overexploitation, excessive fertilization and raw wastewater leaching (Rosen et al., 1998; Refsgaard et al., 1999).

GCA is an important source of water to over 1.4 million residents in Gaza Strip and is utilized extensively to satisfy agricultural, domestic, and industrial water demands (UNEP, 2003). Pollution of the groundwater in GCA is a major problem. Evidence indicates that nitrate levels routinely exceeded the MCL of 10 mg/L NO_3-N in 90 percent of the water supply wells in the GCA (Almasri et al., 2005). Of the sources responsible for the elevated nitrate concentrations in GCA are the agricultural activities including the use of fertilizers, waste dumping, discharge of raw sewage, and irrigation with water contaminated by nitrate.

GCA and the overlying soil are composed mainly of sands which indeed promote the vulnerability of GCA to contamination through the high potential of nitrate leaching to groundwater. Since GCA is the main source of water for the residents of Gaza Strip, nitrate contamination of the aquifer is a public-health concern. A recent survey curried by the Ministry of Health shows that 124 of 640 infants (children under the age of 6 months) have methemglobin levels above 20 percent. The average concentration of nitrate in GCA is three times higher than the MCL.

The degradation of groundwater quality in the GCA has stepped up public concern in recent years and has motivated the restoration and preservation of the aquifer especially when considering that most municipalities in Gaza Strip use groundwater without any treatment except for disinfection. To address the water-quality related issues and problems, the Palestinian Water Authority (PWA) in collaboration with the Environmental Quality Authority (EQA) has developed the first National Water Plan and the National Environmental Action Plan in part to better manage and preserve the water resources including groundwater and to set up policies and strategies that aim at protecting the Palestinian water resources. Such policies demand that the agricultural and industrial development to be in full compliance with the available water resources based on sustainable development and that pollution control measures should be introduced and ensured through enforcement if needed.

As such, restoration efforts have intensified the need for developing protection alternative measures and management options such that the high contamination occurrences in the aquifer are reduced. That is, nitrate concentrations at the critical receptors are below the MCL. Such measures include the restriction on the use of fertilizers and the proper treatment and disposal of wastewater. A major step in proposing and developing efficient protection alternatives is through the development of a mathematical model for the simulation of nitrate occurrences in the aquifer. In other words, we need to adopt a nitrate contamination management scheme that aims at minimizing nitrate concentration in groundwater such that the outcome of these management options is quantified using mathematical models.

This research focuses on the analysis and modeling of nitrate contamination in the groundwater of Gaza City and Jabalia Camp (GCJC). The GCJC area is part of the Gaza Coastal Aquifer. The different components of the model will be elucidated and discussed.

Thereafter, the model output for different proposed management options will be analyzed and presented. As part of the research work, the extent of nitrate contamination in the GCJC area will be analyzed spatially using ArcView geographic information systems (GIS) (Lasserce et al., 1999).

1.2 Justifications for the Selection of the Study Area

Many reasons compelled the motivation to select GCJC as a study area. Among these reasons are the following:

1. GCJC has a large intensity of population where over half a million people live in it;
2. Groundwater contamination by nitrate is an on-going problem in GCJC;
3. A total of 39 municipal wells operate in GCJC for water supply;

4. The problem of nitrate pollution is attributed to internal and external sources. This indeed offers a good and realistic case for the management of groundwater contamination from nitrate;
5. GCJC suites the development of a lumped parameter model which was developed in this research to study the overall nitrate concentration due to current and future practices; and
6. Data availability for the selected study area.

Jabalia Camp was taken in this research work with Gaza City since the water supply system is the same for both areas and the two areas are undergoing elevated nitrate concentration problem.

1.3 Research Question

What would be the future overall nitrate concentration in GCJC due to current practices and potential management options?

1.4 Research Objectives

The objectives of this research are the following:

1. To characterize and analyze nitrate occurrences in the groundwater of GCJC area;
2. To identify and quantify the probable sources of nitrate contamination in the groundwater of GCJC area;
3. To assess nitrate concentration in the groundwater of GCJC due to the adoption of protection measures. This specific objective entails the development of a mathematical model; and
4. To set up recommendations for efficient management options that can lead to aquifer recovery from nitrate pollution.

1.5 Research Outcome

The following summarizes the research outcome:

1. Improve public awareness. Residents of GCJC area will gain an appreciation to the extent of the problem of nitrate contamination of groundwater;
2. Aid the decision makers. The developed mathematical model will definitely facilitate the decision making process in relation to the minimization of nitrate concentration in the groundwater of GCJC area;
3. Generalization. It is quite straightforward to generalize the application described

herein to the aquifers of the West Bank; and

4. New insights. This research furnishes new insights and solutions to groundwater resources problems that involve nitrate contamination. In other words, this research is a contribution toward an efficient management of the Palestinian water resources.

1.6 Research Output

The following summarizes the research output:

1. Analysis of the temporal distributions of nitrate concentration in the groundwater of GCJC area;
2. A groundwater mathematical model of nitrate concentration in GCJC area;
3. A set of recommended and verified management options to minimize groundwater nitrate contamination of GCJC area.

1.7 Thesis Organization

The general structure of the thesis is as follows. Chapter II describes the study area. Chapter III provides related literature review and general background. Chapter IV demonstrates the general methodology. In chapter V, model development is elucidated. Chapter VI furnishes analyses and discussions regarding model output. In Chapter VII, preliminary management options are demonstrated and their efficiencies are assessed. Conclusions and recommendations are provided in Chapter VIII.

CHAPTER 2
DESCRIPTION OF THE STUDY AREA

2.1 Introduction

The GCJC area is located in the north side of Gaza Strip, which is a narrow, low-lying stretch of sand dunes along eastern Mediterranean Sea. It forms the foreshore that slopes gently up to elevation of 105 m above main sea level (masl). Figure (1 depicts the regional setting of Gaza Strip and the surrounding countries. Figure (2 shows the location of the study area. Over 1.4 million Palestinians live in Gaza Strip; about one third of that lives in GCJC. The total area of GCJC is (58) km^2.

Figure 3 depicts different features of the GCJC area.

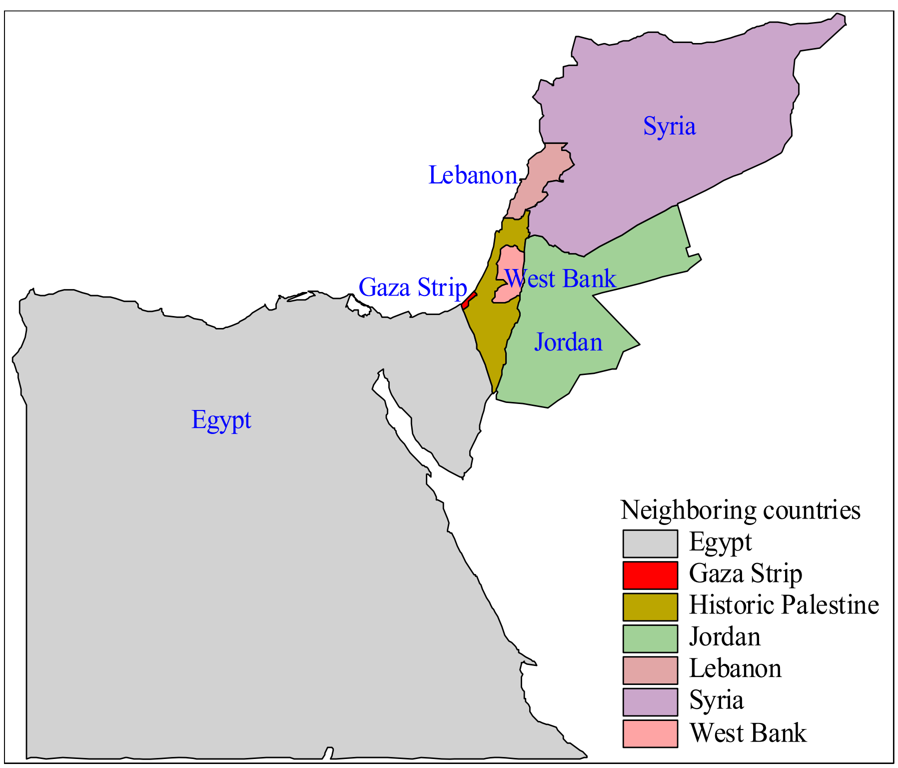


Figure (1): Regional setting of Gaza Strip and the neighboring countries.

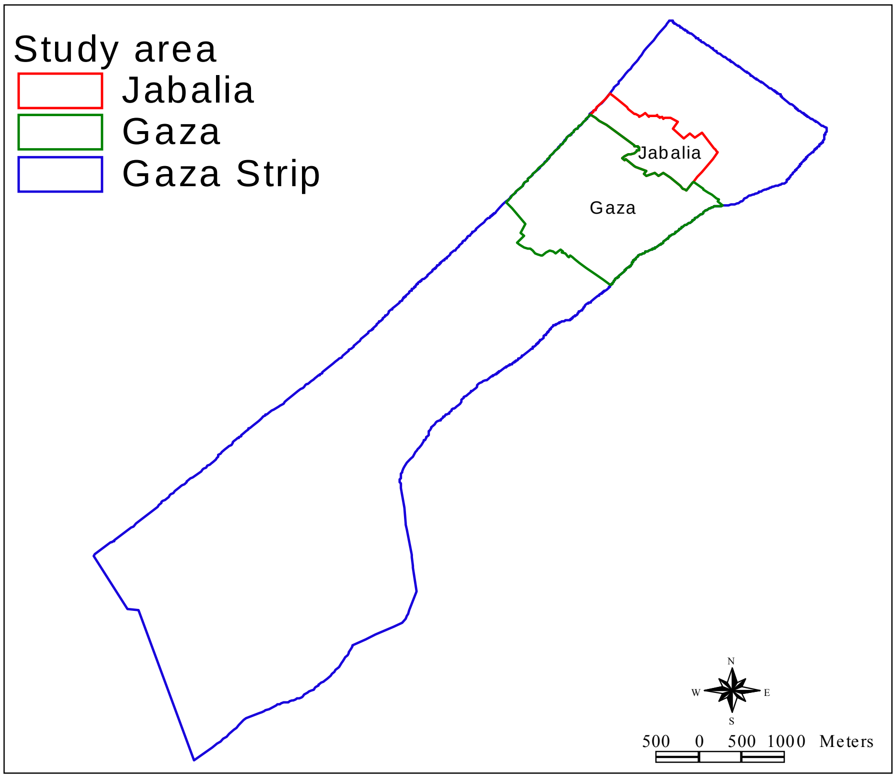


Figure (2): The location of GCJC area within Gaza Strip.

2.2 Topography

The topography of the study area is characterized by elongated ridges and depressions, dry streambeds and shifting sand dunes. The ridges and depressions generally extend parallel to the coastline. The height of the land surface increases from west to east. The lowest height of the study area is zero which increases eastward gradually to 70-75 masl.

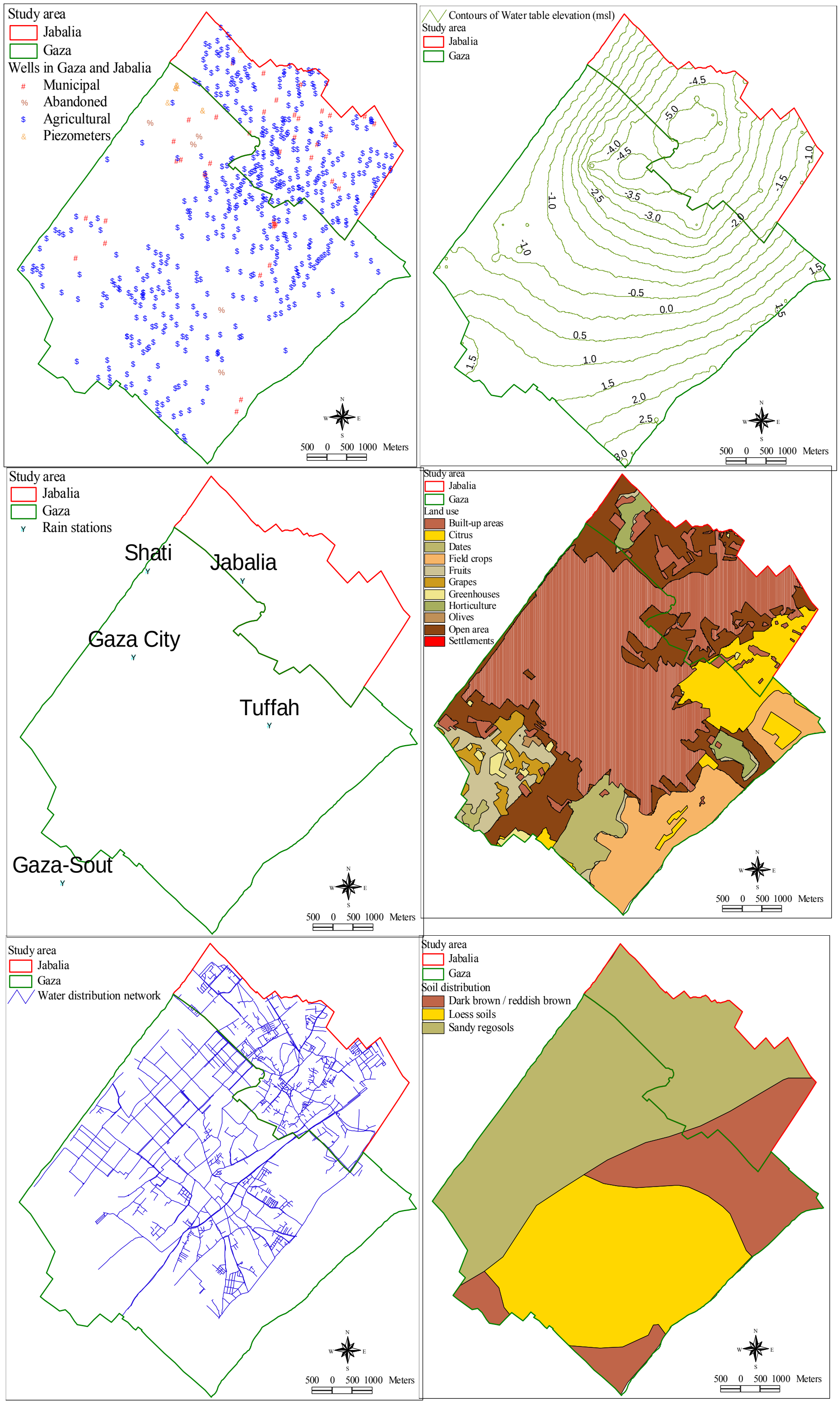


Figure (3): Different information categories for the GCJC area.

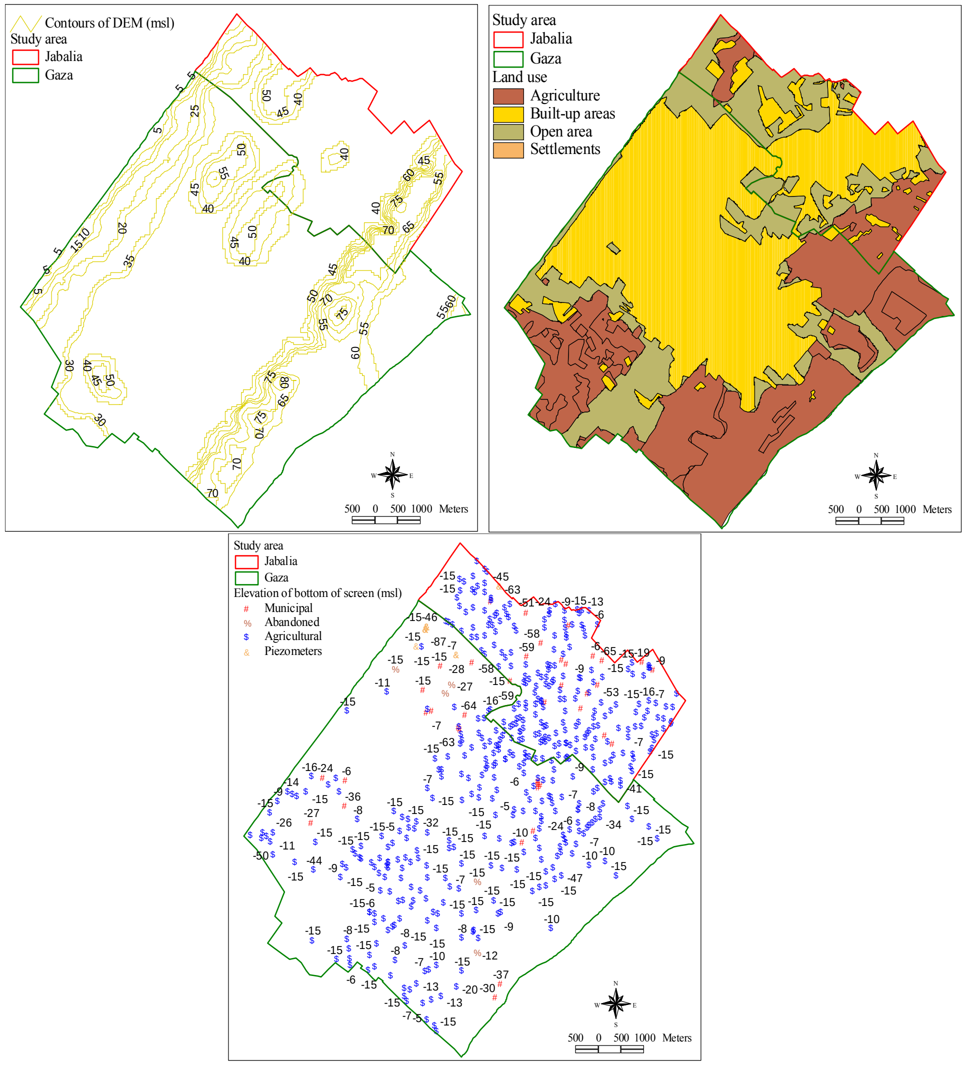


Figure (3): Continue

2.3 Climate

The Gaza Strip has a characteristically semi-arid climate. There are two well-defined seasons: the wet season starting in October and extending through March, and the dry season from April to September. Peak months for rainfall are December and January. The average mean daily temperature in Gaza Strip ranges from 25°C in summer to 13°C in winter. The annual average relative humidity is about 72 percent. Evaporation is high in summer when there is always a water deficit. Winds prevail from the northwest but come from the southwest in winter.

2.4 Rainfall Distribution

There are five rainfall stations in the study area and these are: Gaza City, Southern Gaza, Tuffah, Shati, and Jabalia. For efficient creation of Thiessen polygons (to be used later in model development), additional rainfall stations were considered that are located outside the study area. Rainfall data for these rainfall stations for the period from 2000 to 2004 are listed in Table (1).

Table (1): Annual rainfall data (in mm) for the relevant rainfall stations for the years from 2000 to 2004.

Name	2000	2001	2002	2003	2004
Beit Hanon	406	498	548	802	357
Beit Lahia	391	490	542	724	397
As-shati	425	479	522	627	343
Gaza City	335	512	544	599	385
Southern Gaza	368	564	661	791	503
Jabalia	389	540	566	693	374
At-tuffah	357	533	604	654	432

2.5 Land Use

A land use map of the GCJC area is shown in Figure 3. The breakdown of land use by category is summarized in Table (2) and Table (3). Agricultural land occupies about 34% of the land surface and is the dominant economic sector in the study area. Built-up areas occupy 45% while almost 21% of the land is characterized as open area.

Table (2): Detailed categories of land use for the study area. This table is based on the land use map of the entire Gaza Strip as obtained from the PWA and later processed using GIS capabilities for the GCJC area.

Land Use Category	**Area (km^2)**	**%**
Built-up areas	26.27	45
Citrus	5.24	9
Dates	2.60	4
Field crops	6.42	11
Fruits	2.86	5
Grapes	1.26	2
Greenhouses	0.51	1
Horticulture	1.08	2
Olives	0.09	0
Open area	12.21	21
Settlements	0.001	0

Table (3): Lumped categories of land use practices for the study area.

