An-Najah National University
Faculty of Graduate Studies

Modeling Nitrate Contamination of the Eocene Aquifer, Palestine

By
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DEDICATED TO MY LOVELY PARENTS

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الإقـــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Modeling Nitrate Contamination of the Eocene Aquifer, Palestine

تطوير نموذج رياضي لتمثيل تلوث الحوض الجوفي الايوسيني بالنيترات، فلسطين

اقر بأن ما اشتملت عليه هذه الرسالة إنما هو نتاج جهدي الخاص، باستثناء مـــا تمــت الإشارة إليه حيثما ورد، وان هذه الرسالة ككل، أو أي جزء منها لم يقدم من قبل لنيل أية درجة علمية أو بحث علمي أو بحثي لدى أية مؤسسة تعليمية أو بحثية أخرى.

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's name:	**اسم الطالب:**
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Date:	**التاريخ:**

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Abstract

The Eocene Aquifer is one important aquifer in the northern West Bank. Recent measurements have indicated an increasing trend in the nitrate contamination in several monitoring wells of this aquifer. The continuing nitrate pollution of the aquifer without implementing protection measures will lead to a poor water quality. This research focuses on developing a nitrate fate and transport model for the Eocene Aquifer using MODFLOW and MT3D. The development of the MT3D model started by identifying the different sources of nitrogen in the aquifer, then both models was compiled to develop the model. The nitrate fate and transport model simulated the spatial distribution of nitrate concentration in the aquifer under the current conditions. The calculations indicated excessive nitrogen-based fertilizing rates and thus considerable nitrate leaching into the aquifer. Other responsible sources for the elevated concentrations are attributed to the use of cesspits for wastewater disposal. Features of a groundwater quality monitoring system of the Eocene Aquifer have been developed. Sensitivity analysis indicated a high influence of decay rate and the mass of nitrate leaching on nitrate concentrations.

CHAPTER ONE

INTRODUCTION

1.1 Background

Groundwater is the primary source of drinking water in many parts of the world and the sole supply of potable water in many rural communities (Solley et al., 1993). Therefore, it is essential to protect the groundwater from any potential contamination. Sources of groundwater contamination are widespread and include accidental spills, landfills, storage tanks, pipelines, agricultural activities, and many other sources (Bedient et al., 1994). Groundwater contamination by nitrate is a globally growing problem. This is because of the population growth and the increase in the demand for food. Both have intensified the agricultural activities that entail the excessive use of fertilizers, the major source for nitrate. In addition to agriculture, the unsewered sanitation in densely populated areas and the irrigation of land by sewage effluents are potential sources of nitrate contamination (Babiker et al., 2004).

Contamination by different pollutants might render groundwater unsuitable for use and put human and the whole environment at risk. But nitrate is the most frequently introduced pollutant into groundwater systems (Solley et al., 1993).

Although groundwater quality in the West Bank is generally good, the continuation of the existence of pollution sources without implementing groundwater protection measures may render the groundwater resources unsuitable for utilization.

The degradation of the water quality in the West Bank aquifers is due mainly to untreated wastewater and agricultural activities in addition to the salinization problem. This degradation has led to increased levels of sodium, chloride, and nitrates in the groundwater in many areas in the West Bank (Aliewi and Mimi, 2005).

The Eocene aquifer is one of the major aquifer systems in Palestine and is heavily utilized for both agricultural and residential activities. The aquifer is subject to an on-going contamination from nitrate and other pollutants.

This thesis focuses on developing a nitrate fate and transport model using MODFLOW and MT3D to simulate the spatial distribution of nitrate concentration in the Eocene aquifer under the existing conditions. The developed model is utilized to predict the potential impacts of possible policies for the mitigation of the nitrate contamination problem in the Eocene Aquifer.

1.2 Research Motivation

For the Palestinians, groundwater is the most important source of water that needs to be protected from nitrate contamination. The Eocene Aquifer is one important aquifer in the northern West Bank, Palestine.

Recent studies did show an increase in the nitrate concentrations in several wells of the Eocene Aquifer as evident by measurements conducted regularly by the Palestinian Water Authority (PWA). Apparently, the time series presented in Figure 11, section 3.3 show elevated concentration at different well locations within the aquifer. These elevated concentrations exceed by far the Maximum Contaminant Level (MCL) of 45 mg/l-NO_3 or 10 mg/l NO_3-N.

This situation compels the motivation for controlling the nitrate contamination in the Eocene Aquifer and provides proper tools for protecting its water quality from nitrate pollution. On-ground nitrogen loadings need to be controlled (reduced) such that the nitrate concentrations in the aquifer become lower than the MCL. Therefore, this work focuses on modeling the nitrate fate and transport in the Eocene Aquifer.

1.3 Research Problem

Depending upon simple analysis of nitrate concentration at wells in the Eocene aquifer, it was concluded that there are concentrations higher than the MCL. This may affect the public health of the residents who mainly depend upon this aquifer as the main source of water for domestic uses.

There is no sufficient knowledge about fate and transport of nitrate in the Eocene Aquifer of the West Bank. Therefore it is important to set up a model to understand the problem and to provide tools for managing the aquifer.

1.4 Research Questions

The key purpose of this research is to address, and if possible to answer, the following questions related to the nitrate contamination of the Eocene Aquifer in the northern West Bank:

1. What are the probable sources of nitrogen in the Eocene Aquifer that leads to the elevated nitrate concentration?
2. What is the spatial distribution of nitrate concentration in the Eocene aquifer?
3. How to control the nitrate concentration in the Eocene Aquifer?