General	**Area (km^2)**
Agriculture	20.05
Built-up	26.27
Open area	12.21
Settlements	0.001

2.6 Soil Types

In the study area, there are three types of soil and these are: dark brown/ reddish brown, loess soils, and sandy regosols. Table (4) summarizes the different soil types that exist in the GCJC area along with the total area for each type. As can be inferred from Table (4), sandy regosols type covers about 47% of the surface area followed by loess soils of approximately 21% of the surface area.

Table (4): Classification of the soil types for the study area and the corresponding area. This table is based on the soil map of the entire Gaza Strip as obtained from the PWA and later processed using GIS capabilities for the GCJC area.

Soil Type	Area (km^2)
Dark brown/ reddish brown	12.45
Loess soils	18.48
Sandy regosols	27.82

2.7 Water Resources

There are an estimated 534 wells within the GCJC area (see Figure 3). The majority of these wells are privately owned and used for agricultural purposes. A total of 39 wells are owned and operated by municipalities and are used for domestic supply. The distribution of these wells is depicted in Figure (3). Agricultural wells are mostly drilled and installed as large diameter boreholes. Most agricultural wells in GCJC are shallow and extend only a few meters (5-10) below the water table. Municipal wells are deeper depending on location and distance from the coast.

2.8 Nitrate Pollution in the Groundwater of GCJC

Pollution of the groundwater of GCJC area is a major problem. There are many sources of pollution and the aquifer is highly vulnerable to pollution. Many years of over-pumping have resulted in seawater intrusion and upcoming of saline groundwater. Furthermore, human activities including agriculture and inadequate waste management have increased groundwater contamination levels. Intensive cultivation and efforts to boost production have led to excessive use of fertilizers, pesticides, herbicides and soil fumigants, while collection, treatment and disposal of wastewater and solid waste (including hazardous materials) are wholly inadequate in many areas (see Figure 4 and Figure 5).

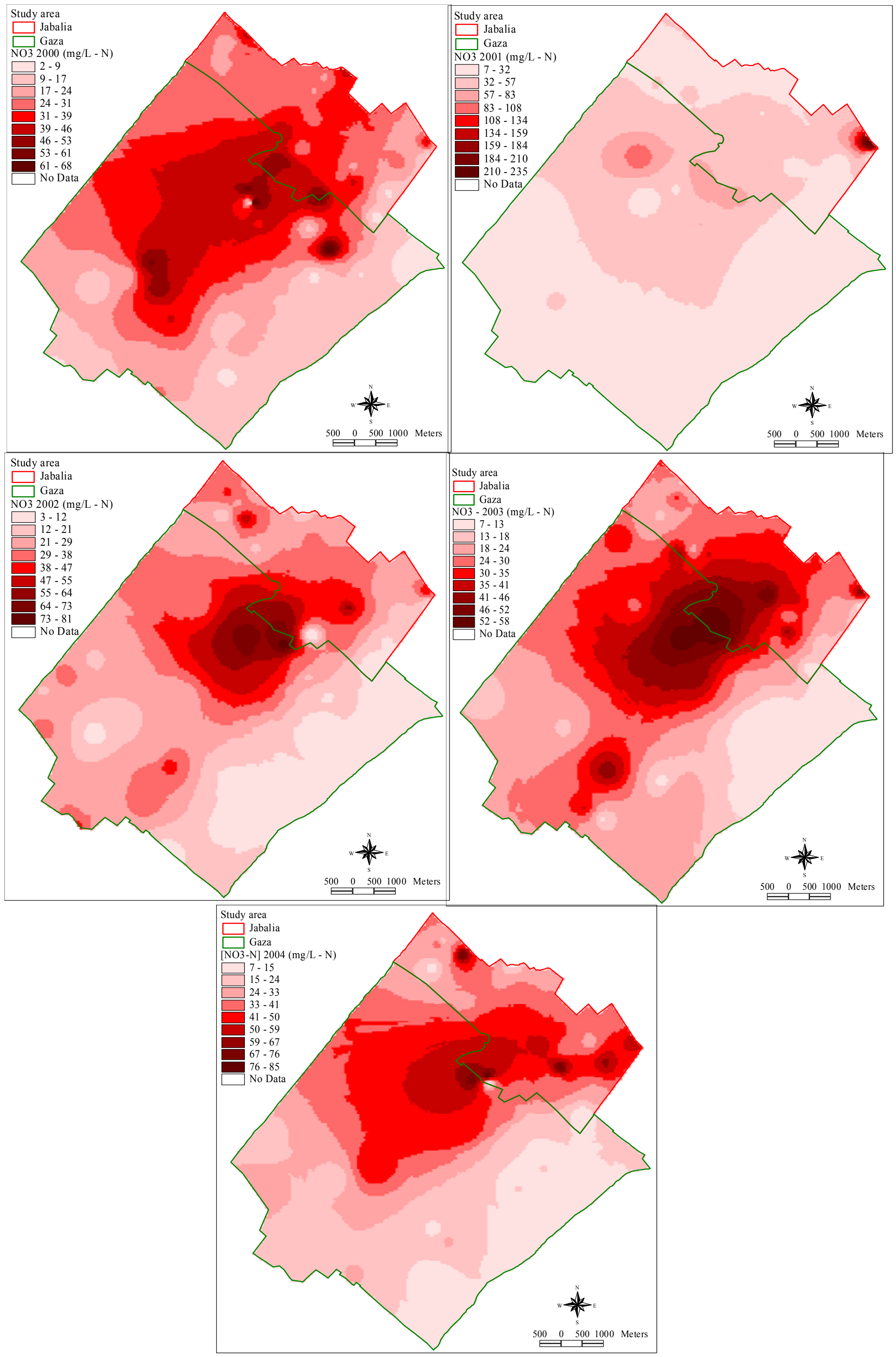


Figure (4): Average nitrate concentration in the study area for the years from 2000 to 2004. (Source: Database of PWA)

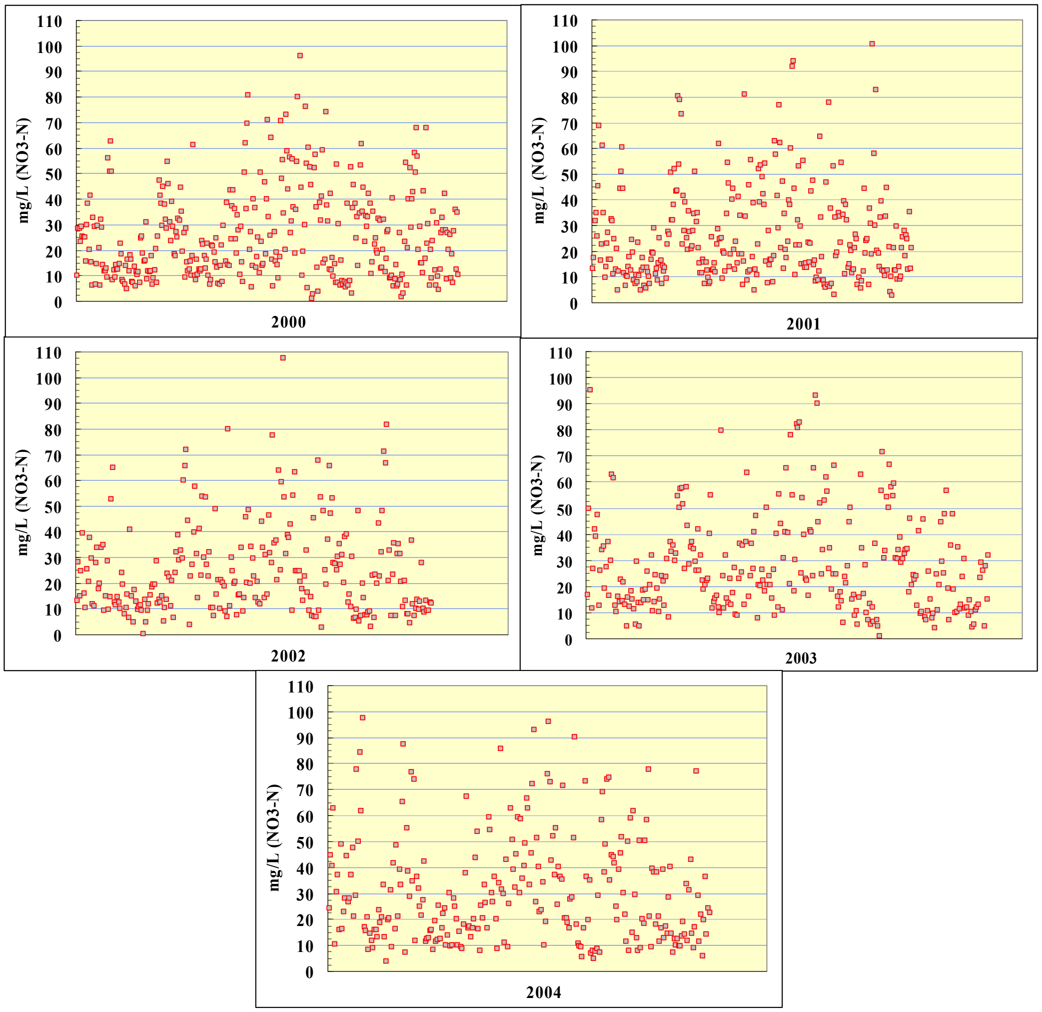


Figure (5): Nitrate concentrations for different wells in the study area for the years from 2000 to 2004.

2.9 Geology

The aquifer of the GCJC consists of the Pleistocene age Kurkar Group (Gvirtzman, 1969) and recent (Holocene age) sand dunes. The Kurkar Group consists of marine and aeolian calcareous sandstone, reddish silty sandstone (‘hamra’), silts, clays, unconsolidated sands, and conglomerates.

Regionally, the Kurkar Group is distributed in a belt parallel to the coastline, from north of Haifa to the Sina in the south. Near the Gaza Strip, the belt extends about 15-20 km inland, where it unconformably overlies Eocene age chalks and limestones (the “Eocene”), or the Miocene-Pliocene age Saqiye Group, a 400-1000 meter thick sequence of marls, marine shales, and claystones. The transition from the Kurkar Group to the Saqiye Group is sometimes obscured by the presence of a thin, basal conglomerate. Figure (6) presents a generalized geological cross section of GCA.

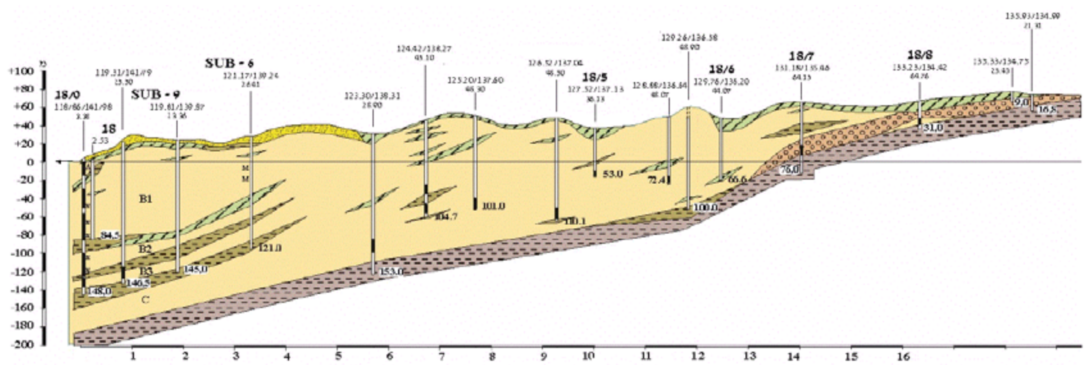
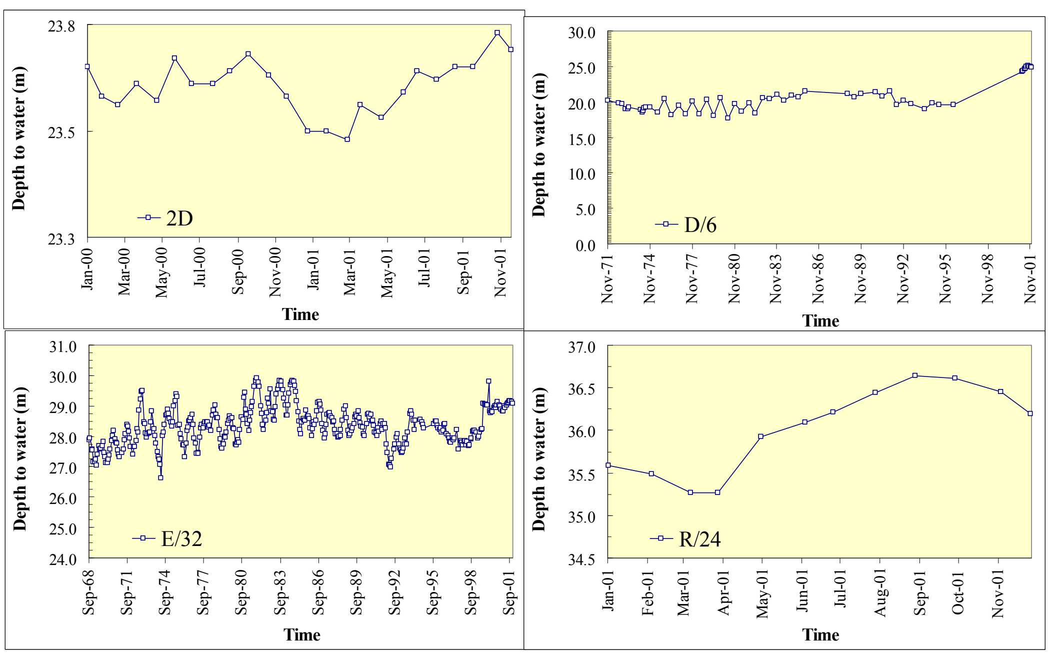


Figure (6): A general cross section of GCA. (Metcalf and Eddy, 2000)

Clay formations or units within Gaza, and the coastal aquifer in general, are of two types: marine and fluvial. Marine clays are present along the coast, at various depths within the formation. They pinch out about 5 km from present coastline, and based on existing data, appear to become more important towards the base of the Kurkar Group. Three major clay layers extend inland about 2 to 5 km, depending on location and depth. GCA is composed of sands, calcareous sandstone and pebbles. Semi-per-meable and impermeable layers are sandwiched in between, dividing the system into sub-aquifers. This subdivision is especially developed in the western part of the coastal plain, water level and quality. Further inland, the sub-aquifers effectively merge to form on system. All along the coast, there are areas of seawater intrusion due to over-pumping of the freshwater aquifer.

2.10 Water Table Elevation

In order to spell out the variability of water table elevation with time in GCJC, selected time series were prepared from the available data and plotted accordingly as can bee seen from Figure (7). However and in order to arrive at meaningful impressions, depth to water table instead was computed and presented.



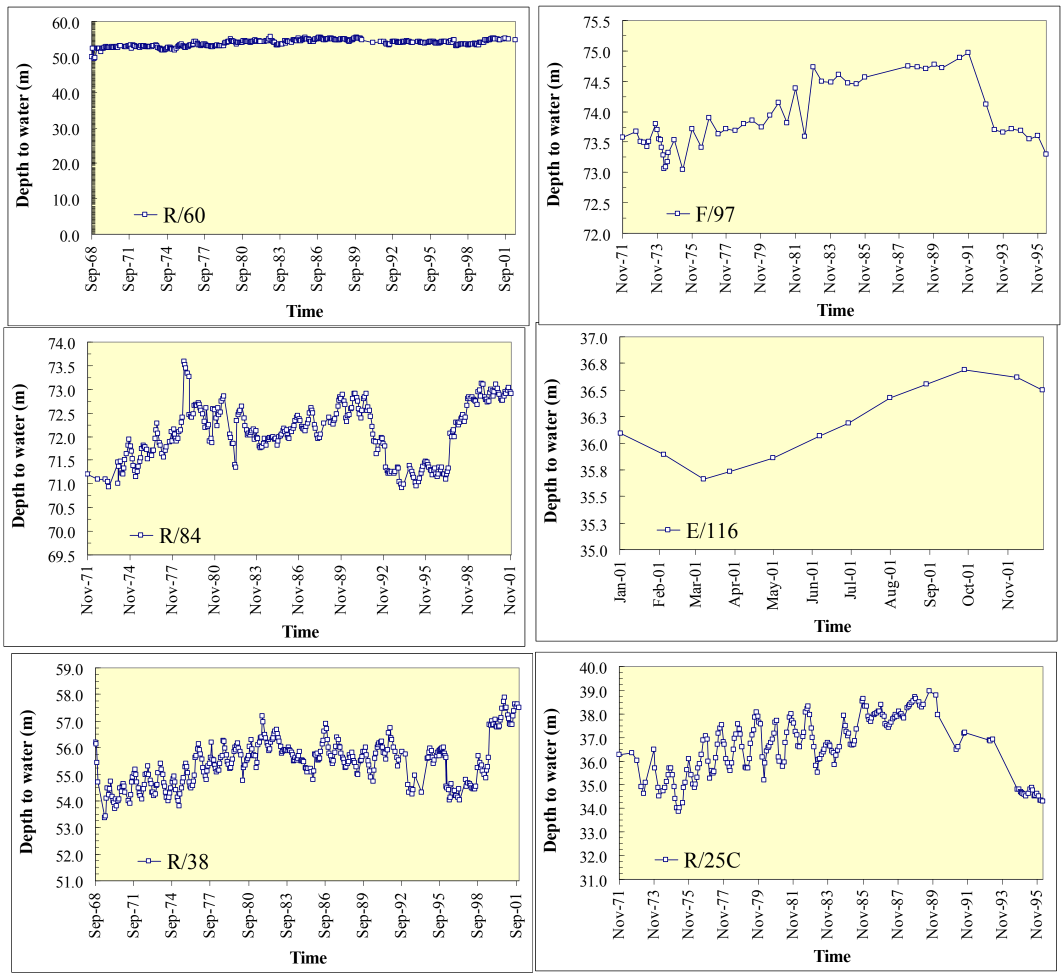


Figure (7): Time series of depth to water table for selected wells in the GCJC area. (Source: Database of PWA)

CHAPTER 3

LITERATURE REVIEW AND GENERAL BACKGROUND

This chapter provides information about nitrate contamination of groundwater, health problems associated with nitrate contamination, management of nitrate contamination of groundwater, and about the groundwater model.

3.1 Nitrate Contamination of Groundwater

Nitrogen (N) exists in the soil as nitrite (NO_2), nitrate (NO_3^-), ammonium (NH_4^+), ammonia (NH_3), and organic-nitrogen (organic-N). Ammonium is easily adsorbed on to the soil particles. Nitrate is the primary nitrogen species lost from soils by leaching due to its high mobility (Almasri and Kaluarachchi, 2004).

Nitrate in water is present as a highly soluble salt. Standard water treatment practices do not affect nitrate concentrations in water (Bhumble, 1999; Mourabit et al., 2002). Nitrates from water can be removed by specialized water treatment technologies, which increase the cost of water treatment. Nitrate contamination of groundwater depends upon climate, fertilizer or manure management, soil, crop, and farming systems. A climate with rainfall exceeding evapotranspiration often leads to the infiltration of rainwater to groundwater. A portion of the water received through precipitation becomes surface runoff and is lost from the land to rivers or streams. When water moves on the surface of a soil, it dissolves some nitrates that are present in the surface layers of soils which may cause contamination to surface water. Another portion of the precipitation seeps into the soil and recharges the groundwater. This seeping water dissolves soil nitrates. Any excess nitrates that are present in this groundwater-recharge zone will leach down to the groundwater and contaminate the aquifer (Bhumble, 1999).

Nitrate is a world-wide problem which contaminates both soil and groundwater (Mitchell et al., 2003; Kraft and Stites, 2003; Liu et al., 2004). The US Environmental Protection Agency (US EPA) has established a maximum contaminant level (MCL) of 10 mg/L NO_3-N (US EPA, 1995). Contaminated water by nitrate may cause methemoglobinemia in infants and stomach cancer in adults (Wolfe and Patz, 2002). Nitrate may indicate the presence of bacteria, viruses, and protozoa in groundwater if the source of nitrate is animal waste or effluent from septic tanks (Almasri and Kaluarachchi, 2004).