1.5 Research Objectives

The objectives of the research are to:

1. Identify the different sources of nitrogen in the Eocene Aquifer;
2. Develop a nitrate fate and transport model (using MT3D and MODFLOW) for the Eocene Aquifer to map the current and future nitrate concentrations under current practices; and
3. Recommend realistic nitrogen loadings for the minimization of nitrate occurrence in the Eocene Aquifer.

1.6 Methodology

The main objective of this research is the development of a mathematical model to simulate the spatial distribution of nitrate in the Eocene Aquifer. The process of model development entails the computation of on-ground nitrogen loading and the corresponding net nitrate leaching to the aquifer. Thereafter, MOFDFLOW and MT3D models are used to simulate the spatial distribution of nitrate concentration within the Eocene Aquifer for the existing conditions and for the potential future reduced on-ground nitrogen loadings.

The research methodology concentrates on linking the developed model to the research components as shown in figure 1. The methodology starts by setting up the research objectives, thereafter, the study area is investigated and relevant studies and related reports are collected. Nitrate data and existence in the groundwater of the Eocene aquifer are modeled and assessed.

The nitrate fate and transport model was developed after the development of the groundwater flow model, on-ground nitrogen loading distribution and nitrate leaching. These models are important in mapping the nitrate concentration in the groundwater of the Eocene Aquifer under the current practices.

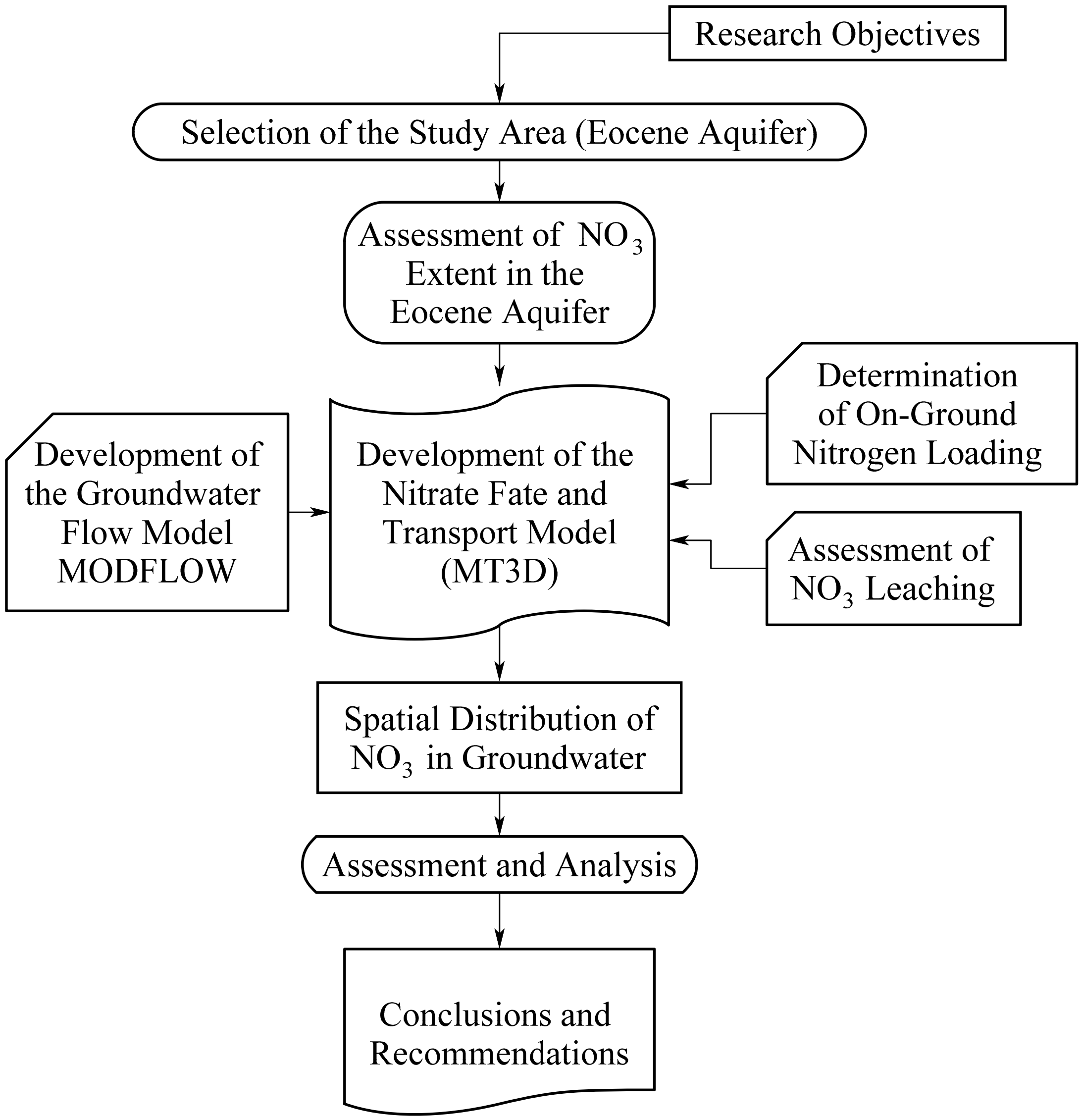


Figure 1: Research methodology

The modeling results are analyzed and conclusions and recommendations were made regarding the potential implementation of management options to control nitrate occurrences in the Eocene Aquifer. Both MODFLOW and MT3D software were utilized in the model development with the aid of GIS.

MODFLOW is a groundwater flow model while MT3D is a fate and transport model. MT3D model was chosen due to the following reasons:

1. MT3D is a three-dimensional contaminant fate and transport model for simulation of advection, dispersion, and chemical reactions of dissolved constituents and contaminants in groundwater systems (Zheng, 1990).
2. MT3D is based on modular structure that permits simulation of transport components independently or jointly with MODFLOW. It retrieves the saturated thickness, fluxes across cell interfaces in all directions, and locations of flow rates of various sources and sinks.

1.7 Thesis Outline

The general structure of the thesis is as follows. Chapter two provides the description of the study area. Chapter three presents the related literature review and chapter four presents the details of the model development and analyses of the model output. The key conclusions and recommendations are furnished in chapter five.

CHAPTER TWO

DESCRIPTION OF THE STUDY AREA

2.1 General

In the West Bank, groundwater resources form the main source of potable water. Therefore, it is essential to manage the groundwater resources and protect these from any potential contamination, especially nitrate.

The West Bank groundwater aquifer system is compromised of three major drainage basins as illustrated in figure 2 (Abu Zahra, 2001):

- The Western Basin is mainly supplied and recharged from the West Bank Mountains located within the boundaries of the West Bank;
- The Northeastern Basin is located inside the West Bank near Nablus and Jenin and drains into the Eocene and Cenomanian –Turonian aquifers;
- The Eastern Basin .The springs of this basin represent 90% of the springs discharge in this area.

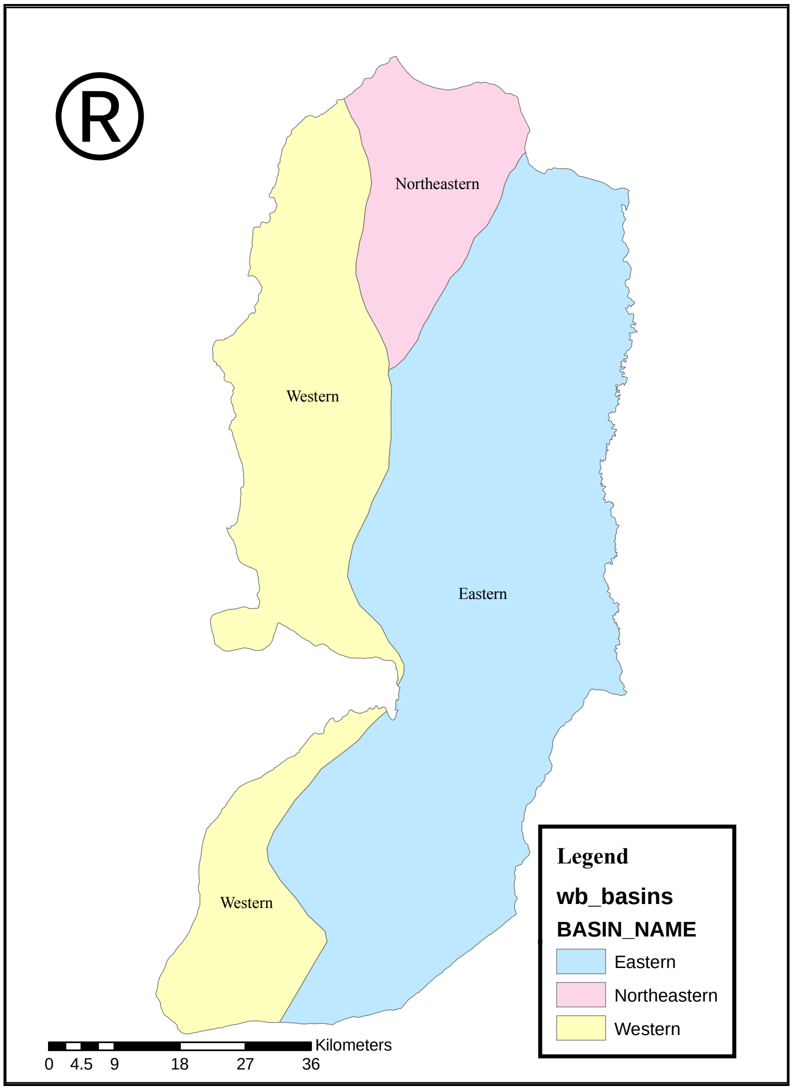


Figure 2: West Bank groundwater basins

2.2 The Eocene Aquifer

The Eocene Aquifer is part of the northeastern aquifer systems. It is located in the north-eastern part of the West Bank. To the north-east of the groundwater divide, which runs through the Jenin and Nablus districts. Part of the Eocene Aquifer is located in Tubas and outside the West Bank boundaries as shown in figure 3 (SUSMAQ, 2003).

The Eocene aquifer system overlies the Upper Cenomanian-Turnoian aquifer system, with a transition zone of chalk of variable thickness ranging from 0 to 480 m. This system is represented by the Jenin subseries of the Tertiary age and exposed in 80% of the Jenin area. It constitutes a fully utilized shallow aquifer which is lithologically composed of reef limestone, numulitic, and limestone with chalk and chalk with numulitic limestone. In this system, limestone rocks form the aquifer while chalk rocks form the aquiclude (SUSMAQ, 2003).

The Eocene Aquifer lies over an area of about 526 km^2. The quantity of annual rainfall over the area is about 270 mcm/yr; the total recharge from rainfall ranges from 45-65 mcm/yr. The irrigated area is about 11,780 dunums consuming about 7.4 mcm/yr of water (SUSMAQ, 2003).