Nitrogen applied through organic fertilizers or manure is converted to plant-available-nitrate by bacteria living in the soil. The growing plants uptake part of this nitrate. The growing bacteria also utilize nitrates. When sufficient decomposable organic matter is present, soil bacteria can remove a significant amount of nitrate through a process called immobilization. Another group of bacteria uses nitrates as a substitute for oxygen when oxygen is limited. These bacteria convert nitrate to gases such as nitrogen, nitrous oxide, and nitrogen dioxide. This is known as denitrification. Nitrate not taken up by crops or immobilized by bacteria into soil organic matter or converted to atmospheric gases by denitrification can leach from the root zone and possibly end up in groundwater (Bhumble, 1999). Figure (8) depicts a representation of the surface and subsurface activities related to nitrate application and leaching.

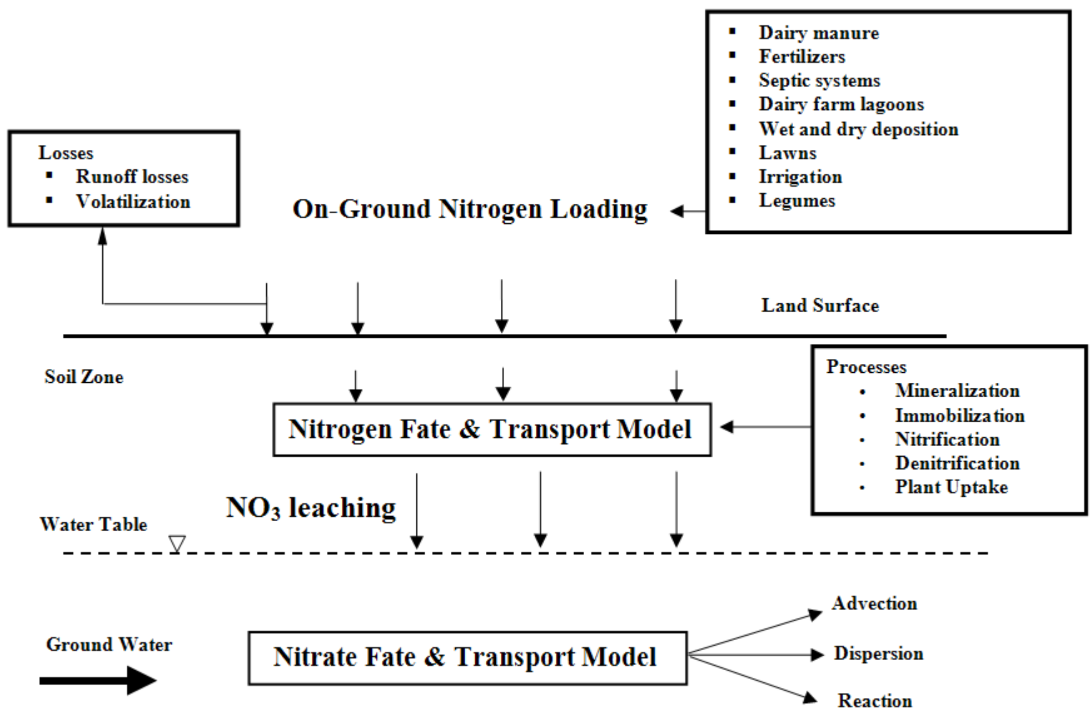


Figure (8): A schematic describing the proposed conceptual model of nitrogen loading and transformations.

Among the many influencing factors, nitrate leaching from fertilizer use depends upon the fertilizer types, method of application, and climatic conditions. Nitrate leaching may be greater when a fertilizer contains the nitrate compared to the situations where ammoniacal nitrogen is the major component of a nitrogen-based fertilizer. Nitrate losses are likely to be more when all the nitrogen is applied in one application compared to split applications.

Nitrogen fertilizers or manure used on a sandy soil are more vulnerable to leaching to groundwater than nitrogen used on a clay soil. Water moves rapidly through sandy or other coarse-textured soils (Kraft and Stites, 2003; Babiker et al., 2003). The negative charge on the clay particles retains ammonium ions. This retention prevents them from leaching. Nitrate ions are negatively charged and are not retained by clay particles. More nitrates are lost by denitrification in clay soils than in sandy soils due to the low presence of oxygen in the clay soils as compared to sandy soils. (Stournaras, 1998; Bhumble, 1999; Rodvang et al., 2002).

Soil thickness and distance between the root zone and groundwater also determine the vulnerability of an aquifer to pollution (see Figure 8). Nitrate leaching from shallow soils on fractured rocks such as limestone can cause extensive contamination of groundwater. Storage of manure in open fields with no protection from rain, direct discharge of manure overflow water to a stream, or leaking manure lagoons can all contribute to nitrate pollution of surface and groundwater (Bhumble, 1999; Liu et al., 2004).

To estimate nitrate leaching, many approaches have been used. Some studies assumed a specific fraction of the on-ground nitrogen loading to leach as nitrate. Others have used soil nitrogen models to simulate the nitrogen dynamics in the soil. A few studies conducted simple yet efficient nitrogen mass balance calculations to estimate the nitrate leaching to groundwater (Meisinger and Randall, 1988). In general, accurate estimates of nitrate leaching are obtained when soil transformation models and nitrogen mass balance calculations are utilized.

Once it is established that contamination of groundwater has occurred, management actions must be considered to restore the aquifer. Such actions may imply the identification of areas that witness the contamination, characterization of sources responsible for contamination, development of alternative measures and options to restore the quality of the affected groundwater.

Al-Agha (2004) showed in his study different environmental problems in Gaza Strip and he discussed approaches, measures and steps for an environmental management and legislation plan. Shomar (2006) showed that NO3-, Cl- and F- exceeded 2 to 9 times the World Health Organization (WHO) standards in 90% of the wells tested with maximum concentrations of 450; 3,000; and 1.6 mg/L, respectively. Abu Maila, El-Nahal, and Al-Agha (2004) investigated the seasonal variation in nitrate concentration to understand the mechanisms and parameters controlling this pollutants.

3.2 Health Problems Associated with Nitrate Contamination

Nitrate contamination of fresh water can cause methemoglobinemia; a blood disorder to which infants are particularly susceptible. The risk comes from the reduction of NO_3 to NO_2, a process which occurs naturally in human saliva and in gastric fluid of infants. When NO_2 is present, the blood compound hemoglobin is converted to methemoglobin, which cannot carry oxygen. In the blood of normal adults, enzymes convert the methemoglobin back to hemoglobin, but newborn infants and adults taking certain medications or with certain diseases do not have enough enzymes to make this reconversion.

Symptoms of methemoglobinemia are bluish mucous membranes and digestive and respiratory problems. If the condition is severe, brain damage or death can result. In less severe cases or if diagnosed early, the condition can be reversed. (University of Wisconsin Extension, 1983; USEPA, 1985b; Wolfe and Patz, 2002).

Nitrites and nitrates have been linked to cancer, but the evidence thus far is inconclusive.
The US federal drinking water standard MCL for NO_3 is 10 mg/L of NO_3-N. It may also be expressed as 45 mg/L NO_3. The drinking water standard is based on the risk of methemoglobinemia to infants, the group at highest risk to this condition (USEPA, 1989).

Nitrate is not just a problem for human health; domestic animals may also be adversely affected by high NO_3 in water. Many plants and feeds are naturally high in NO_3. If groundwater well is contaminated with NO_3 and used to feed animals, NO_3 poisoning is possible, particularly in ruminants such as cows or sheep. The University of Wisconsin suggests that NO_3 levels above 40 mg/L in NO_3 are risky for livestock, and water with more than 100 mg/L NO_3 should not be used for livestock watering (University of Wisconsin Extension, 1983).

3.3 General Sources of Nitrate Contamination in Groundwater

Sources of groundwater contamination by nitrate can be classified into point and non-point sources. Non-point sources such as fertilizer, dairy farms, manure application, leguminous crops, dissolved nitrogen in precipitation, irrigation return-flows, and dry deposition are considered the common non-point sources of nitrate. Point sources of nitrogen such as septic systems and cesspits can be major sources of nitrate pollution (Joosten et al., 1998; Stournaras, 1998; Rodvang et al., 2002; Mitchell et al., 2003; Babiker et al., 2003). Septic tanks produce significant amount of nitrogen that leaches to the groundwater when there are no sewer systems.

3.4 Management of Nitrate Contamination of Groundwater

In general, management alternatives for groundwater quality protection are practices designed to prevent further pollution or reduce the existing occurrences of pollution to acceptable levels (Almasri and Kaluarachchi, 2004). The agricultural best management practices to minimize NO_3 inputs to groundwater encompass a broad and diverse area of crop and soil management options as well as socio-economic and possibly regulatory activities (Moore, 1979; Bear et al., 1992; Broeke and Putten, 1997).

The guiding principle is to minimize the amount of NO_3 in the rooting zone, especially during periods when leaching is likely to occur. This could involve multiple fertilizer applications; use of cover crops or deep-rooted crops; genetic selection to improve crop N-use efficiency; chemical additives that inhibit the rate of nitrification; slow-release of inorganic or organic fertilizers; the careful management of irrigation to minimize leaching; and inclusion of available N from NO_3 in the rooting zone and N mineralized from organic matter, manure, and crop residues in N fertilizer recommendations. Considerable refinement of N-fertilizer recommendations, taking into account such factors as weather, N cycle, and level of management, is needed (Hasler, 1998; McLay et al., 2001; Oenema et al., 2004).

Other solutions may be required in extreme cases. These could include land-use zoning to lower the density of cropland in, a tax, or legal restrictions on fertilizer use (Keeney and Follett, 1991; Meisinger and Delgado, 2002).

Improvements in irrigation water-use efficiency with new irrigation technologies and water needs forecasting can be expected as water costs rise. These approaches will also greatly improve N-use efficiency by lessening the amount NO_3 leached (Zhangand and Jorgasen, 2004). Animal operations require special management of wastes to minimize NO_3 pollution. These include proper management of feedlots to minimize nitrification, leaching, and application of the wastes to cropland at rates based on agronomic principles, including N needs of the crop (Anderson, 1978).

It is critical to use system analysis to develop nitrate BMPs. Nitrogen-fertilizer recommendations using soil-plant mass balances (Meisinger, 1984) should aid greatly in lowering fertilizer use and environmental consequences of over fertilization without lowering greatly the economic returns. Developing these models requires multidisciplinary teams (Keeney and Follett, 1991).

3.5 Groundwater Modeling

3.5.1 Introduction

Knowing and expecting the behavior of groundwater systems is not easy. Solutions of complex groundwater problems must involve formulating a correct conceptual model, selecting parameter values to describe spatial variability within the groundwater flow system, as well as spatial and temporal trends and past and future trends in water levels. Although some decisions can be made using best engineering judgment, in many instances human reasoning alone is inadequate to synthesize the conglomeration of

factors involved in analyzing complex groundwater problems. The best tool available to help groundwater hydrologists meet the challenge of prediction is usually a *groundwater model*.

3.5.2 Model Definition

A Model can be defined as a simplified version of a real world system that approximately simulates the relevant excitation – response relations of the real–world system (Bear et al., 1992). Others define model as any tool that represents an approximation of a field situation.

A *mathematical* model simulates groundwater flow indirectly by means of a governing equation thought to represent the physical processes that occur in the system, together with equations that describe heads or flows along the boundaries of the model (boundary conditions). For time-dependent problems, an equation describing the initial distribution of heads in the system also is needed (initial conditions). Mathematical models can be solved *analytically* or *numerically*.

The set of commands used to solve a mathematical model on a computer forms the computer program or code. Models provide a framework for synthesizing field information and for testing ideas about how the system works. They can alert the modeler to phenomena not previously considered. They may identify areas where more field information is required.

3.5.3 Why Do We Need a Model in this study?

Most groundwater modeling efforts are aimed at *predicting* the consequences of a proposed action. Models can be used in an *interpretive*

sense to gain insight into the controlling parameters in a site-specific setting or as a framework for assembling and organizing field data and formulating ideas about system dynamics. Models can also be used to study processes in *generic* geologic settings. Generic models have been used to study lake-groundwater interaction. Generic modeling studies also may be helpful in formulating regional regulatory guidelines and as screening tools to identify regions suitable or unsuitable for some proposed action.

3.5.4 Main Output of Groundwater Modeling

The basic processes that may be considered part of many groundwater problems include groundwater flow and solute transport. Groundwater flow is a process that can be modeled without consideration of solute transport. In this process we can find hydraulic head. Solute transport requires either simultaneous solution with or results from a groundwater flow model to find concentrations. This is because the movement (transport) of solutes is controlled partially by the groundwater movement. Solute transport models are used for a wide variety of groundwater quality problems, such as point source pollution (e.g. waste disposal wells), spread source pollution (e.g. landfills) or sea-water intrusion.

3.5.5 Mathematical Models

Groundwater modeling begins with a conceptual understanding of the physical problem. The conceptual model usually consists of a set of assumptions that describe the system's composition, the transport processes, the mechanisms that govern them, and the relevant medium

properties (Faust and Mercer; 1980; Bear et al., 1992). The next step in the modeling process is to express the conceptual model in the form of a mathematical model. The mathematical model contains the information as the conceptual one, but expressed as a set of equations which are amenable to analytical and numerical solutions. The solution of the mathematical equations yields the required predictions of the real-world system's behavior in response to various sources and/or sinks.

The permeability of a porous medium, aquifer transmissivity, aquifer storativity, and porous medium dispersivity are examples of model coefficients. The numerical values of all the coefficients appearing in the model must be known unless that no model can be employed in any specified domain. To obtain the values of the coefficients, start by investigating the real-world aquifer system and find a period in the past for which information is available on: (i) initial conditions; (ii) excitations of the system; and (iii) observations of the response of the system. If such a period can be found, one can: (i) impose the known initial conditions on the model; (ii) excite the model by the known excitations of the real systems; and (iii) derive the response of the model to these excitations. In order to derive the model's response, one has to assume some trial values for the coefficients and compare the response observed in the real system with that predicted by the model (Bear et al., 1992).

The sought values of the coefficients are those that will make the two sets of values of state variables identical. Sensitivity analysis enables the modeler to investigate whether a certain percentage change in a parameter has any real significance, that is whether it is a dominant parameter or not. There are two methods of solutions, analytical and numerical. The preferable method is the analytical one, as once such a solution derived; it can be used for a variety of cases.

A number of simplifying assumptions regarding the groundwater system are necessary to obtain an analytical solution. Once the conceptual model is translated into a mathematical model in the form of governing equations with associated boundary and initial conditions, a solution can be obtained by transforming it into a numerical model and writing a computer program (code) for solving it.

Mathematical models consist of partial differential equations for groundwater flow and solute transport. The groundwater flow equations with appropriate boundary and initial conditions are used to analyze many groundwater problems, such as water supply.

The solute transport equation is used with the groundwater flow equation to address pollution problems. These problems are not as well understood, especially the characterization of source terms and dispersion. These equations and their boundary conditions can be simplified and solved analytically.

More complex forms of the equations and boundary conditions may be solved numerically. Mathematical model of any physical system can be generalized as shown in Figure (9).

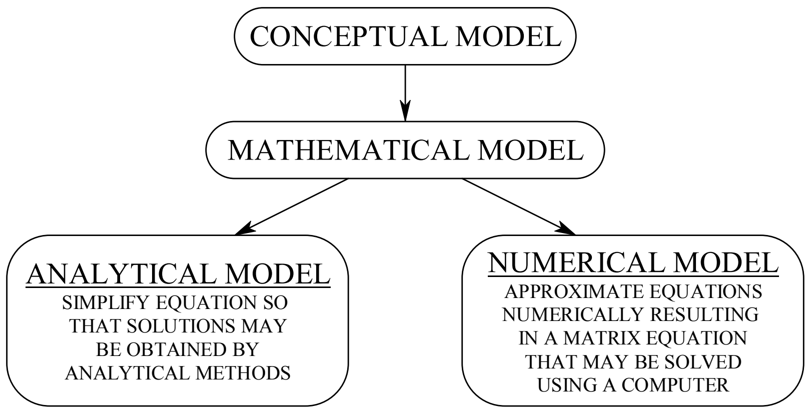


Figure (9): A Logic diagram for developing a mathematical model

3.5.6 Initial and boundary conditions

The initial condition in general describes the state of the system at the beginning of simulation. For instance, the initial condition may describe the distribution of the contaminant in the groundwater within the domain at the beginning of simulation. A general form of initial condition can be written as $C(x, t=0) = f(x)$ where $f(x)$ is a function defining the variation in concentration in the *x* direction at $t=0$. A common initial condition is $C(x, t)=0$ or $C(x, t)=C_I$ to provide a constant concentration within the system.

Boundary conditions are mathematical statements specifying the dependent variable (head or concentration) or the derivative of the dependent variable (flux) at the boundaries of the problem domain. Correct selection of the boundary conditions is a critical step in model design. In steady-state simulations, the boundaries largely determine the flow pattern. Boundary conditions influence transient solutions when the effects of the transient stress reach the boundary. In this case, the boundaries must be selected so that the simulated effect is realistic. Physical boundaries of groundwater flow systems are formed by the physical presence of an impermeable body of rock or a large body of surface water. Other boundaries form as a result of hydrologic conditions. These invisible boundaries are hydraulic boundaries that include groundwater divides. Hydrogeologic boundaries are represented by the following three types of mathematical conditions:

- *Type 1.* Specified head boundaries (Dirichlet conditions) for which head is given;
- *Type 2.* Specified flow boundaries (Neumann conditions) for which the derivative of head (flux) across the boundary is given. A no-flow boundary condition is set by specifying flux to be zero;
- *Type* 3. Head-dependent flow boundaries (Cauchy or mixed boundary conditions) for which flux across the boundary is calculated given a boundary head value. This type of boundary condition is sometimes called a mixed boundary condition because it relates boundary heads to boundary flows. There are several types of head- dependent flow boundaries.

There are three types of boundary conditions in transport models:

- Concentrations are specified along a boundary;
- Concentration gradients are specified across a boundary, and
- Both concentrations along a boundary and concentration gradients across that boundary are specified.

3.5.7 Model Calibration

The act of calibration standardizes a model. Many models are developed for specific situations and are, by definition, calibrated to that situation. Such models usually are not useful outside of their particular environment. The act of calibration is needed to increase the accuracy of the models. Calibration is the process of determining if there is any deviation from a standard observed (monitored) in order to compute a correction factor.

The calibration procedure is theoretically very simple. It is simply running the model with normal inputs against items for which the actual values are known. These estimates are then compared with the actual values and the average deviation becomes the correction factor for the model. The actual data used for the calibration runs determines what type of calibration is done. In essence, the calibration factor obtained is really good only for the type of inputs that were used in the calibration runs.

For a general total model calibration, a wide range of components with actual values need to be used. Better yet, numerous calibrations should be performed with different types of components in order to obtain a set of calibration factors for the various possible expected estimating situations.

3.5.8 Sensitivity Analysis

A sensitivity analysis is the process of varying model input parameters over a reasonable range (range of uncertainty in values of model parameters) and observing the relative change in model response. Typically, the observed changes in hydraulic head, flow rate or contaminant transport are noted.

The purpose of the sensitivity analysis is to demonstrate the sensitivity of the model simulations to uncertainty in values of model input data. The sensitivity of one model parameter relative to other parameters is also demonstrated. Sensitivity analyses are also beneficial in determining the direction of future data collection activities. Data for which the model is relatively sensitive would require future characterization, as opposed to data for which the model is relatively insensitive. Model-insensitive data would not require further field characterization. If data are determined to be insensitive to variations in model input parameters, the modeler should assess the possible reasons for this insensitivity. Figure (10 depicts an example of results of sensitivity analysis.