The springs in the Eocene aquifer are classified into two groups; northern and north-eastern springs which include Yizrael, Harod, Amal, Shoqeq and Jalod springs; and eastern and south-eastern springs that include Al-Faria and Al-Badan springs. The annual average of these springs is estimated at around 39 mcm mostly flowing in the wadies. The recharge from the wadies and return flow is estimated at 3 mcm/yr. The long-term average abstractions from the Eocene aquifer for all uses is about 16.4 mcm/yr pumped by the wells tapping the aquifer (SUSMAQ, 2003). Figure 3 presents the location, extension, and boundaries of the Eocene Aquifer.

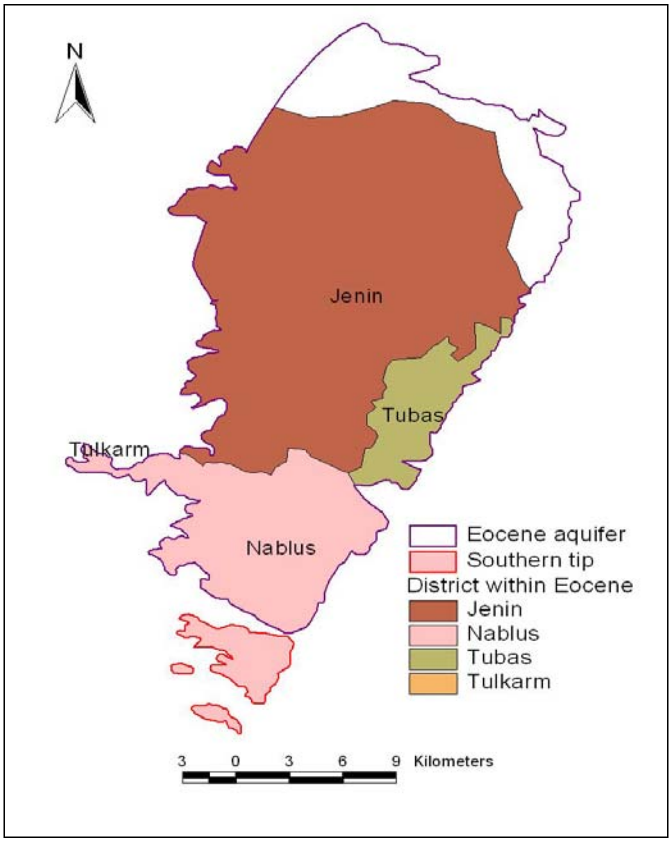


Figure 3: The Eocene Aquifer

2.2.1 Hydrogeology

The thickness and lithology of the Eocene Aquifer varies widely in the center and in the west. It is mostly highly karstic reef limestone in the east and soft chalk dominates. The primary hydrostratigraphic formation of the

Eocene Aquifer as summarized and arranged from oldest to youngest are as follows (Arij, 2002):

1. Limestone, dolomite and marl (Cenomanian to Turonian);
2. Chalk and chert of Senonian age;
3. Chalk, limestone and chert of Eocene age; and
4. Alluvium of Pleistocene to recent age.

According to the Jordanian nomenclature, the detailed geology of the Eocene aquifer shows the following geological formations (Arij, 2002):

1. Cretaceous Rocks

Cretaceous Rocks can be divided into the following formations:

Lower Beit Kahil Formatiom : Outcrops of this formation exist in the core of the Faria anticline. The lower part of the sequence consists of thick and massive limestone and sandy marl shales in the middle and sandy ferruginous limestone at the top. This formation is considered a good aquifer.

Upper Beit Kahil Formation: Outcrops of this formation exist in the north on the deeply eroded flanks of the Faria anticline. This formation is composed mainly of limestone, marl, dolomite and dolomitic limestone. It is a moderate to good aquifer.

Yatta Formation: Outcrops of this formation exist in the north of Jenin district. The formation consists of chalky limestone, marl and calcareous karstic limestone. Hydrogeologically, it is regarded as a poor aquiclude.

Hebron Formation: The main outcrops are exposed mainly in the northwestern part of Jenin district as well as in the Faria anticline. The lithological composition consists of limestone, dolomite and chalky limestone; it is regarded as the important aquifer in the district.

Bethlehem Formation: Outcrops exist on the flank of the Anabta anticline. This formation consists of dolomite, limestone and chalky marl.

Jerusalem Formation: The most extensive outcrops are in the Anabta anticline and in the flanks of the Faria anticline. It consists of massive, bedded limestone, dolomite and chalky limestone. The formation forms a good aquifer.

2. Rocks of Cretaceous to Tertiary Transition Chalk

The outcrops exist in the western limb of the Nablus-Beit Qad syncline. The chalk faces make the formation a good aquiclude.

3. Tertiary Rocks

These are represented by two lithological units:

Jenin Subseries: this consists mainly of chalk of Eocene age. Outcrops are widely spread covering large areas of the district. In this formation, five faces of limestone and chalk are described: chalk with minor chert, chalk with inter-bedded limestone, limestone with minor chalk, massive limestone and reef limestone. Generally, it forms a good aquifer except in the chalk zone, where it forms an aquiclude. Variable thickness reaches about 700 meters in some places of Jenin district.

Bayda Formation: this ranges in age from the Miocene to Pliocene. Conglomerate forms the main composition of this formation, with some marl and limestone. There is unconformity between the conglomerate and Cretaceous rocks. Outcrops are extensive in the northeast of the district in the Bardala-Bayda area.

4. Quaternary Rocks: this consists of unconsolidated laminated marl with some siliceous sand know as alluvium rocks. It has a red color and fine texture which is due to its derivation from limestone.

5. Igneous Rocks: These are widespread east of Beit Qad. These rocks are dark, green, fine-grained, basic or sub-basic, and have a strong jointing.

The cross-section in figure 4 presents the geological strata and aquifers in the northern West Bank and the study area.

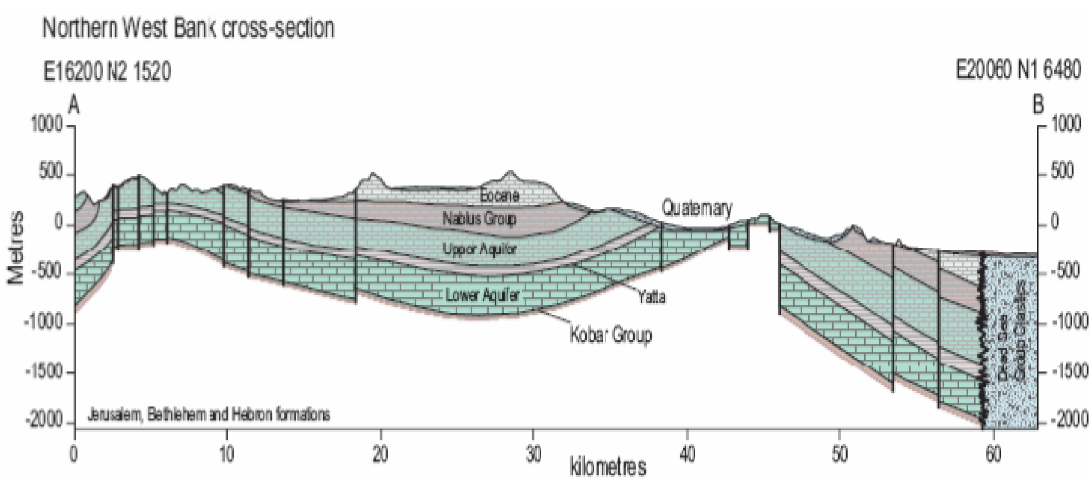


Figure 4: North-eastern cross-section of the West Bank (BGS, 2005)

Hydro-geological cross-sections are the cornerstone to the conceptualization of the hydostratigraphy of any aquifer. They are used to evaluate the three-dimensional characteristics of folding, faulting and thickening of hydrostratigraphic units. Hydro-geologic cross-sections are essential to building a representative groundwater model because they allow the evaluation of the ways that subsurface geometry of hydrostratigraphic units affects groundwater flow. Once these features are conceptualized using cross-sections, they can be accurately represented mathematically in the groundwater model (MEG, 1999).

2.2.2 Topography

The central and northeastern parts of the Eocene Aquifer system have relatively flat to hilly topography that rises about 300 to 600 m above sea level. The area is characterized by closed and semi-closed depressions such as Marj Sanur and Arrabeh plain as well as the flat area in the north of Jenin City. Figure 5 depicts the topography of the area overlaying the Eocene Aquifer.

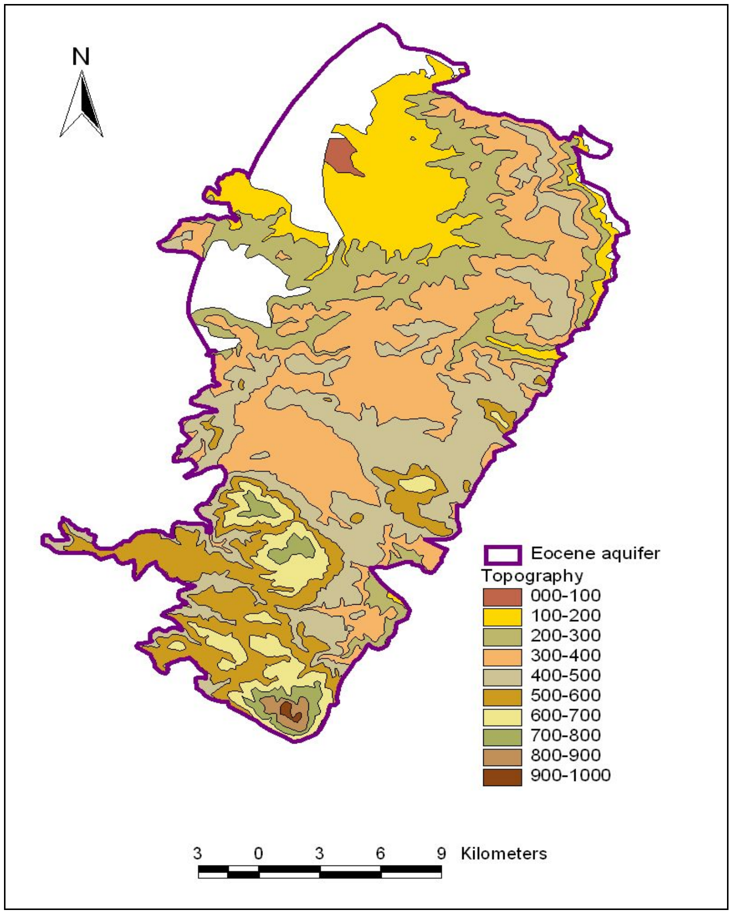


Figure 5: Topography of the Eocene Aquifer (BGS, 2005)

2.2.3 Climate

The Mediterranean climate dominants the West Bank where wet winter and dry summer are considered as clear climate seasons. The rainy season extends from October to May. Approximately 3.2% of the annual rainfall falls in October while almost 80% falls during November through February (Arij, 2002).