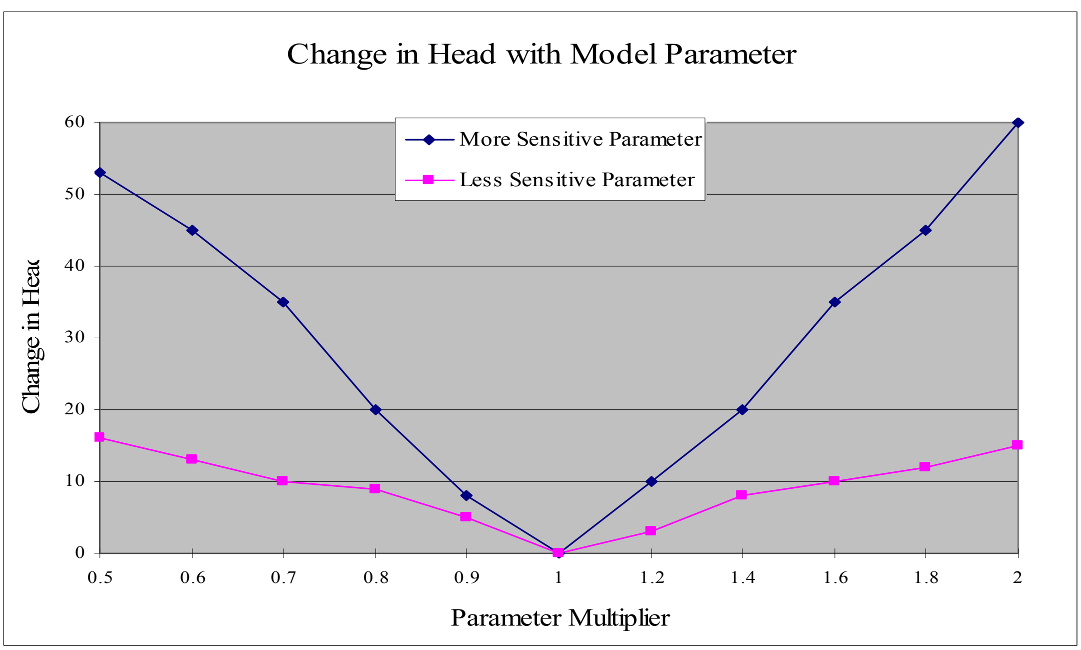


Figure (10): Simulated change in hydraulic head resulting from change in parameter value.

3.5.9 Lumped Parameter versus Distributed Groundwater Models

Selecting the appropriate model for estimating impacts of nonpoint sources of pollution is a major task. An appropriate conceptual model should be sufficiently simple so as to be amenable to mathematical treatment, but it should not be too simple so as to exclude those features which are of interest to the investigation at hand. The information should be available for calibrating the model and the model should be the most economic one for solving the problem at hand (Bear, 1979).

To completely model a system requires a very detailed knowledge of the physical properties and the processes governing groundwater movement. The virtue of a model rests in its ability to predict a general system from incomplete or partial data. The parsimonious model simplifies the representation of the physical structure and of the processes involved.

Numerous types of models have been developed and used to predict water levels. The simplest are black box models that contain no spatial information, but can predict aquifer properties (Mercer and Faust, 1980).

Lumped parameter models lack the spatial dimension in the equations describing flow and transport; consequently, only simple equations must be solved. These models offer the opportunity to simulate a given system with fewer data requirements for parameterization and calibration than their distributed counterparts. Lumped parameter models in groundwater applications generally were single cell models such as those developed by Gelhar and Wilson (1974) and Mercado (1976).

Distributed parameter models are normally chosen to increase the accuracy of predictions and to achieve a higher degree of spatial resolution. The more spatially and detailed the models, the more they have been difficult to calibrate and verify. In addition, input data must be developed for each cell; consequently, these models are not used to any great extent by regulatory agencies or other groups (Cary and Lloyd, 1984; Refsgaard et al., 1999).

CHAPTER 4
METHODOLOGY

4.1 Introduction

Contamination of groundwater in the study area and elsewhere in Gaza Strip is a major problem due to the numerous sources of pollution and the high vulnerability of the aquifer to pollution. Human activities including excessive use of fertilizers, inadequate waste management, and disposal of raw wastewater have led to nitrate pollution of Gaza coastal aquifer. In order to understand the extent of the problem and to design efficient management options, a mathematical model was developed and utilized. In this chapter, a brief illustration of the methodology followed in carrying out the research work is provided.

4.2 Methodology description

Figure (11 depicts the overall conceptual methodology followed in carrying out the research work. The methodology starts with the identification of the research objectives. This step is important since the objectives dictate to a great deal of extent the entire pathway of the work. So, I collected only the data which I need in my research work. In the process of data collection, I relied on different sources including internet, reports, journal articles, textbooks, and personal interviews. The study area which includes Gaza City and Jabalia Camp was selected based on different motivations, justifications and reasons as mentioned earlier in the first chapter.

To gain insight regarding contamination extent from nitrate in the study area, GIS was employed. Using the outcome of the characterization of nitrate contamination extent and the data collected and with the aid of GIS and MS Excel, the nitrate model was developed. Model development did pass through a variety of processes and steps including mainly the development of the conceptual model, mathematical model, calibration, and sensitivity analysis.

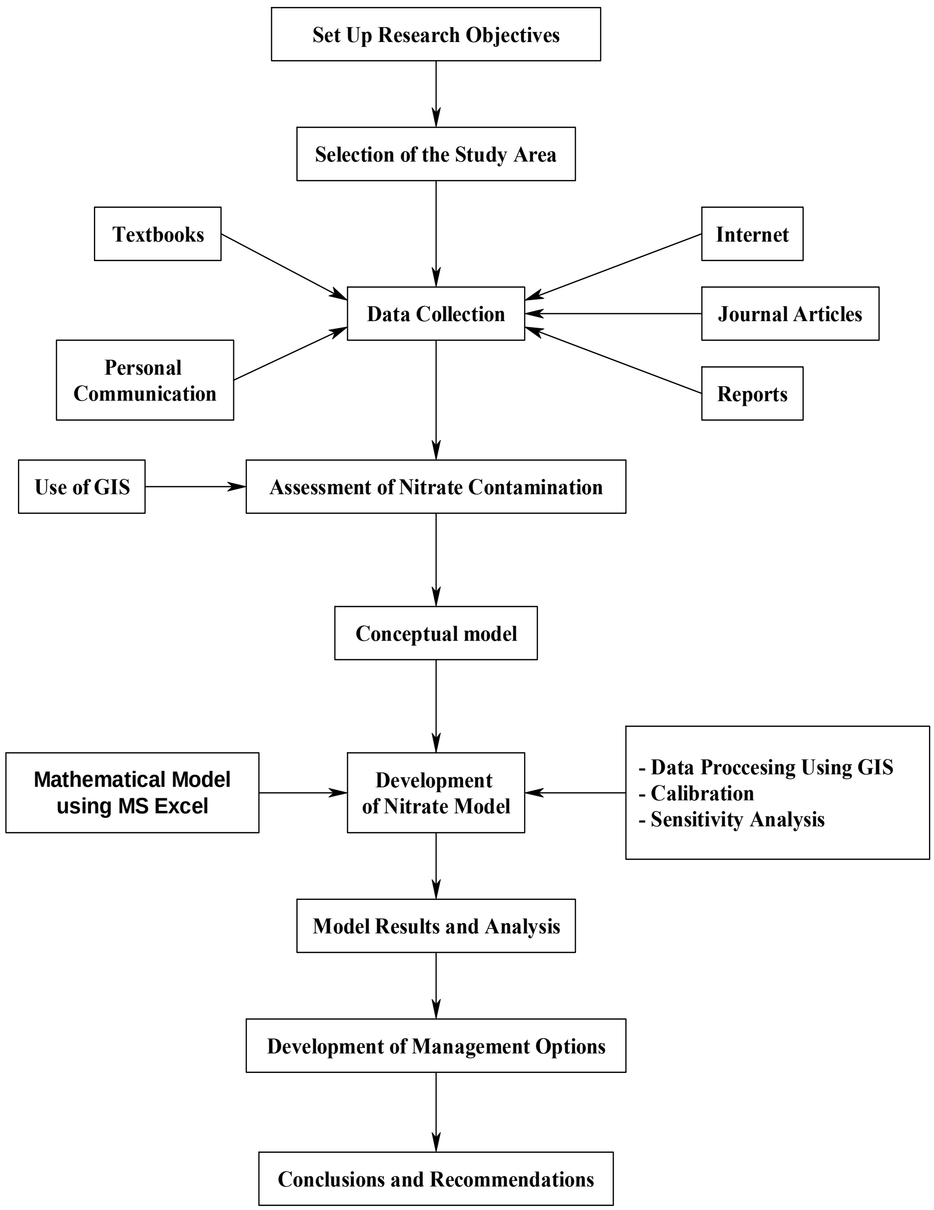


Figure (11): A flowchart of the methodology.

MS Excel was used for the numerical modeling. Thereafter, model output was analyzed, assessed, and evaluated. The model was later used in the development and assessment of the management options to mitigate the impact of nitrate contamination of the groundwater of the study area. Based on the research carried out herein, conclusions and recommendations for future relevant research work were set up.

CHAPTER 5
MODEL DEVELOPMENT

5.1 Introduction

The main objective from the development of the model is to find out the overall nitrate concentration of the aquifer as a function of time; that is C(t). The developed model is a single-cell lumped parameter model. The mass balance approach was used for both water and nitrate. This concept implies that the difference between what gets in and leaves out equals the change in the storage for the study area (model domain). Figure (12) depicts a schematic of the conceptual representation of the single cell lumped parameter model along with all the related parameters.

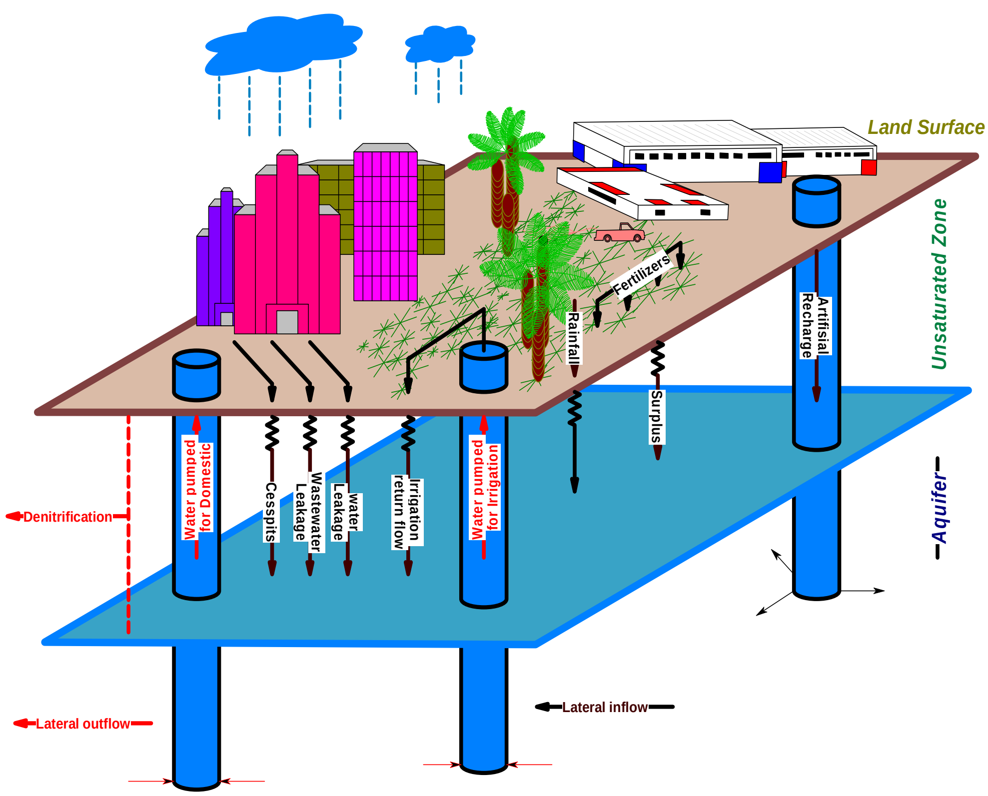


Figure (12): Conceptual representation of the single-cell model.

The developed model is comprised of two key components and these are the quantity (water) and quality (nitrate). The development of the nitrate model is the key target. However, the nitrate model development compels the prior development of the quantity model. This is because the nitrate mass in the aquifer depends on the available water quantity which can only be computed through the use of a quantity model. Figure (13 depicts the overall schematic for model development and the linkage between the water and the nitrate models.

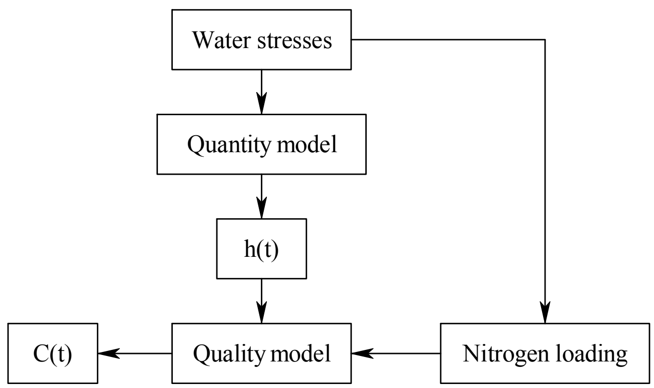


Figure (13): Schematic of the overall model development.

5.2 Development of the conceptual quantity model

To better comprehend the conceptual model development and model functionality, a flowchart was developed for the quantity model as shown in Figure (14. As depicted in Figure (12, Lateral inflow, artificial recharge, and natural recharge were classified as quantity model input. Lateral outflow and water pumped for irrigation and domestic purposes were classified as quantity model output. In the following, the details of the input parameters of the quantity model are illustrated. This section focuses on the conceptual methodology used in the computation of the different input parameters pertaining to the quantity model.

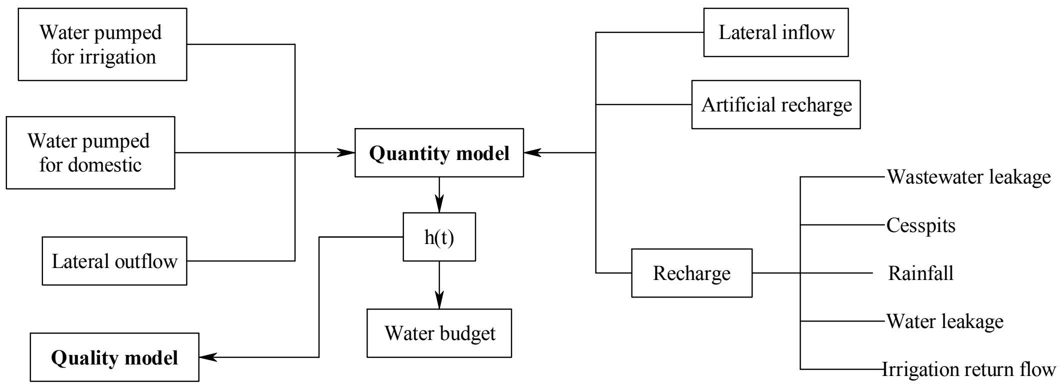


Figure (14): Schematic of the overall flowchart of the development of the conceptual quantity model.

5.2.1 Lateral Inflow (G_{in})

Lateral inflow is the subsurface flow that enters the model domain from its lateral boundaries and can be computed from the following equation (Darcy's law):

$$G_{in} = K \times i \times b \times w \times \cos\theta \qquad [1]$$

where

K: hydraulic conductivity (L/T)

i: hydraulic gradient (-)

b: aquifer saturated thickness (L)

w: width of the aquifer (L)

θ: angel between the flow direction and the imaginary line perpendicular to the boundary (º)

The hydraulic gradient can be computed from the groundwater elevation contour lines and is given by the following equation:

$$i = \frac{\Delta h}{\Delta x} \quad [2]$$

where

Δh: the change in the hydraulic head (L)

Δx: the distance between contour lines upon which Δh is measured (L)

The aquifer average thickness is computed using the following equation:

$$b = |D_p| + wt \quad [3]$$

where

$|D_p|$: the absolute value of the distance from the sea level to the average bottom of the aquifer for the study area (L)

wt: the average water table elevation from sea level (L). This value can be positive or negative

D_p represents the average depths to the bottom of pumping wells in the study area. Since the model that is being developed is a lumped parameter model, D_p was determined by computing the weighted average of the depth of each pumping well within the study area after considering both well depth and pumping rate as shown in the following equation:

$$D_p = \frac{\sum_{k=1}^{n} Q_k D_k}{\sum_{k=1}^{n} Q_k} \quad [4]$$

where

Q_k: the pumping rate for well k (L^3/T)

D_k: the depth of well k (L)

n: number of wells (-)

In order to persuasively compute the lateral inflow that enters the model domain, the boundaries were discretized into segments as shown in Figure 15. For each segment, equation [1] was computed. Total lateral inflow equals the summation of all lateral inflows through all segments.

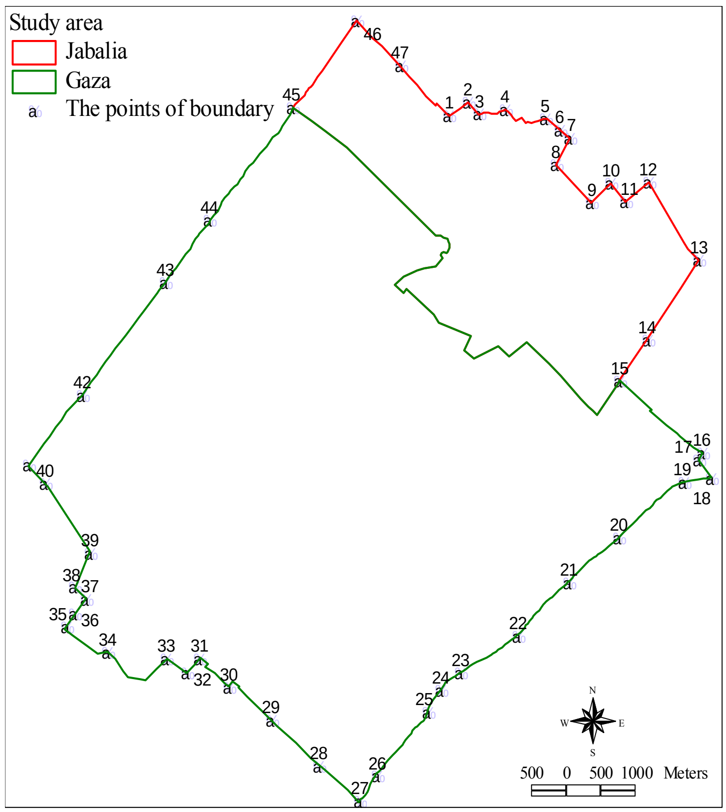


Figure (15): Segmentation of model boundaries for the computation of lateral inflow and outflow.

Equation [1] is based on Darcy's law. The hydraulic conductivity was assumed to be constant for the entire area and lies within a range of 20 to 80 m/d. To find the hydraulic gradient and the cross sectional area, a water table contour map was created using GIS. This map was obtained from a groundwater flow model for the entire Gaza Strip (see Figure 3) after clipping it to the study area. In this map, the difference between any two contour lines is always constant which results in a constant change in the hydraulic head (Δh) between any two contour lines. Thus, the changes in the distances between the contour lines dictate the values of the gradient and also dictate the segmentation of the boundaries of the model domain. The angel between the flow direction and the imaginary line perpendicular to the boundary was measured at each segment. Flow directions were drawn perpendicular to the counter lines and the angels between these two lines were measured. The saturated thickness was assumed to decrease on monthly basis based on the average decline in the water table that was encountered in the past 30 years and amounts 10 cm per year.

To find the aquifer saturated thickness, the distance from sea level to the water table (wt) and the distance from sea level to the bottom of the aquifer D_p were considered using equation [3]. Maps of D_p and wt (see equation [3]) were created using GIS and were used in the analysis and computation.

5.2.2 Artificial recharge (Q_{Ar})

Artificial recharge is the amount of water injected intentionally into the aquifer in order to increase the water table elevation to serve a management objective for the mitigation of seawater intrusion into coastal aquifers. In our case and to the best of my knowledge, there are no artificial injection wells in the study area. As such, Q_{Ar} was set to zero. However, model formulation is flexible in the essence that Q_{Ar} appears in all computations with a zero value.