Figure 6 shows the location of rainfall stations and the distribution of rainfall in the study area. There are nine rainfall stations within the Eocene Aquifer boundary that have a rainfall range between 642 mm in Tallozah station to 400 mm in Beit Dajan station.

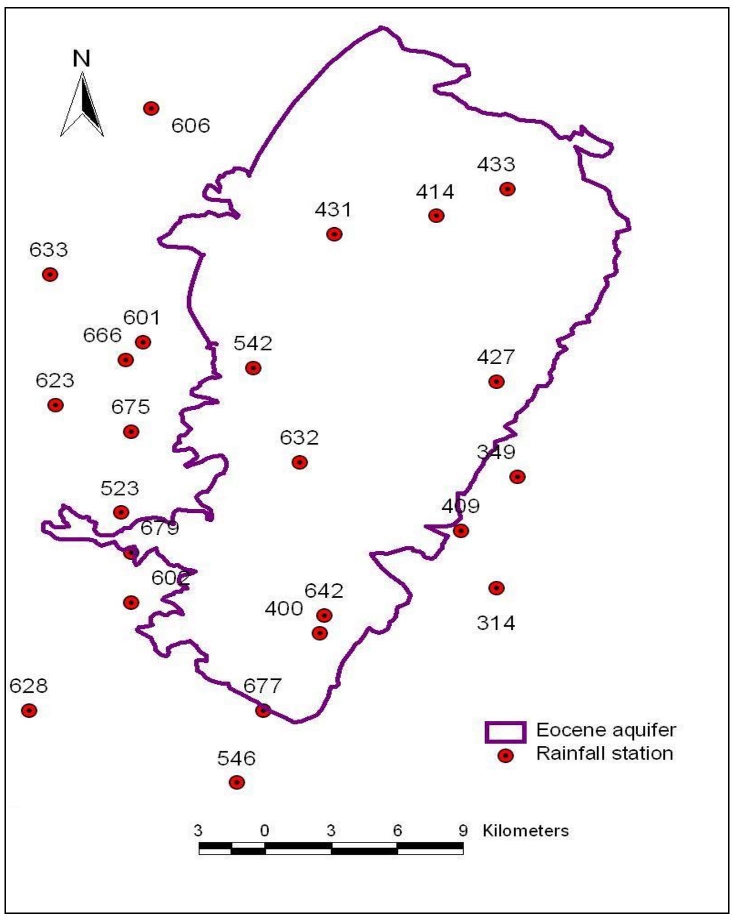


Figure 6: Spatial distribution of the rainfall in the study area (BGS, 2005)

The number of rainy days in the study area range from 25 days to 60 days. Evaporation is particularly high in summer and low in winter (MEG, 1999).

The average annual relative humidity is around 62% with peak values in winter up to 84%. It drops to 40% during May. In summer the humidity is 56% (Kharmah, 2007).

The minimum temperature in winter season ranges from 7C^o to 15C^o. Temperatures below the freezing point are rare. The average maximum temperature in summer is 33C^o while the average minimum is 20C^o (Arij, 2002).

2.2.4 Land Use

The land use patterns in the West Bank are greatly influenced by topography and climate, political conflict over land and, natural resources. Such factors affect the distribution of cultivated areas, urban areas, road construction and other land uses (Arij, 2002). The land use can be classified into the following classes:

- Built-up areas: due to the restrictions imposed by Israelis on granting building permits to the Palestinians, the Palestinian built-up areas are very limited.
- Israeli Settlements: several settlements are distributed over the study area and there is a gradual progressive expansion in the Israeli settlements;

- Closed military and bases: the Israeli army occupies Palestinian land by claiming that these areas are important both as security zones and for military purposes;
- Natural reserves: there is a piece of land in the northern part of the aquifer declared as a natural reserves;
- Forests: there are many forests in the study area and most of these forests are located in fertile soil types;
- Cultivated areas: the total cultivated area varies from one year to another depending on the annual amount of rainfall. About 8% of the cultivated areas are irrigated and about 92% of are irrigated by another sources of water as illustrated by figure 7;
- Industrial areas: there are few industrial zones in the study area;
- Dumping sites: there are many random dumping sites in the study area. Later Zahrat Al-Finjan sanitary landfill site was constructed and many of these dumping sites have been closed.
- Quarries: there are five quarries in Jenin district;
- Roads: there are 77 km of main roads and 382 km of secondary roads in Jenin district.

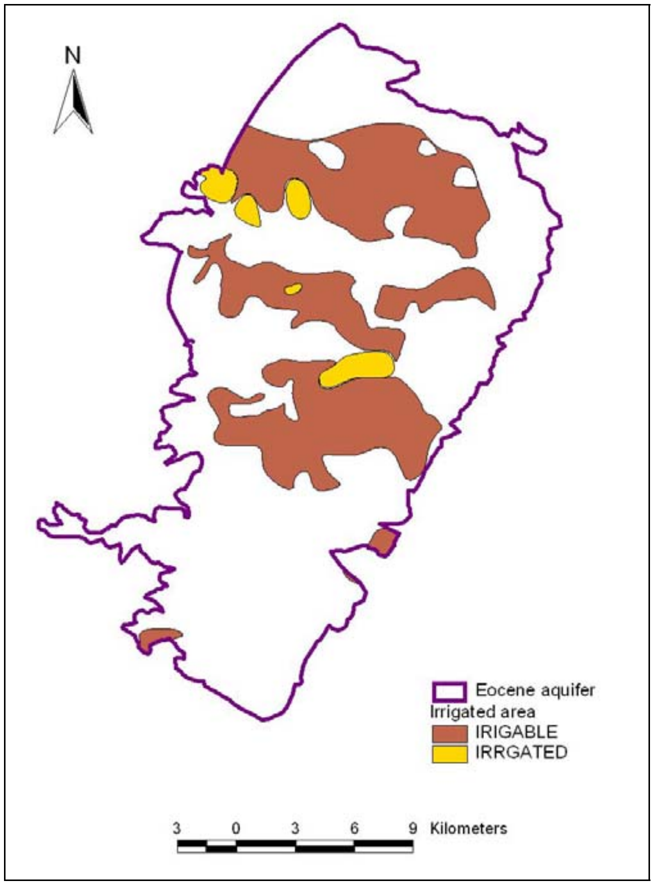


Figure 7: Cultivation area within the Eocene Aquifer (BGS, 2005)

2.2.5 Soil Types

There are three types of soil presents in the study area as shown in figure 8:

1. Terra Roza, Brown Rendzinas and Pale Rendzinas: this type of soil association occupies about 63% of the study area;

2. Brown Rendzinas and Pale Rendzinas: this type of soil association occupies about 9% of the study area;

3. Grumusols: the topography of this soil is almost flat and is organically formed from fine textured alluvial or Aeolian sediments. This soil occupies about 28% of the study area.

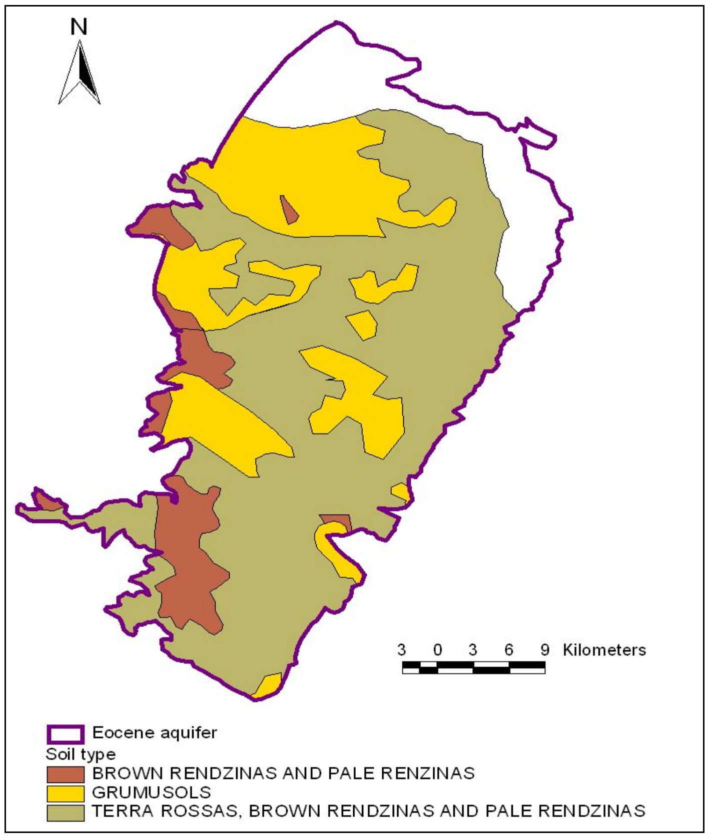


Figure 8: Soil Association within the Eocene Aquifer (Kharmah, 2007)

2.2.6 Local Communities

There are 27 local communities that live within the outline of the Eocene Aquifer as shown in figure 9. These communities are located within

Nablus, Jenin, and Tubas districts. Table 1 summarizes the information related to these communities in terms of census and areas.