5.2.3 Recharge (R)

Total recharge to the groundwater of the study area equals the summation of recharge from rainfall, irrigation return flow, wastewater leakage, leakage from water networks, and cesspits as depicted in Figure (14. Equation [5] was used to compute the over all recharge to the model domain as follows:

$$R = R_{ra} + R_{Ir} + R_{WWL} + R_{WL} + CSPT \qquad [5]$$

where

R: total recharge (L^3)

R_{ra}: recharge from rainfall (L^3)

R_{Ir}: recharge from irrigation return flow (L^3)

R_{WWL}: recharge from wastewater leakage (L^3)

R_{WL}: recharge from water leakage (L^3)

CSPT: recharge from cesspits (L^3)

In the following subsections, all recharge components depicted in equation [5] are illustrated and explained.

<u>Recharge from rainfall</u>

In order to compute recharge from rainfall, the locations of rainfall stations were mapped using GIS. As such a GIS point shapefile of rainfall stations was created and used. For each station, the total monthly rainfall depth was computed based on the available daily values. Thiessen polygons were created for each station using GIS such that each transpired polygon was represented by a single station as shown in Figure (16.

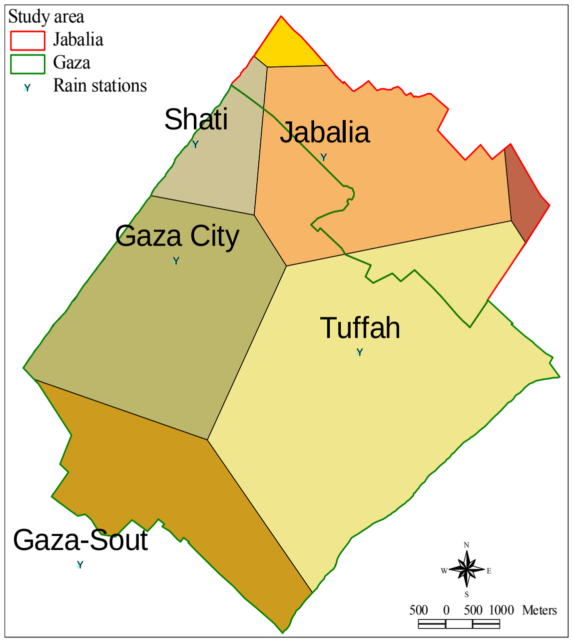


Figure (16): Thiessen polygons of the rainfall stations for the GCJC area.

In order to account for the recharge variability with soil type, each Thiessen polygon was intersected by the soil type shapefile using GIS to further divide each rainfall polygon to areas of different soil types that carry different fractions of recharge from rainfall. Total recharge from rainfall was then computed using the following equation [6]:

$$R_{ra} = \sum_{i=1}^{z} \left(ra_i \times Ara_i \times fra_i \right) \qquad [6]$$

where

ra_i: monthly rainfall depth for each subdivided polygon i (L)

Ara_i: area for each subdivided polygon (L^2)

fra_i: fraction of recharge for a specific soil type (-)

z: total number of subdivided polygons (-)

i: a specific subdivided polygon (-)

The estimation of the areas of the subdivided polygon (Ara_i) was determined using GIS.

Recharge from irrigation return flow

Generally, not all the water used in irrigation is consumed by plants. In fact, a proportion of this may percolate beyond the soil zone and later recharge the aquifer. This recharge equals the multiplication of the total volume of water used for irrigation by the fraction of return flow as in the following equation:

$$R_{Ir} = V_{Irr} \times \delta_{Irr} \qquad [7]$$

where

V_{Irr}: total volume of water used for irrigation in the study area (L^3)

δ_{Irr}: fraction of irrigation return flow that becomes recharge (-)

In turn, V_{Irr} can be computed using the following equation:

$$V_{Irr} = \sum_{i=1}^{z} \left[d_{Irr} \times A_{Irr} \times BIN(k) \right] \qquad [8]$$

where

d_{Irr}: monthly irrigation rate for each crop type i (L);

A_{Irr} : area for each crop type (L^2);

BIN(k): a binary integer multiplication factor to account for the months that may receive irrigation water. This factor may have either the value of 1 or 0;

The fraction of return flow from irrigation is within the range of 15 to 30% (Mercado, 1976). The area of each land use type (crop type) was obtained using GIS. Based on the personal communications and the interviews, the monthly irrigation rates for each crop type were obtained (Eng. Mohammad Al-Hanbali and Dr. Hassan AbuQaoud, Personal Communication, 2006). Needless to mention that the land use map (see Figure (3) that was utilized herein reflects the different kinds of plantations. Since there are months without irrigation, irrigation in these months were nullified. To do so, the monthly irrigation rate was multiplied by a binary encoding scheme (see BIN(k) in equation [8]) where a value of 1 was used for the months when there was irrigation and 0 when otherwise.

The multiplication of area by the monthly irrigation rate gives the monthly irrigation volume for each land use type. The summation of all these monthly volumes produces the total volume of the recharge from irrigation return flow.

Recharge from wastewater leakage

In this subsection, the quantification procedure of recharge from wastewater leakage from the sewage system is illustrated. This recharge equals the multiplication of the total volume of wastewater leakage from sewerage system by the fraction of wastewater recharge as illustrated in the following equation:

$$R_{WWL} = WWL \times \delta_{WWL} \qquad [9]$$

where

WWL: total monthly wastewater leakage from the sewerage network (L^3)

δ_{WWL}: recharge fraction of wastewater leakage (-)

The monthly wastewater leakage is given by the following equation:

$$WWL = POP \times W_{consm} \times \Phi \times \Omega_{ww} \times PERSERV \quad [10]$$

where

POP: total monthly population living within the study area (capita)

W_{consm}: per capita monthly water consumption (L^3)

Φ: percentage of water that becomes wastewater (%)

Ω_{ww} : leakage percentage of wastewater from sewerage system (%)

PERSERV: percentage of population serviced by the sewerage system (%)

The monthly population living in the study area is computed using the following formulas:

$$POP_E = POP_I \times (1+GR)^a$$
$$POP_M = \tfrac{1}{12}(POP_E - POP_I) \quad [11]$$
$$POP = POP_I + POP_M \times STEP$$

where

POP_E: population at the end of the year (capita)

POP_I: initial population at the beginning of simulation (capita)

POP_M: monthly increase in population (capita)

STEP: the month number for a specific year (-)

GR: population growth rate (%)

a: number of years for population projection (-)

To find out the total volume of wastewater leakage from the sewerage system, the following issues were considered. First, the population in the study area serviced by the wastewater collection network was estimated on monthly basis. Initial population was taken from the Palestinian Central

Bureau of Statistics (www.pcbs.gov.ps). Personal communication was made to find out the percentage of population serviced by the sewage system (Dr. Said Ghabayen, formerly at PWA, 2005). Using a growth rate of 3.5%, monthly population were estimated.

The second issue that was considered is the per capita water consumption. This was computed by considering the total monthly water consumption for the study area. The third issue was the determination of the fraction of wastewater leakage which was left to be determined through the calibration process though estimates from local reports provide a value of 10% (Metcalf and Eddy, 2000). The percentage of water that becomes wastewater was taken as 85%.

Recharge from water leakage

The water distribution network of the study area encounters leakage due probably to the lack of proper maintenance. It is expected that the leaking water will eventually recharge the aquifer. This recharge equals the multiplication of the total volume of water leakage and the fraction of the leakage that becomes recharge as can be seen from equation [12] and equation [13].

$$WL = PUMPDOM \times \Omega_w \qquad [12]$$

where

WL: volume of leakage from the water network (L^3).

PUMPDOM: volume of water pumped for domestic purposes on monthly basis (L^3)

Ω_w: water leakage fraction from the network (-)

The recharge to the aquifer from the leakage of water from the network is given by the following formula:

$$R_{WL} = WL \times \delta_{WL} \quad [13]$$

where

δ_{WL}: fraction of water leakage that becomes recharge (-)

Recharge from cesspits

The recharge from cesspits equals the total wastewater leaching from cesspits multiplied by the fraction of wastewater that becomes recharge. Since the percentage of study area that is serviced by the sewage system is 90% then the percentage of study area with cesspits is 10%. Using a similar concept to that used in computing wastewater recharge, the total wastewater generated from cesspits was computed as shown in equation [14] and equation [15].

$$CSPT = WW_{cesspits} \times \delta_{CSPT} \quad [14]$$

and

$$WW_{cesspits} = POP \times W_{consm} \times \Phi \times (100 - PERSERV) \quad [15]$$

where

$WW_{cesspits}$: total wastewater generated from cesspits (L^3)

δ_{CSPT}: recharge fraction of wastewater from cesspits (-)

5.2.4 Lateral outflow (G_o)

Lateral outflow (G_o) was computed using the same concept for determining lateral inflow (see equation [1]).

5.2.5 Water pumped for irrigation (Q_{Irr})

Water pumped for irrigation (Q_{Irr}) was only considered for irrigation purposes. It was estimated using equation [8].

5.2.6 Water pumped for domestic purposes (Q_{DO})

Water consumed for domestic purposes (Q_{DO}) equals the population size multiplied by the per capita water consumption. To account for the actual amount being pumped from the aquifer, the following equation was used:

$$Q_{DO} = \frac{(POP \times W_{consm})}{(1 - \Omega_w)} \qquad [16]$$

5.3 Development of the conceptual quality model

As mentioned earlier in this chapter and depicted in Figure (13, the quality model relies on the outcome of the quantity model; h(t). Mass balance of nitrate for the study area was employed in order to simulate the overall nitrate concentration.

The sources of nitrate which were considered for the study area include lateral inflow, artificial recharge, fertilizer loading, and recharge. The denitrification, lateral outflow, groundwater pumped for domestic and irrigation purposes were considered as the main sinks of nitrate for the study area.

Figure (17 shows a flowchart that depicts the development of the conceptual quality model and the following subsections illustrate the parameters pertaining to the development of this model.

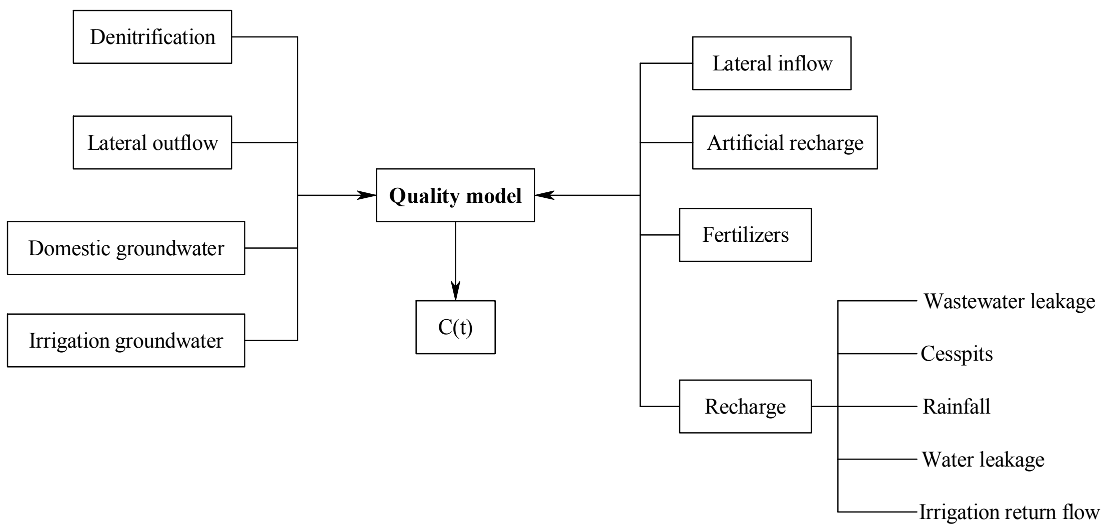


Figure (17): Schematic of the overall flowchart of the conceptual quality model development.

5.3.1 Nitrate from lateral inflow (NO_3G_{in})

The amount of nitrate (as mass) that enters the aquifer with lateral inflow from the surrounding areas (NO_3G_{in}) can be calculated using the following two equations ([17] and [18]):

$$NO_3G_{in} = \sum_{i=1}^{z} M_j \quad [17]$$

$$M_j = G_{inj} \times C_{inj} \quad [18]$$

where

M_j: mass of nitrate entering the study area by lateral inflow through segment j (M)

z: total number of segments comprising the boundaries of the model domain (-)

C_{inj}: the average concentration of nitrate for segment j (M/L^3)

Using GIS, maps of average nitrate concentrations were created for years 2000 to 2004. The locations of nitrate wells were obtained using a GIS shapefile. For each year, the average nitrate concentration for each well was computed. After that, Thiessen polygons were created for each well such that each transpired polygon was represented by a single well and thus a single nitrate concentration value. This enabled the designation of nitrate concentration for lateral inflow that enters the study area through each segment (see Figure (15). These concentrations were multiplied by their corresponding lateral inflow values to obtain nitrate mass flux. Summing up these mass fluxes provides the amount of nitrate that enters the study area by lateral inflow.

5.3.2 Nitrate from artificial recharge (NO_3QA)

The amount of nitrate (as mass) that enters the aquifer through artificial recharge (NO_3QA) can be calculated using the following equation:

$$NO_3QA = Q_{Ar} \times C_{Ar} \qquad [19]$$

where

C_{Ar}: nitrate concentration in artificial recharge (M/L^3)

5.3.3 Nitrate from fertilizer surplus (NO_3SURP)

The amount of nitrate (as mass) that enters the aquifer due to the fertilizer use in agricultural areas (NO_3SURP) can be calculated from the following set of equations:

$$NO_3SURP = SURP \times \alpha_{FERT}$$
$$SURP = \sum_{i=1}^{z}(FERT - CONS) \times A_{type} \times BIN(k) \qquad [20]$$
$$CONS = FERT \times PERCONS$$

where

SURP: total monthly mass of fertilizer surplus from all the agricultural land use types and corresponding crops (M)

i: an indicator for land use type (crop type)

FERT: amount of fertilizer applied for each type of land use per unit area (M/L^2)

α_{FERT}: linear fraction for fertilizer that describes the transformations in the soil zone (-)

A_{type}: area planted for each type of land use (L^2)

CONS: consumption of fertilizer for each crop (M/L^2)

PERCONS: percentage of fertilizers applied that would be taken up by plants (%)

BIN(k): a binary integer multiplication factor to account for the months of fertilization. This factor may have the value of either 1 or 0

To implement the set of equations in [20], many parameters must be determined. First of all, the amount of fertilizers being applied to different crop types ought to be determined. This peace of information was obtained through personal communication (Dr. Hassan Abuqauod, An-Najah National University, 2006). The area of each crop type was determined using GIS. An assumption was made that not all the fertilizers are taken up by plants and that a percentage of fertilizers are consumed. This leaves an amount that is ready to leach to groundwater. The set of equations in [20] are utilized for each crop type and the summation would give the total surplus of NO_3 from fertilizers.

5.3.4 Nitrate from recharge (NO_3R)

Total nitrate that reaches the aquifer via recharge equals the summation of nitrate from rainfall, irrigation return flow, wastewater leakage, leakage from water networks, and cesspits. This can be expressed by the following equation:

$$NO_3R = NO_3Rra + NO_3Rir + NO_3WWL + NO_3WL + NO_3CSPT \quad [21]$$

where

NO_3R: total mass of nitrate entering aquifer via recharge (M)

NO_3Rra: mass of nitrate entering aquifer via recharge from rainfall (M)

NO_3Rir: mass of nitrate entering aquifer via irrigation return flow (M)

NO_3WWL: mass of nitrate entering aquifer via leakage of wastewater (M)

NO_3WL: mass of nitrate entering aquifer via leakage of water (M)

NO_3CSPT: mass of nitrate entering aquifer from cesspits (M)

In the following subsections, a detailed description of all the components that appear in equation [21] is provided.

Nitrate from rainfall recharge

Nitrate that enters the aquifer from rainfall recharge can be estimated using the following equation:

$$NO_3Rra = R_{ra} \times C_p \times \alpha_p \quad [22]$$

where

C_p: nitrate concentration in rainfall (M/L^3)

α_p: linear fraction for rainfall that describes the transformations in the soil zone (-)

Equation [22] simply states that the value of recharge from rainfall (can be obtained using equation [6]) is multiplied by nitrate concentration in rainfall and the linear fraction for rainfall.

Nitrate from irrigation return- flow recharge

Nitrate that enters the aquifer from irrigation return flow can be estimated using the following equation:

$$NO_3Rir = R_{Qir} \times C_{IR} \times \alpha_{Ir} \qquad [23]$$

where

C_{IR}: nitrate concentration in irrigation return flow (M/L^3)

α_{IR}: linear fraction for irrigation that describes the transformations in the soil zone (-)

The value of C_{IR} equals the initial nitrate concentration, C_0 for the entire aquifer for the first time step (at the beginning of simulation). Thereafter and for each time step, nitrate concentration at the preceding time step is used. The value of recharge from irrigation return flow which can be obtained using equation [7] is multiplied by the nitrate concentration in irrigation return flow. After that, it has to be multiplied by the linear fraction of irrigation return flow.

<u>Nitrate from leakage of wastewater</u>

Nitrate that enters the aquifer from leakage of wastewater can be estimated using the following equation:

$$NO_{3WWL} = R_{WWL} \times C_{WWL} \times \beta_{WWL} \qquad [24]$$

where

C_{WWL}: total nitrogen concentration in the leakage of wastewater (M/L^3)

β_{WWL}: linear fraction for wastewater leakage that describes the transformations in the soil zone (-)

The value of recharge from leakage of wastewater which can be obtained using equation [9] is multiplied by the concentration of total nitrogen in leakage of wastewater. After that it is multiplied by the linear fraction for rainfall.

Nitrate from leakage of water

Nitrate that enters the aquifer from leakage of water can be estimated using the following equation:

$$NO_3WL = R_{WL} \times C_{WL} \times \alpha_{WL} \qquad [25]$$

where

C_{WL}: nitrate concentration in the leaking water (M/L^3)

α_{WL}: linear fraction for water leakage that describes the transformations in the soil zone (-)

The value of recharge from leakage of water which can be obtained using equation [13] is multiplied by the nitrate concentration in water that leaks from the water distribution network. This amount is then multiplied by the linear fraction of rainfall.

Nitrate from cesspits

Nitrate that enters the aquifer from cesspits can be estimated using equations [26]:

$$NO_3CSPT = NO_3GENCSPT \times \beta_{CSPT}$$
$$NO_3GENCSPT = NGENCSPT \times FraNO_3N \qquad [26]$$
$$NGENCSPT = POP \times PERUNSER \times N_{CAPITA}$$

where

$NO_3GENCSPT$: nitrate mass that originates in cesspits (M)

β_{CSPT}: linear fraction for cesspits that describes the transformations in the soil zone (-)

$FraNO_3N$: fraction of nitrogen from cesspits that becomes nitrate (-)

NGENCSPT: total mass of nitrogen generated from the cesspits of the study area (M)

N_{CAPITA}: the generated mass of nitrogen per capita (M)

5.3.5 Nitrate lost through lateral outflow (NO_3Go)

The amount of nitrate lost from the aquifer through lateral outflow is computed using the following equation:

$$NO_3Go = G_o \times C \times \varepsilon \qquad [27]$$

where

C: nitrate concentration in the aquifer (M/L^3)

5.3.6 Nitrate lost through irrigation (NO3Irr)

The amount of nitrate lost from the aquifer through water pumped from the aquifer for irrigation is given by the following equation:

$$NO_3Irr = Q_{Irr} \times C \qquad [28]$$

5.3.7 Nitrate lost through domestic use of groundwater (NO3DO)

The amount of nitrate lost from the aquifer through water pumped for domestic purposes is given by the following equation:

$$NO_3DO = Q_{Do} \times C \quad [29]$$

5.3.8 Nitrate lost through denitrification (NO_3DEN)

The amount of nitrate lost by denitrification is given by equations [30], [31], and [32]:

$$NO_3DEN = V_{w0} \times \lambda \times C \quad [30]$$

$$V_w = (h_0 + |D_p|) \times A \times n \quad [31]$$

$$\lambda = \frac{0.693}{\sqrt{t}} \quad [32]$$

where

λ: denitrification rate (T^{-1})

t: half-life time of nitrate (T)

V_w: the monthly water volume in the aquifer at the beginning of each time step (L^3)

h_0: water table elevation with reference to the sea level at the beginning of each time step (L)

A: total area of the model domain (L^2)

n: aquifer porosity

5.4 Development of the mathematical models

As mentioned earlier in this chapter, the development of the model of nitrate concentration in groundwater compels the development of a model for simulating the water table elevation (see Figure (13, Figure (14, and Figure (17). Two major equations were used to implement the mass balance approach for the study area where the aquifer system was simulated as a single-cell lumped parameter model.

The general mass balance equation for groundwater quantity and quality can be expressed by the following equation:

$$\begin{aligned} & Q_{IN} - Q_{OUT} = \Delta S_W && \text{(Water)} \\ & Q_{IN}C_{IN} - Q_{OUT}C_{OUT} = \Delta S_N && \text{(Nitrate)} \end{aligned} \qquad [33]$$

For the groundwater quantity (the water table elevation), equation [33] would become as follows:

$$\begin{aligned} & G_{in} + Q_{Ar} + R_{ra} + R_{Ir} + R_{wwl} + R_{wl} + CSPT - G_0 - Q_{irr} - Q_{Do} \\ & = \Delta S_W \\ & \Delta S_W = V_{w1} - V_{wo} \\ & V_{wo} = (h_o + \left| D_{from\ msl} \right|) \times A \times n \\ & V_{w1} = \Delta S_W + V_{wo} \\ & h_1 = V_{w1} / A \times n + D_{from\ msl} \end{aligned} \qquad [34]$$

For the groundwater quality (the nitrate concentration in the aquifer), equation [33] would become as follows:

$$\begin{aligned} & \begin{bmatrix} NO3Gin + NO3QA + NO3SURP + NO3Rra + NO3Rir + \\ NO3WWL + NO3WL + NO3CSPT \end{bmatrix} - \\ & [NO3Go + NO3Irr + NO3Do + NO3Den] = \Delta S_N \\ & \Delta S_N = V_{w1} C_1 - V_{w0} C_0 \\ & C_1 = \frac{\Delta S_N + V_{w0} C_0}{V_{w1}} \end{aligned} \qquad [35]$$

The solution of equation [34] provides the variability of water table elevation of the aquifer with time. This enables the computation of the variability of the water volume in the aquifer and thus enables the simulation of the concentration in the aquifer. The solution of equation [35] provides the overall concentration of nitrate in the aquifer with time.

5.5 The numerical solution of the mathematical models

The last step in model development (after the development of the conceptual and mathematical models) is obtaining a numerical solution. The numerical solution of equation [34] and equation [35] (to find out h(t) and C(t), respectively) was obtained using MS Excel. The choice of MS Excel for solving the mathematical models was made for the following reasons:

- Ms Excel does not require past knowledge in programming;
- An easy-to-use program;
- Enables the modularity in model structure such that a specific sheet is allocated for each component;
- Quick analysis of model results;
- Produces neat figures that illustrate model output;
- Can be easily distributed to interested users.

5.6 Model Calibration

Model calibration was carried out in two phases. In the first phase, the quantity model was calibrated. Since no recent data is available on water table elevations, the calibration process was carried out by forcing the model to produce a decline rate in water table elevation similar to the reported rates in the literature. In doing so, the **Goal Seek** option of MS

Excel was used to figure out the appropriate hydraulic conductivity value. The hydraulic conductivity was selected because the water table is sensitive to changes to its value. The calibrated hydraulic conductivity value for the study area is 42.1 m/d. The calibration process covers the time period from 2000 to 2003.

In the second phase, the quality model was calibrated. Optimization was utilized herein in model calibration using the **solver** package of MS Excel. The solver package has three main components and these are:

[1] The objective function. In our case, the objective function is to minimize the summation of square errors which are the differences between the observed values of the average nitrate concentration for years 2000 to 2003 and the simulated values;

[2] The decision variables. These decision variables are the calibration parameters and include the following:

   a. Lateral inflow multiplication factor
   b. Fertilization multiplication factor
   c. Linear fractions (α) for rainfall, water leakage, and fertilizers
   d. Linear fractions (β) for wastewater leakage and cesspits;

[3] The constraints. These are the ranges of the decision variables (calibration parameters). For lateral inflow, the factor range is from 100% to 120%. For fertilization factor, the range is from 100% to 150%. For linear fractions α, the range is from 27% to 46%; for linear fraction β, the range is from 70% to 100% (Mercado, 1976).

Calibration results of the quality model are depicted in Figure (18. Apparently, simulated nitrate concentration for years 2000, 2002, and 2003 match well the observed values. For year 2001, it is apparent that there is a higher error compared to the other three years.

Nevertheless, the difference between the observed and simulated nitrate concentration for year 2001 is less than 15% which in turn is acceptable.

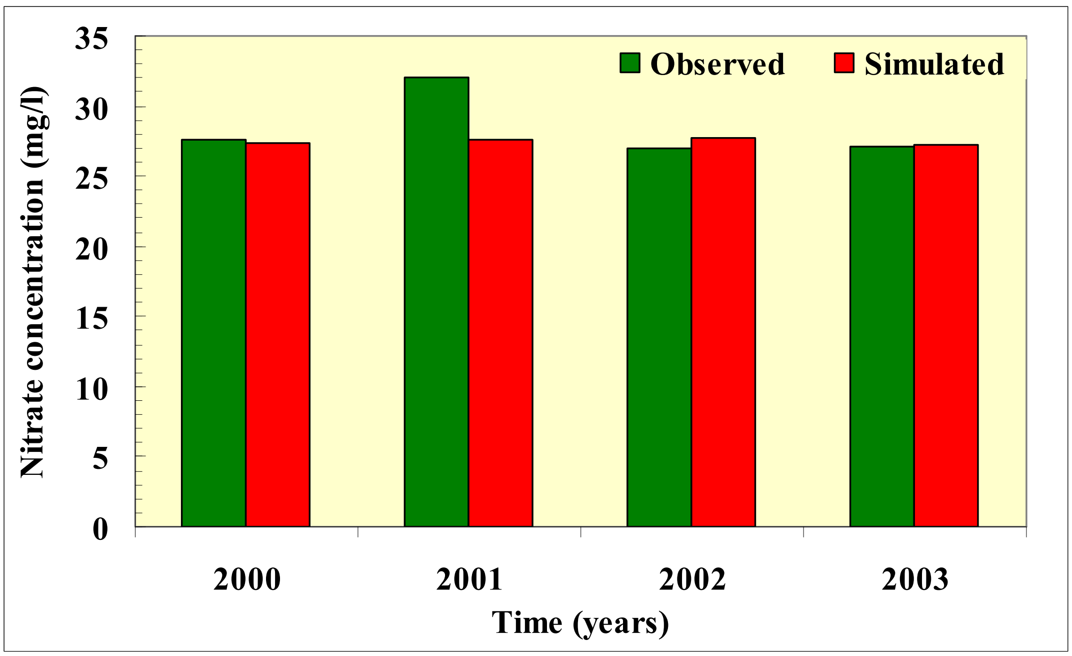


Figure (18): The average nitrate concentration for observed and simulated values for years 2000 to 2003.

5.7 Sensitivity Analysis

As mentioned earlier, the purpose of the sensitivity analysis is to demonstrate the sensitivity of the model output to the uncertainty in values of model input. A set of model parameters were selected for the sensitivity analysis and these are summarized in Table (5. The parameters (summarized in Table (5) were altered (decreased by 10%) and the corresponding head and concentration values were obtained using the developed models. Thereafter, the relative sensitivity coefficients for head and nitrate concentrations were computed using the following formula:

$$\upsilon_{\Re} = \frac{\Delta M_O / M_O}{\Delta M_I / M_I} \qquad [36]$$

where

M_O: model output

M_I: model input

ΔM_O and ΔM_I are the change in model output and input parameter values

$\upsilon_{\Re}$ is convenient for comparing sensitivity coefficients for different parameters of different physical units.

Figure (19 shows the different head relative sensitivity coefficients for the parameters summarized in Table (5. Obviously, parameter #18 (water consumption) had the highest value and thus has the highest impact on water table elevation. Parameters 1, 2, 6, 16, 18, 19, 22, and 23 (see Table (5 for parameter description) had sensitivity coefficients that are notably high. The other issue to consider herein (Figure (19) is that with decreasing the selected parameters, different responses in terms of corresponding increase and decrease in model output are encountered.

Table (5): Selected parameters for model sensitivity analysis.

#	Parameter	Symbol
1	Hydraulic conductivity	K (m/d)
2	Percentage of wastewater generation from water	Φ(-)
3	Growth rate	(-)
4	Linear fractions (Rainfall, artificial recharge, water leakage, and fertilizers)	α (-)
5	Linear fractions (Wastewater leakage and cesspits)	β (-)
6	Recharge fraction for sandy soil (regosols)	(-)
7	Recharge fraction for dark-brown soil	(-)
8	Recharge fraction for sandy soil (loess soil)	(-)
9	Leakage percentage of water network	Ω_W (-)
10	Leakage percentage of sewerage system	Ω_{WW} (-)
11	Per capita monthly generation rate of nitrogen	(Kg N)
12	Initial nitrate concentration for the study area	C_0 (mg/L)
13	Initial water table elevation for the study area	h_0 (m)
14	Irrigation return-flow fraction	δ_{Irr} (-)
15	Fraction of wastewater that becomes recharge	δ_{WWL} (-)
16	Fraction of water recharge	δ_{WL} (-)
17	Fraction of cesspits recharge	δ_{CSPT} (-)
18	Water consumption	W_{consm} (L/c-d)
19	Irrigation rate	d_{Irr} (m/month)
20	Concentration of nitrate that enters the study area via lateral inflow	C_{in} (mg/L)
21	Fertilizer application for each crop type of land use	FERT (kg/m^2/month)
22	Rainfall depth	ra (mm/month)
23	Percentage of area serviced by sewerage system	PERSERV

Figure (20 shows the different relative sensitivity coefficients of nitrate concentration in the aquifer for the selected model input parameters. Apparently, parameter #12 (initial nitrate concentration) has the highest positive sensitivity coefficient while parameter #23 (percentage of area serviced by the sewerage system) had the highest negative sensitivity coefficient. The model output in terms of nitrate concentration is insensitive to the initial water table elevation and thus has a zero sensitivity coefficient.

Upon comparing both Figure (19 and Figure (20, we can easily notice that the parameters #6, #22, and #23 have a large impact on model output in terms of water table elevation and nitrate concentration. On the contrary, the parameters #3, #7, #8, #13, #14, and #17 are of low impact on model output.

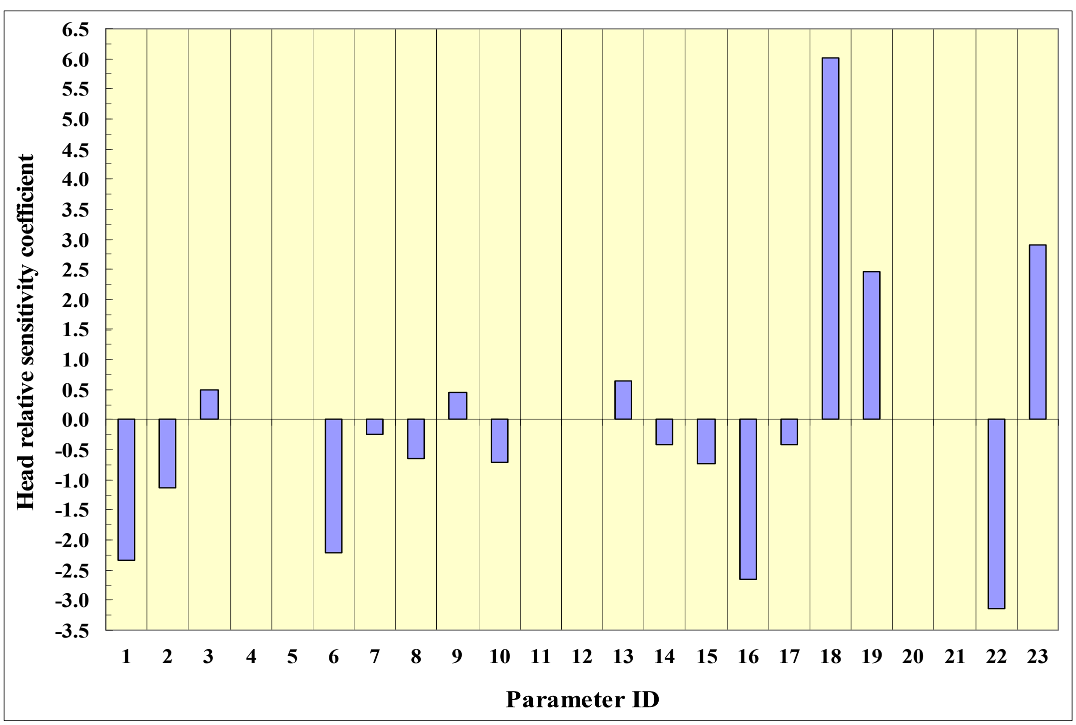


Figure (19): Relative sensitivity coefficients of water table elevation for selected model parameters. Parameter IDs are as summarized in Table (5.

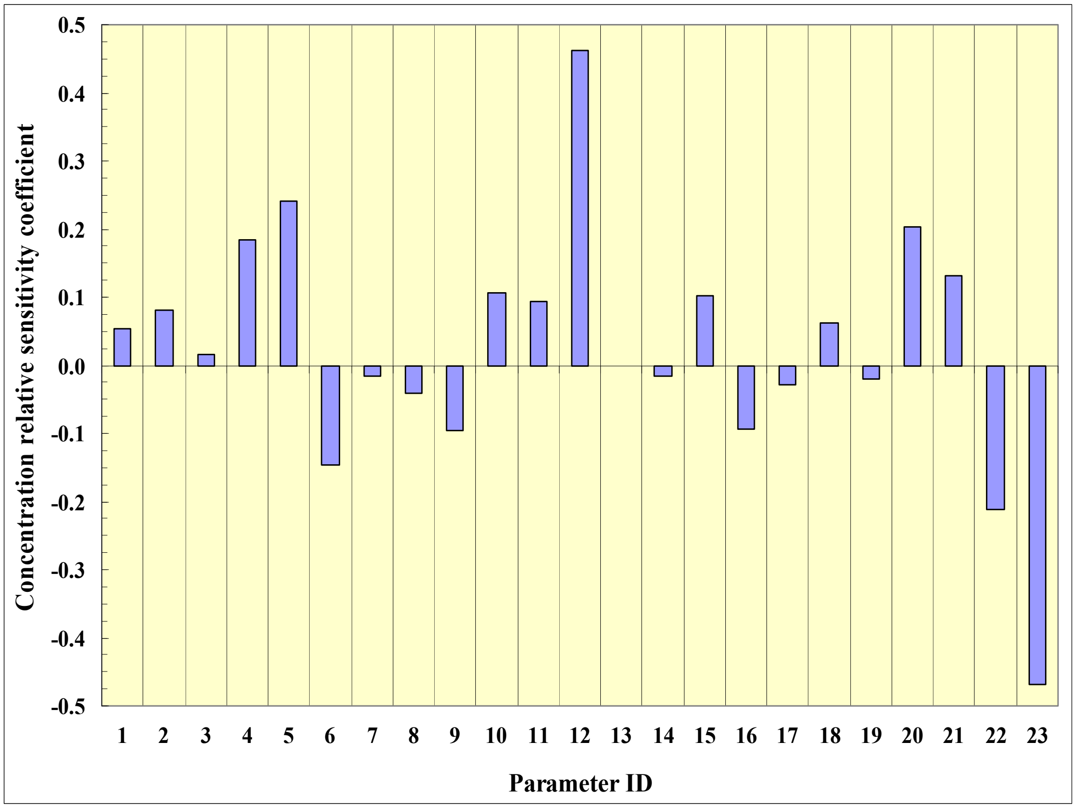


Figure (20): Relative sensitivity coefficients of nitrate concentration for selected model parameters. Parameter IDs are as summarized in Table (5.

CHAPTER 6

ANALYSIS AND DISCUSSION OF MODEL OUTPUT

6.1 Introduction

As mentioned earlier, the developed model is a single-cell lumped parameter model. This means that model output in terms of nitrate concentration is averaged over the entire area for a certain month. After the completion of model calibration (which was done successfully and satisfactorily), the model can be used with a great deal of confidence in terms of result accuracy and reality expressiveness. This chapter presents general analysis and discussion of the model output.

6.2 Quantity Model Output

Water table elevation is the main output from the quantity model. Figure (21 depicts the time series of the water table elevation for the groundwater of the study area for the period from October 99 to March 2004. To some extent, there is a cyclic periodic behavior in water table variation where the maximum value occurs in March while the minimum value occurs in November. This behavior can be attributed to recharge from rainfall and indeed due to the decrease in the water consumption during the summer time.

To further illustrate the issue of the declining head over time, Figure (22 and Figure (23 were developed. These two figures depict the general inflow and outflow quantities for the groundwater of the study area. Apparently, more water leaves the aquifer of the study area than entering into it. This creates a deficit in water storage in the GCJC across the years.

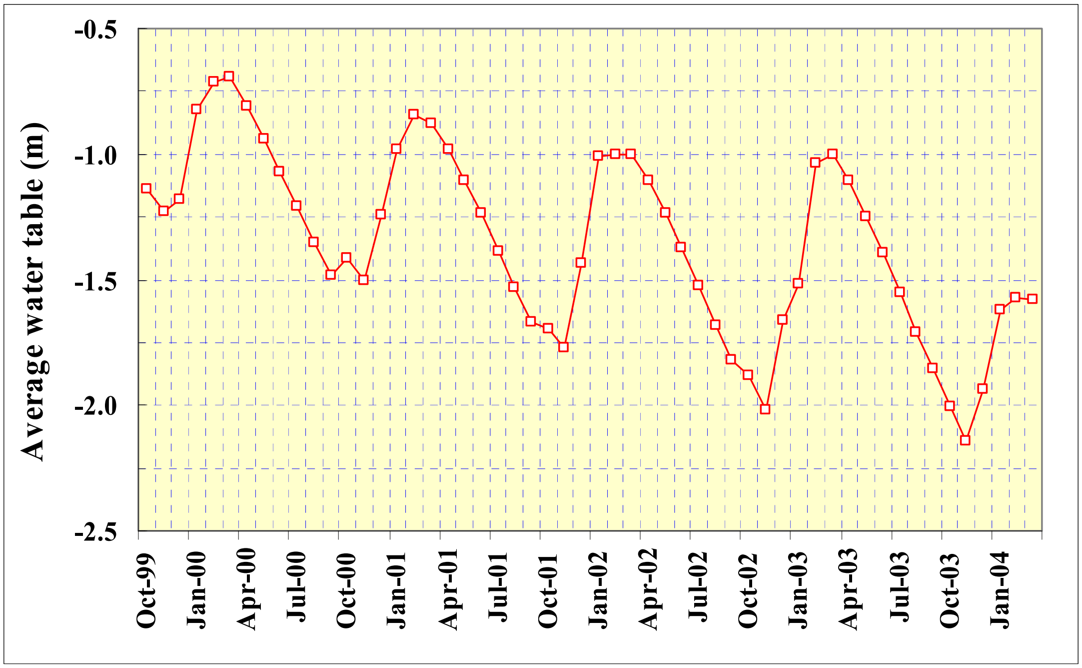


Figure (21): The variability of the average water table elevation with time.

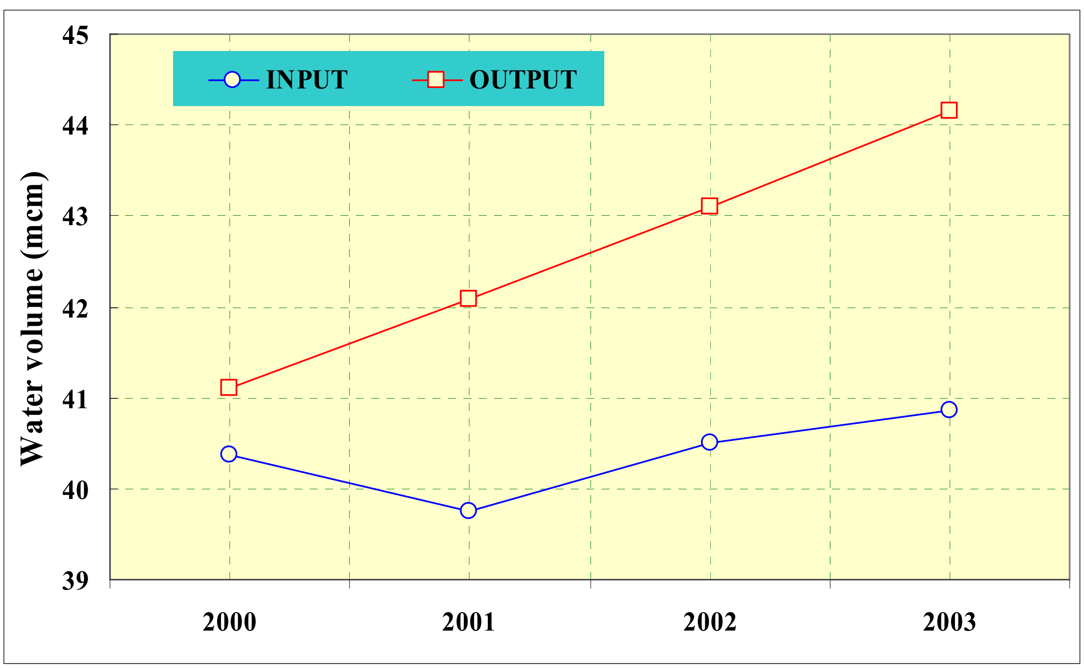


Figure (22): The total input and output of water volume for the years from 2000 to 2003.

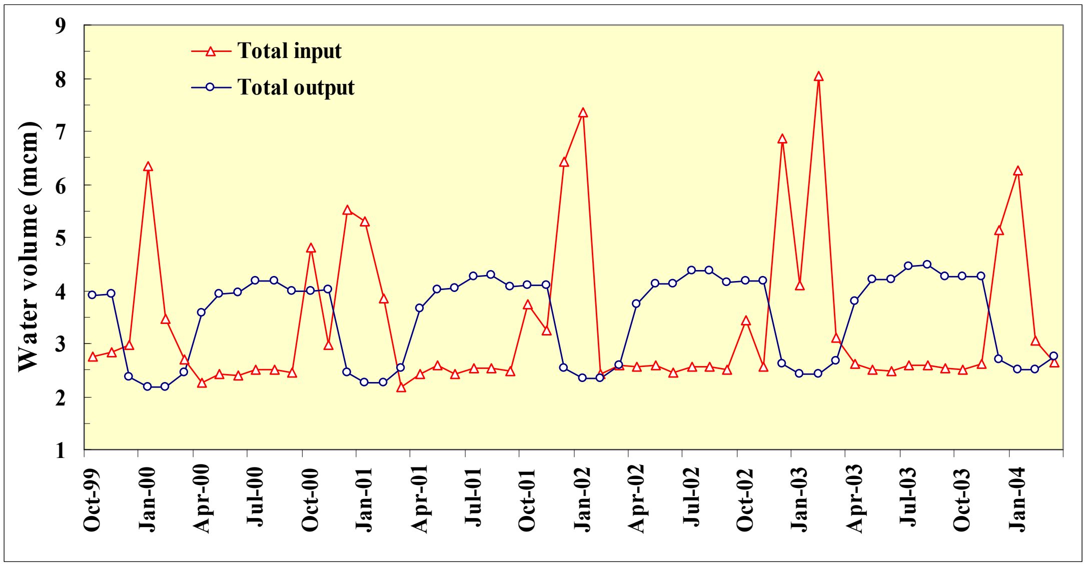


Figure (23): Time series of total input and output of water volume for the study area.

To show the water budget for the groundwater of the GCJC area in 2004, the different components of the water input and output were listed in Table 6. From this table we conclude that the total output exceeds the total input by almost 9 mcm. By examining the components of the water budget (in Table 6) we find that the maximum contribution of water to the groundwater of the study area comes from the recharge from water leakage followed by lateral inflow. This helps in setting up the management options in the essence that a great deal of water comes from the adjacent area.

Table (6): The water budget for the groundwater of the GCJC area in 2004.

In (m^3)			**Out** (m^3)	
Lateral Inflow		9,930,260	Lateral Outflow	369,145
Artificial Recharge		0	Domestic Pumpage	32,216,498
Recharge from	Wastewater Leakage	3,291,587	Irrigation Pumpage	12,645,949
	Cesspits	1,828,659		
	Rainfall	7,566,995		
	Water Leakage	11,602,381		
	Irrigation return flow	1,896,892		
	Total Input	**36,116,774**	**Total Output**	**45,231,592**

To get a better idea about the different components of the water input and output for the groundwater of the GCJC area, pie charts were developed as shown in Figure (24 and Figure (25 for the year 2004. Apparently, recharge from rainfall, water leakage, and lateral inflow are forming the major amount of water that enters the aquifer of the GCJC area. It is worth mentioning that irrigation return flow makes up almost 5% of the total groundwater inflow due to the fact that the area is not an agriculture-dominated area within the GCJC. As for groundwater outflow, the majority (70%) is lost through domestic use. Lateral outflow accounts for only 1%.

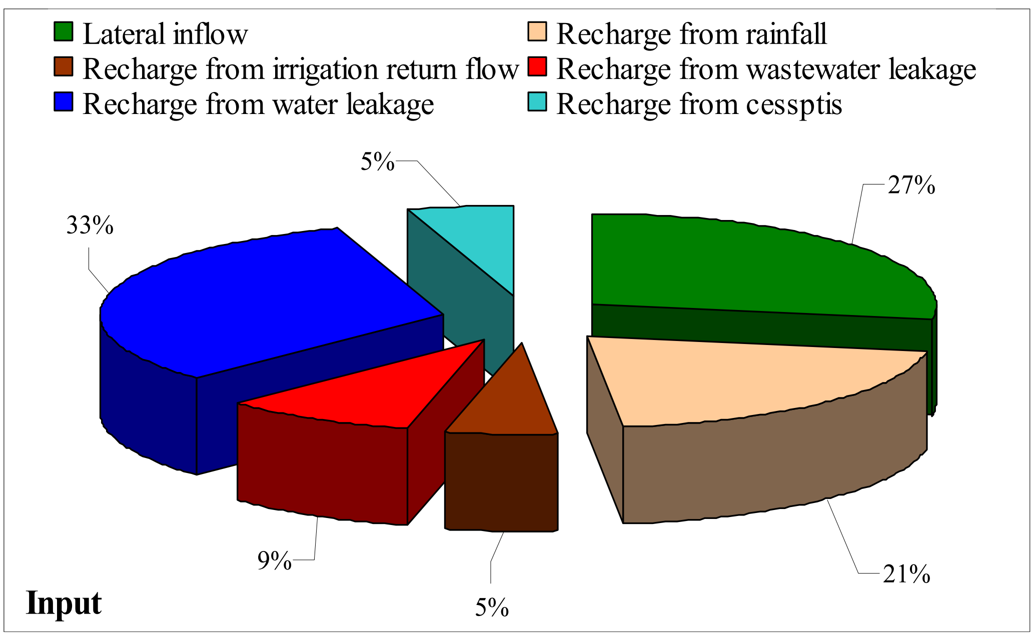


Figure (24): Pie chart of the components of groundwater inflow to the study area for the year 2004.

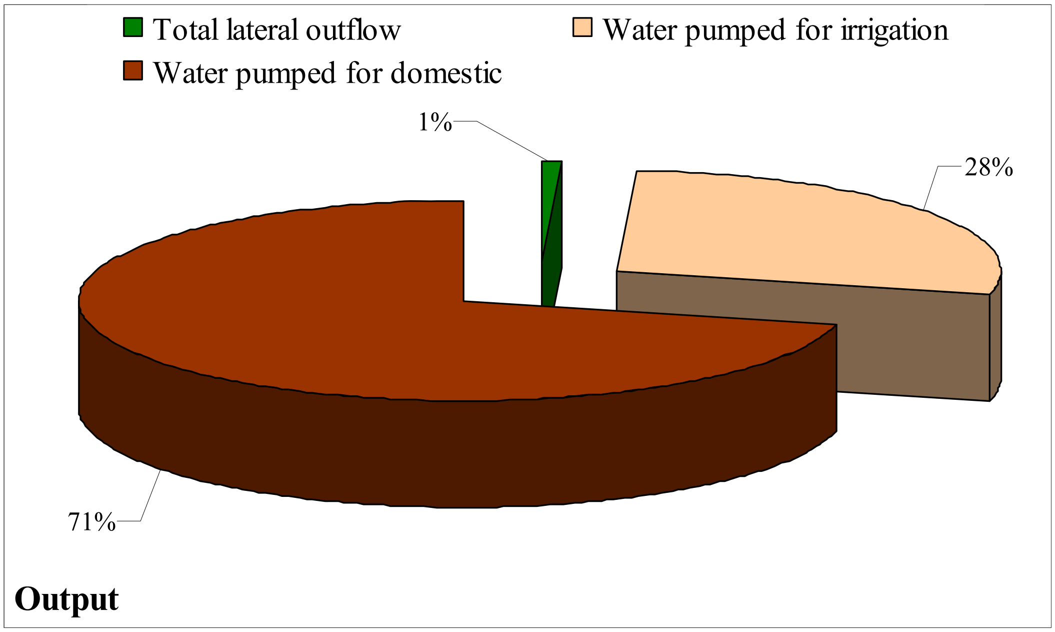


Figure (25): Pie chart of the components of groundwater outflow from the study area for the year 2004.

6.3 Quality Model Output

The main output from the quality model is the nitrate concentration of the groundwater of the study area at monthly time steps. Figure (26 depicts the time series of nitrate concentration for the groundwater of the study area for the period from 2000 to 2003.

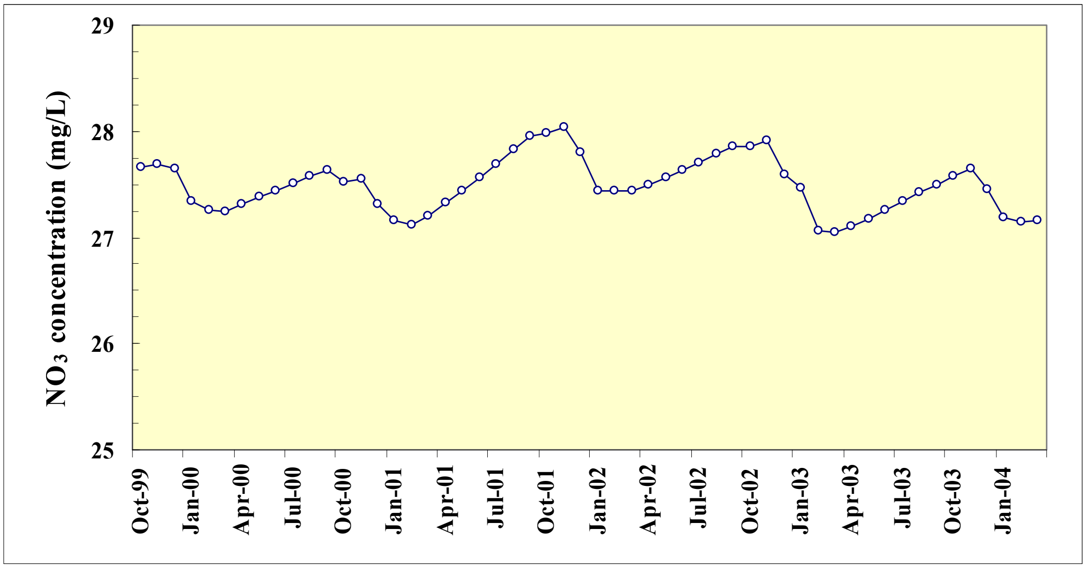


Figure (26): The variability of the average nitrate concentration with time.

The nitrate concentration value ranges between 26.5 mg/L NO_3N and 28.5 mg/L NO_3N. The maximum value of nitrate concentration occurs in November when the average water table is at its minimum value. Obviously, all the monthly values of nitrate concentrations as simulated by the model exceed the MCL of 10 mg/L NO_3N.

Figure (27 shows the variability of the change in the nitrate mass at monthly time steps for the groundwater of the study area. This in other words represents the difference between the mass of nitrate input and output for the study area. Apparently, there are positives and negatives due to the different stresses that impact the groundwater of the study area which in turn dictate the mass of nitrate that enters or leaves the model domain.

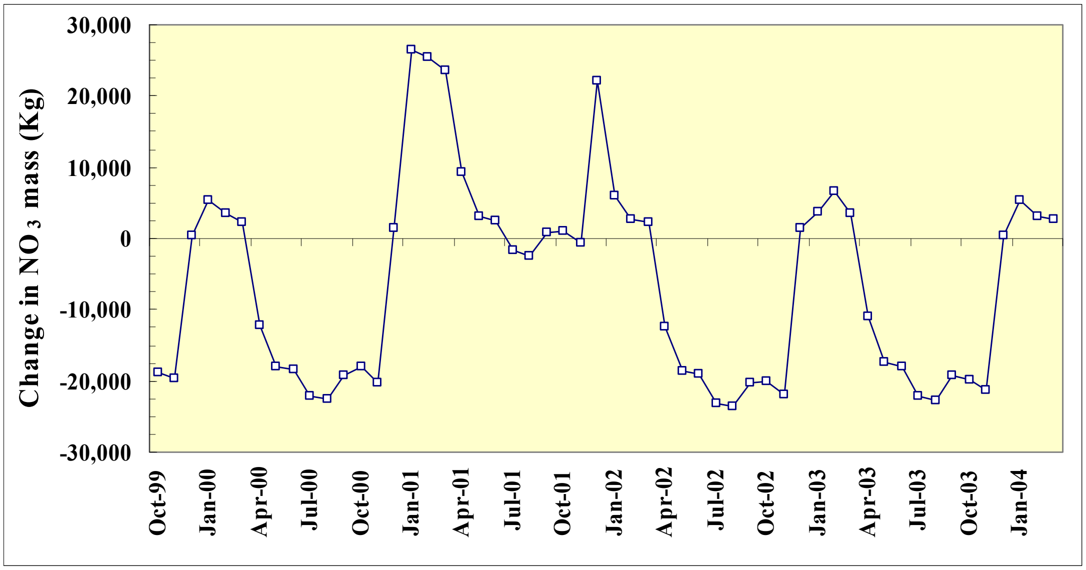


Figure (27): The variability of the monthly variation in the change in nitrate mass in the groundwater of the study area.

Table 7 was carried out in order to compare the amounts of nitrate input components with the amounts of nitrate output for the study area and to get an idea about the sources that contaminate the groundwater of the study area from nitrate. This assessment facilitates the setting up of the management options.

By comparing the total mass of nitrate input with that of output, we find that the mass of nitrate that leaves the groundwater of the study area is more than that enters the aquifer. This is due to the continuous decline in the water table which is noticeable.

If we examine the amount of nitrate that enters the groundwater of the study area, we find that the lateral inflow carries the biggest amount of nitrate compared to the other sources. Apparently, the adjacent areas must be in our management consideration.

The amount of nitrate from cesspit recharge is less than that from wastewater leakage because only 10% of the study area uses cesspits. The contribution of fertilizers to overall nitrate input to the groundwater of the study area is less than that from wastewater leakage since we have residential area (The built up area in the GCJC is about 26.27 km^2 which comprises about 45% from the total area).

Table (7): The nitrate budget for the groundwater of the GCJC area in 2003.

In (Kg)				**Out** (Kg)		
Nitrate from		Lateral Inflow	314,552	Nitrate lost through	Lateral Outflow	10,155
		Fertilizers	162,936		Denitrification	13,585
		Artificial Recharge	0		Domestic groundwater	851,306
	Recharge	Wastewater Leakage	270,324		Irrigation groundwater	346,093
		Cesspits	161,825			
		Rainfall	6,982			
		Water Leakage	143,324			
		Irrigation return flow	23,817			
		Total Input	**1,083,760**		**Total Output**	**1,221,139**

To better gain insight regarding the different sources and sinks of nitrate for the study area, pie charts were developed for the year 2003 to show these sources and sinks. Figure (28 shows that the major source of nitrate to the GCJC area is coming from the surrounding area through lateral inflow. Wastewater leakage is the second major source of nitrate followed by fertilizer surplus and cesspits. Nitrate from irrigation return flow is minor.

Figure (28 also aids in the development of management options that aim at mitigating the problem of nitrate contamination in the groundwater of the study area. This is because Figure (28 points out the major sources contributing to the problem of elevated nitrate concentration.

Figure (29 shows the sinks of nitrate from the GCJC area. Apparently, nitrate is chiefly lost through water pumped for domestic purposes. Denitrification of nitrate is a minor pathway for the loss of nitrate.

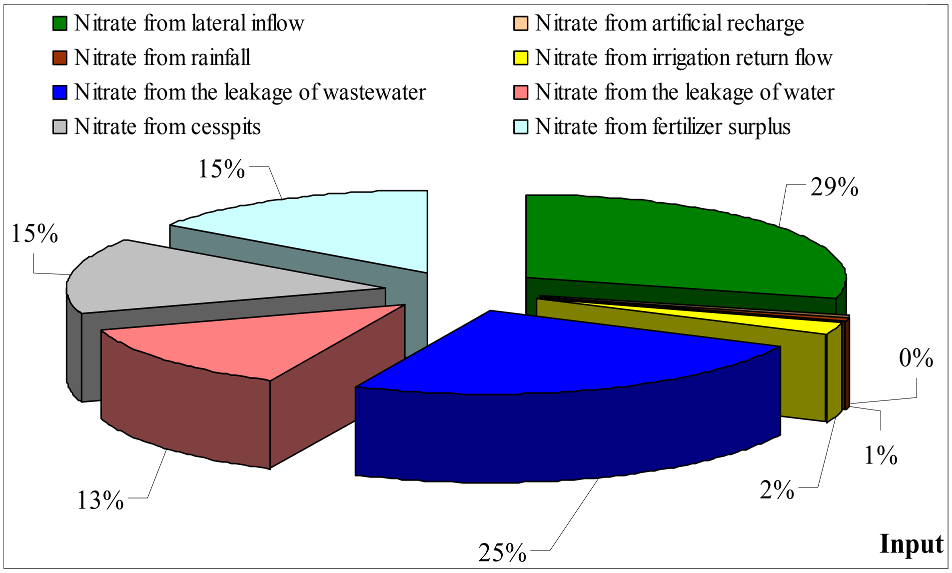


Figure (28): Pie chart of the components of nitrate input to the groundwater of the study area for the year 2003.

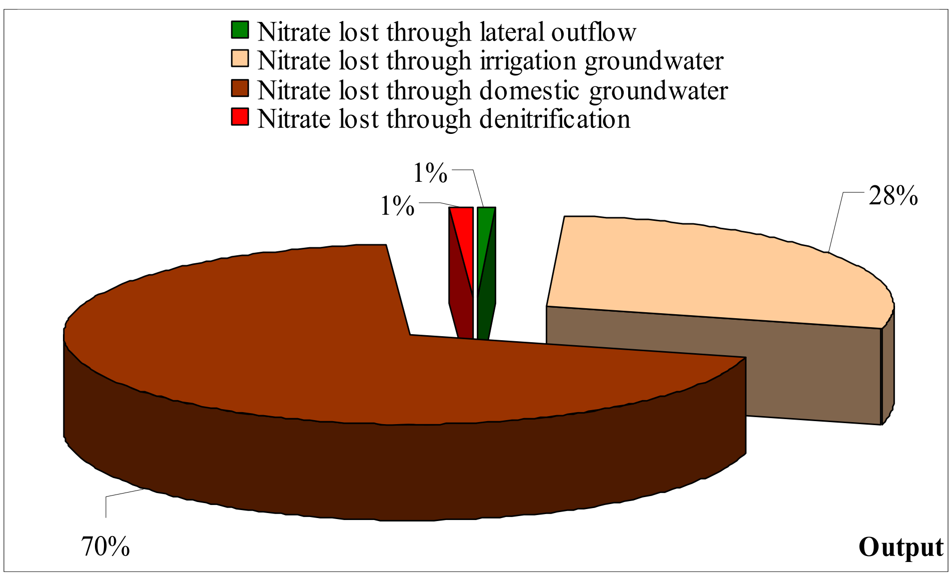


Figure (29): Pie chart of the components of nitrate outflow from the groundwater of the study area for the year 2003.

CHAPTER 7

MANAGEMENT OF NITRATE CONTAMINATION OF THE GROUNDWATER OF THE STUDY AREA

7.1 Introduction

As can be concluded from the previous chapters, the aquifer is undergoing a nitrate contamination problem. This situation necessitates the introduction of management options and the adoption and the implementation of protection actions. As stated earlier, models provide us with a clear idea regarding the aquifer response to the proposed management options before these options being implemented. This is indeed why a great deal of this work was devoted to develop the lumped parameter model for the study area.

This chapter briefly investigates the efficiency and efficacy of the related management options aimed at reducing nitrate concentration in the groundwater of study area. Since the objective is to minimize nitrate concentration down to the MCL, a management period was proposed such that the MCL is ought to be met by the end of this period. As such, a planning period that ends by the year 2015 was considered.

7.2 Proposed Management Options

In determining the related management options that address the nitrate contamination problem, a number of alternatives were proposed and examined. The management options considered herein are the following:

1. Reduction of nitrate concentration in lateral inflow;
2. Rehabilitation of the wastewater network;
3. Full coverage of sewerage system;
4. Restriction on the use of fertilizers; and

5. Combining different management options from the above four alternatives.

The selection of the management options is based on the following considerations:

1. Much of the studies in the literature did point to the effectiveness of the proposed management options in reducing nitrate concentration (see for instance Broeke and Putten, 1997; Hasler, 1998; McLay et al., 2001; Meisinger and Delgado, 2002; Kraft and Stites, 2003; Oenema et al., 2004; Almasri and Kaluarachchi, 2004a; Almasri and Kaluarachchi, 2004b).
2. The analysis of the model results did show that the nitrogen sources targeted by the management options are contributing largely to the elevated nitrate concentration in groundwater of the study area (see for instance Figure (24); and
3. There is a consensus among the Palestinian stakeholders, decision makers, water resources experts, and environmentalists that the proposed management options address the major sources of nitrate contamination of the groundwater in the study area and Gaza strip as a whole.

In the following subsections, an impact analysis of the abovementioned management options is provided using the developed model. Nevertheless, the analysis is limited to the determination of nitrate concentration and did not consider by any mean assessing the economic ramifications.

7.2.1 Reduction of nitrate concentration in lateral inflow

Lateral inflow to the groundwater of the study area comes from the surrounding area of GCJC. This lateral inflow carries with it nitrate to the study area. To investigate the impact of the reduction of nitrate concentration in lateral inflow, a multiplication factor was considered in the model to alter each value of nitrate concentration in the lateral inflow. This factor was then reduced by 10% up to 90%. Thereafter, the model was run accordingly to find out the maximum nitrate concentration in each year throughout the management period. Results are shown in Figure 30. Apparently, with extreme reductions in concentration in lateral inflow, the concentration by the end of the period is still way above the MCL.

7.2.2 Rehabilitation of the wastewater network

This management option implies the decrease of leakage from the sewerage system. In the developed model, the leakage from the wastewater network is assumed to be 20%. Two leakage reductions of 10% and 20% were considered and the model was run accordingly. Results are shown in Figure 30.

7.2.3 Full coverage of sewerage system

The third management option is the full coverage of sewerage system. This implies that the study area will be serviced entirely by the sewerage system and there are no cesspits at all. In GCJC, only 10% of people use cesspits. Reduction percentages in cesspit use were set at 5% and 10% and the model was run to find out the maximum nitrate concentration in each year throughout the management period. Results are shown in Figure 30.

7.2.4 Restriction on the use of fertilizers

The last management option under consideration involves the restriction on the use of agricultural fertilizers. Many studies demonstrated the importance of the application of fertilizers at rates not exceeding the optimal crop demand (see for instance, Mercado, 1976; Varvel and Peterson, 1990; Weed and Karlen, 1992; Puckett et al., 1999). A range of 10 to 90 percent reduction in fertilizer application was considered and results are depicted in Figure 30.

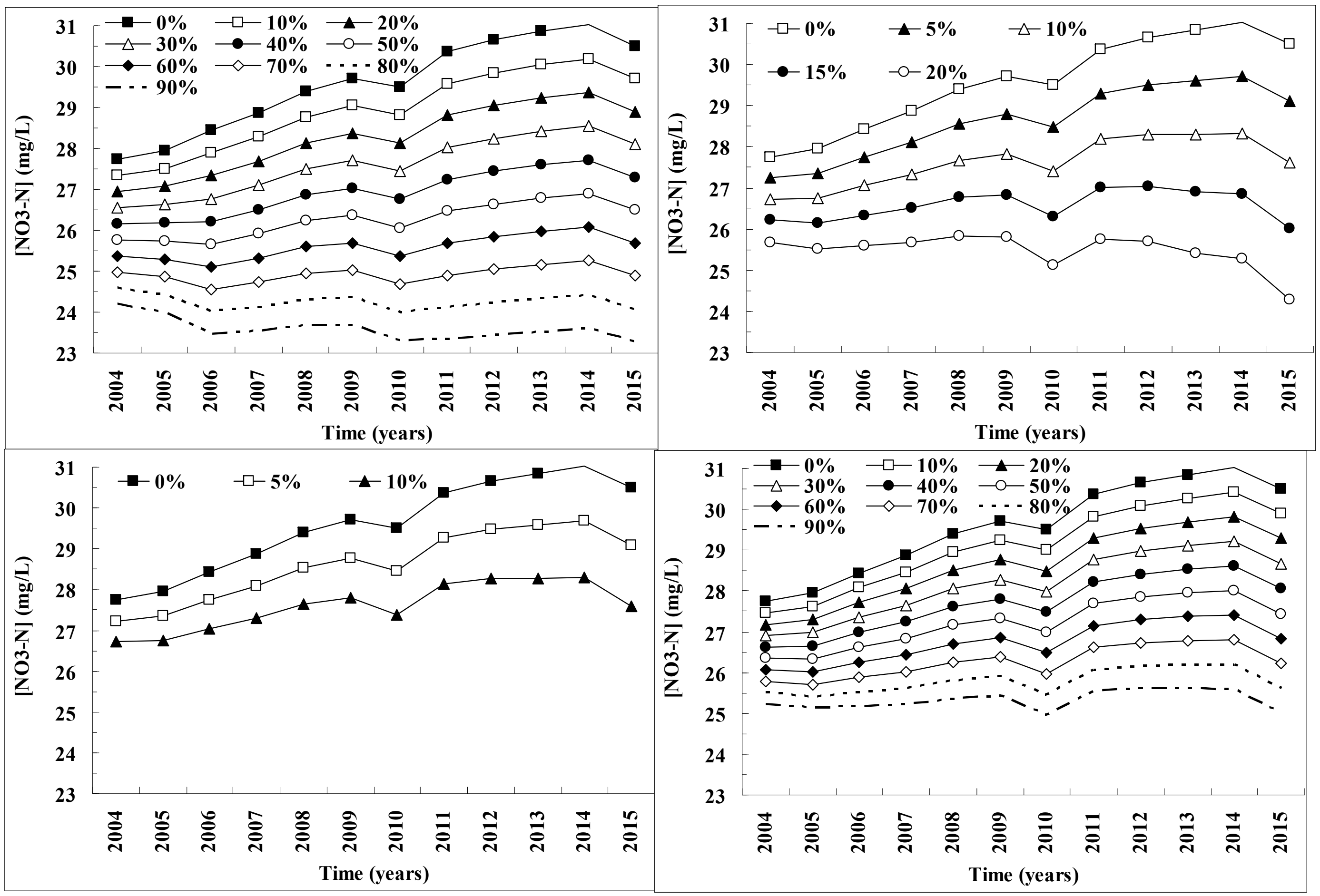


Figure (30): The maximum nitrate concentrations in each year with different reduction percentages corresponding to (i) lateral inflow; (ii) percentages of leakage from wastewater network; (iii) percentages of cesspits; and (iv) percentages of fertilizer reduction.

7.2.5 Combination of management options

In order to improve the efficiency of the management options in reducing nitrate contamination in the aquifer, a combination scheme of the management options was considered. A total of eleven combined management options were developed. The impacts of these eleven combined options were investigated.

Table 8 summarizes the single management options with their IDs. These single management options were combined together to form new management options. Impact assessment of these management options was carried out at different levels where at each level a reduction by 10% was made at once to each single management option. The total number of model runs in order to evaluate the impacts of the combined management options was 103. The different combinations between the management options with their IDs are summarized in Table 9.

Table (8): The individual management options and their corresponding IDs

ID	Description
1	Reduction of nitrate concentration in lateral
2	Rehabilitation of wastewater network
3	Full coverage of sewerage system (no cesspits)
4	Restriction on the use of fertilizers

Table (9): The different combinations between the individual management options with the corresponding IDs.

Level	ID	Option	Description
Single options	1	1	Reduction of nitrate concentration in lateral inflow
	2	2	Rehabilitation of wastewater network
	3	3	Full coverage of sewerage system (no cesspits)
	4	4	Restriction on the use of fertilizer
Two combined options	5	1+2	Reduction of nitrate concentration in lateral inflow + Rehabilitation of wastewater network
	6	1+3	Reduction of nitrate concentration in lateral inflow + Full coverage of sewerage system (no cesspits)
	7	1+4	Reduction of nitrate concentration in lateral inflow + Restriction on the use of fertilizer
	8	2+3	Rehabilitation of wastewater network + Full coverage of sewerage system (no cesspits)
	9	2+4	Rehabilitation of wastewater network + Restriction on the use of fertilizer
	10	3+4	Full coverage of sewerage system (no cesspits) + Restriction on the use of fertilizer
Three combined options	11	1+2+3	Reduction of nitrate concentration in lateral inflow + Rehabilitation of wastewater network + Full coverage of sewerage system (no cesspits)
	12	1+2+4	Reduction of nitrate concentration in lateral inflow + Rehabilitation of wastewater network + Restriction on the use of fertilizer
	13	1+3+4	Reduction of nitrate concentration in lateral inflow + Full coverage of sewerage system (no cesspits) + Restriction on the use of fertilizer
	14	2+3+4	Rehabilitation of wastewater network + Full coverage of sewerage system (no cesspits) + Restriction on the use of fertilizer
Four combined options	15	1+2+3+4	Reduction of nitrate concentration in lateral inflow + Rehabilitation of wastewater network + Full coverage of sewerage system (no cesspits) + Restriction on the use of fertilizer

7.3 Results and discussion

As shown earlier, all individual management options do not lead to a safe level of nitrate concentration at the end of the management period. Table summarizes the outcome from the different combined management options.

Table (10): Summary of the results of the combined management options summarized in Table **9**.

Option	Level (%) and Concentration (mg/L)									
1+2	0% + 0%	10% + 10%	20% + 20%	30% + 20%	40% + 20%	50% + 20%	60% + 20%	70% + 20%	80% + 20%	90% + 20%
	30.0	26.2	21.9	21.0	20.1	19.2	18.3	17.4	16.6	15.7
1+3	0% + 0%	10% + 10%	20% + 10%	30% + 10%	40% + 10%	50% + 10%	60% + 10%	70% + 10%	80% + 10%	90% + 10%
	30.0	26.2	25.4	24.5	23.7	22.9	22.1	21.2	20.4	19.6
1+4	0% + 0%	10% + 10%	20% + 20%	30% + 30%	40% + 40%	50% + 50%	60% + 60%	70% + 70%	80% + 80%	90% + 90%
	30.0	28.6	27.2	25.9	24.5	23.1	21.7	20.3	18.9	17.5
2+3	0% + 0%	10% + 10%	20% + 10%							
	30.0	23.3	18.7							
2+4	0% + 0%	10% + 10%	20% + 20%	20% + 30%	20% + 40%	20% + 50%	20% + 60%	20% + 70%	20% + 80%	20% + 90%
	30.0	26.4	22.3	21.6	20.9	20.3	19.6	18.9	18.2	17.6
3+4	0% + 0%	10% + 10%	10% + 20%	10% + 30%	10% + 40%	10% + 50%	10% + 60%	10% + 70%	10% + 80%	10% + 90%
	30.0	26.4	25.8	25.2	24.5	23.9	23.3	22.6	22.0	21.4
1+2+3	0% + 0% + 0%	10% + 10% + 10%	20% + 20% + 10%	30% + 20% + 10%	40% + 20% + 10%	50% + 20% + 10%	60% + 20% + 10%	70% + 20% + 10%	80% + 20%+ 10%	90% + 20% + 10%
	30.0	22.4	16.8	15.8	14.9	13.9	12.9	12.0	11.0	10.1
1+2+4	0% + 0% + 0%	10% + 10% + 10%	20% + 20% + 20%	30% + 20% + 30%	40% + 20% + 40%	50% + 20% + 50%	60% + 20% + 60%	70% + 20% + 70%	80% + 20%+ 80%	90% + 20% + 90%
	30.0	25.6	20.5	19.0	17.4	15.8	14.3	12.7	11.1	9.6
1+3+4	0% + 0% + 0%	10% + 10% + 10%	20% + 10% + 20%	30% + 10% + 30%	40% + 10% + 40%	50% + 10% + 50%	60% + 10% + 60%	70% + 10% + 70%	80% + 10%+ 80%	90% + 10% + 90%
	30.0	25.6	24.1	22.7	21.2	19.7	18.3	16.8	15.4	13.9
2+3+4	0% + 0% + 0%	10% + 10% + 10%	20% + 10% + 20%	20% + 10% + 30%	20% + 10% + 40%	20% + 10% + 50%	20% + 10% + 60%	20% + 10% + 70%	20%+ 10% + 80%	20% + 10% + 90%
	30.0	22.6	17.2	16.5	15.7	15.0	14.3	13.5	12.8	12.0
1+2+3+4	0% + 0% + 0% + 0%	10%+10%+ 10%+10%	20%+20%+ 10%+20%	30%+20%+ 10%+30%	40%+20%+ 10%+40%	50%+20%+ 10%+50%	60%+20%+ 10%+60%	70%+20%+ 10%+70%	80%+20%+ 10%+80%	90%+20%+ 10%+90%
	30.0	21.7	15.3	13.6	11.9	10.2	8.5	6.8	5.1	3.4

At the end of the management period, the single management option #1 gives a nitrate concentration of 22.9 mg/l which is the lowest (in terms of nitrate concentration) among the other three single management options. Management options 2, 3, and 4 give nitrate concentrations of 23.6, 24.6 mg/l, and 27.04 mg/l, respectively. That is, management option #1 is the most efficient among the four options. However, none of these four options was able to meet the MCL constraint. As such, this ineffectiveness of the individual management options compelled the combination of the single management options.

Table 10 shows the outcome of the 103 management options and the corresponding nitrate concentrations for the 11 scenarios that correspond to the combinations (options from 5 to 15 as summarized in Table). From these 103 concentrations, there are only five options that yield concentrations below the MCL. These five combinations are for the combined management options #12 with level 10 and #15 with levels 7, 8, 9, and 10.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The following are the main conclusions:

1. Groundwater contamination by nitrate is an on-going problem in the GCJC area due to the existence of heavy agriculture in the surrounding areas, disposal of untreated wastewater, and cesspits.
2. After assessing all the management options using the developed model; only five options gave acceptable results and these are:

Option	Description	% Reduction	$[NO_3\text{-}N]$ (mg/L)
1+2+4	Reduction of nitrate concentration in lateral inflow + Rehabilitation of wastewater network + Restriction on the use of fertilizer	90%+20%+90%	9.6
1+2+3+4	Reduction of nitrate concentration in lateral inflow + Rehabilitation of wastewater network + Full coverage of sewerage system (no cesspits) + Restriction on the use of fertilizer	60%+20%+10%+60%	8.5
		70%+20%+10%+70%	6.8
		805+20%+10%+80%	5.1
		90%+20%+10%+90%	3.4

3. If we increase the MCL to 16 mg/L NO_3-N instead of 10 mg/L NO_3-N, then there will be additional 24 acceptable management options on top of the previous five ones;

4. There is an emerging need to manage the nitrate contamination problem in the groundwater of the study area. As such, models are useful for reconnaissance studies preceding the implementation of the proposed management options.
5. Single-cell lumped parameter models are simple, easy to understand and develop, and efficiently aid in the analysis of the impact of the management options on the nitrate occurrences in groundwater.
6. Single management options are not effective when they are considered individually. As such, combinations of individual management options must be considered and implemented in order to arrive at nitrate concentrations below the MCL.

8.2 Recommendations

The following are the main recommendations that can be potentially considered in any future related research work:

1. Since the developed model in this study is a single cell-lumped parameter model, it might be necessary to consider the development of a spatially distributed model in order to pinpoint the areas that have high concentrations of nitrate within the study area.

2. The research although did develop and analyzed the potential impacts of the management options from a quality point of view, yet there is a need to carry out an associated economic analysis to evaluate the benefit cost analysis for the management options.
3. The work did address the issue of nitrate contamination in the groundwater of the study area. However, other pollutants should be considered such as chloride.
4. Since the quality of the aquifer depends upon its quantity, we must first address the quantity problems.
5. An efficient management plan should consider the institutional, social, and legal arrangements.

CHAPTER 9

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قدمت هذه الأطروحة استكمالا لمتطلبات نيل درجة الماجستير في هندسة المياه والبيئة بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس، فلسطين.

2007

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الملخص

تعتبر المياه الجوفية المصدر الرئيسي للمياه في فلسطين للاستخدامات المختلفة، لذلك لا بد من الاهتمام بكمية وجودة المياه الجوفية. في هذا البحث تم اختيار مدينة غزة ومخيم جباليا كمنطقة لدراسة تلوث المياه الجوفية فيها بالنيترات، حيث أظهرت بعض الدراسات أن أكثر من 90% من آبار التزويد بالمياه لقطاع غزة من الحوض الجوفي ملوثة بالنيترات. من أجل ذلك تم تمثيل هذا الواقع من خلال تطوير نموذج رياضي مجمل (Single-cell model) . وبعد التأكد من محاكاة هذا النموذج للوضع القائم تم استخدامه كأداة لدراسة مختلف الخيارات لتقليل تركيز النيترات في المياه الجوفية لمنطقة الدراسة لمستويات أقل من الحد الأعلى المسموح به، ومن ثم قياس فاعليتها والمقارنة في ما بينها وتبني ما يناسب. خرجنا من هذا البحث إلى أن وضع المياه الجوفية يزداد سوءا ويحتاج إلى تدخل عاجل لحل هذه المشكلة المتفاقمة، وأن اعتماد خيار واحد لحل هذه المشكلة لا يجدي نفعا لذلك لا بد من إشراك أكثر من خيار في عملية إصلاح جودة المياه الجوفية في منطقة الدراسة. وبالتحديد فقد أظهرت النتائج أنه لا يمكن أن يتم إصلاح جودة المياه الجوفية إلا إذا تم خفض كمية النيترات التي تصل إلى الحوض الجوفي من المناطق المحيطة بمنطقة الدراسة، ومن الأسمدة المستخدمة بالزراعة، وكذلك يجب عمل إعادة تأهيل لشبكة الصرف الصحي في المنطقة وتغطية المنطقة كلها بهذه الشبكة.