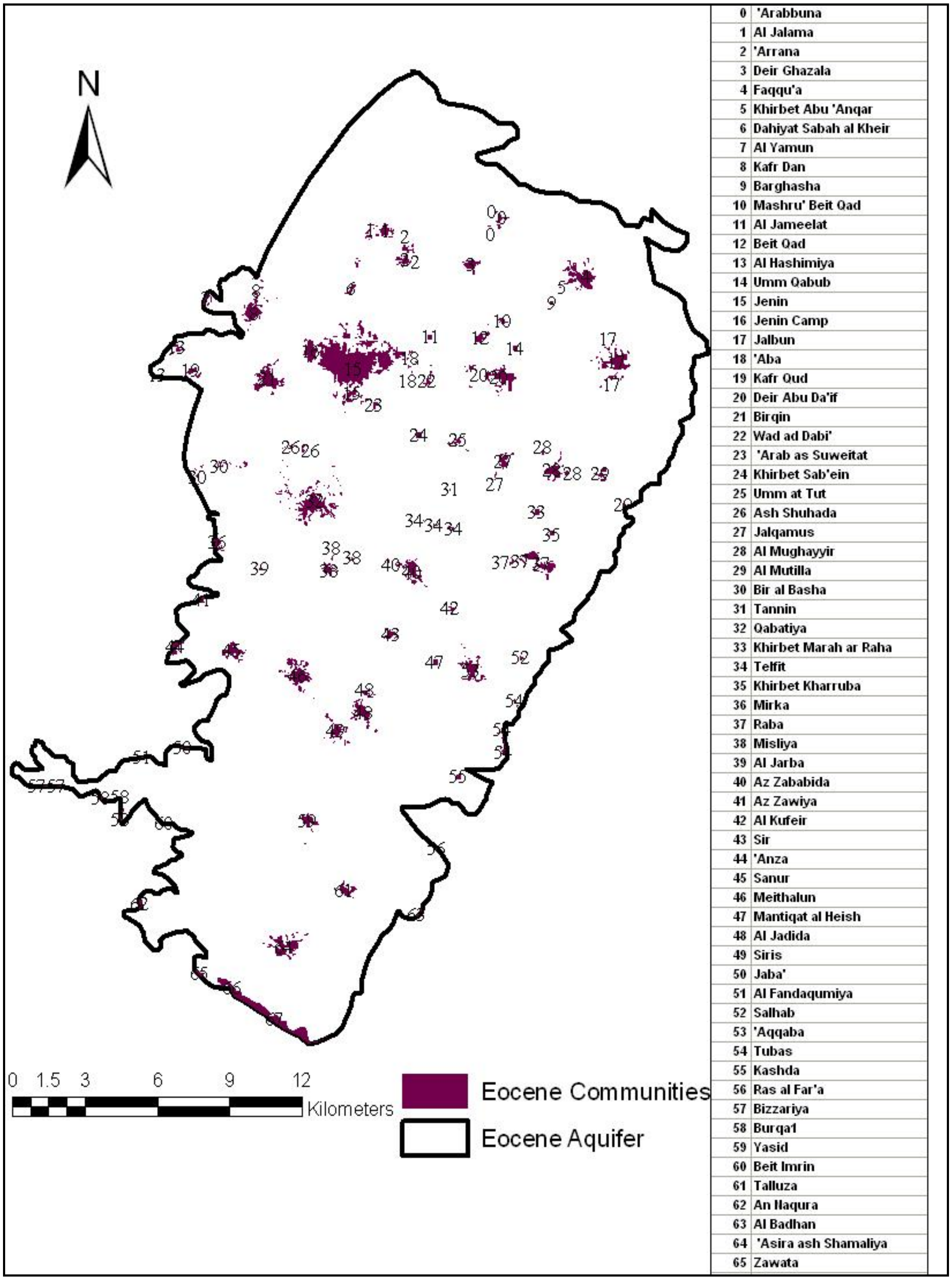


Figure 9: Communities existing within the Eocene Aquifer

Table 1: The communities within the Eocene Aquifer along with population

Name	Population in 2006	Area (km^2)
Al Jalama	2471	0.26
Deir Ghazala	916	0.19
Al Yamun	17851	1.34
Jenin City and Jenin Camp	51450	4.06
Birqin	6328	0.63
Umm at Tut	1075	0.09
Ash Shuhada	1864	0.06
Jalqamus	2002	0.18
Al Mughayyir	2402	0.32
Tannin	621	0.01
Qabatiya	21123	1.1
Telfit	596	0.053
Mirka	1668	0.13
Az Zababida	4143	0.39
Az Zawiya	753	0.037
'Anza	2152	0.18
Sanur	4573	0.29
Jaba'	9335	0.23
Al Fandaqumiya	3607	0.08
'Aqqaba	6512	0.41
Tubas	17254	1.78
Bizzariya	2098	0.14
Burqa	3930	0.43
Beit Imrin	2840	0.12

An Naqura	1617	0.22
'Asira ash Shamaliya	7568	0.54
Total	**176,749**	**13.27**

CHAPTER THREE

LITERATURE REVIEW

3.1 General

Nitrogen is a vital nutrient to enhance plant growth. Nevertheless, when nitrogen-rich fertilizers application exceeds plant demand and the denetrification capacity of the soil, nitrogen can leach into groundwater usually in the form of nitrate (Meisinger and Randall, 1991).

High nitrate levels in water can cause methemoglobinemia or blue baby syndrome, a condition found in infants of less than six months of age.

Nitrogen (N) exists as soil 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 (Jury and Nielsen, 1989; Hubbard and Sheridan, 1994; Ling and El-Kadi, 1998, DeSimone and Hows, 1998; Tesoriero, et al., 2000).

3.2 Nitrate Problem in the World

Kyllmar et al. (2004) used Model-based coefficient method for the calculation of N leaching from agricultural fields in small catchments and the effect of the leaching reducing measures. They developed a method to calculate N leaching from arable fields using model-calculated N leaching coefficients (NLCs). Using the process-based modeling system SOILNDB, they simulated leaching of N for four leaching regions in southern Sweden with 20-year climate series and a large number of randomized crop sequences based on regional agricultural statistics. To obtain N leaching coefficients, mean values of annual N leaching have been calculated by their model for each combination of main crops, following crop and fertilization regime for each leaching region and soil type. The field-NLC method can be useful for following up water quality goals in small monitoring catchments since it allows normal leaching from actual crop rotations and fertilizations to be determined regardless of the weather. Their method was tested using field data from nine small intensively monitored agricultural catchments.

Vinten and Dunn (2001) assessed the effects of land use on temporal changes in well water quality in a designated nitrate vulnerable zone by using a balance sheet approach to estimate nitrate leaching for the range of crops that have been grown in a catchment over the last 30 years. Estimates of denitrification and in-field composting of vegetable crop residues were considered by their model.

Chowdary et al. (2005) used a decision support framework for the assessment of non-point-source pollution of groundwater in large irrigation projects. They found that the concentration of nitrate in the percolated water depends on the distributed field water and nitrogen balances over the area. The nitrate concentration in the groundwater depends on the total recharge, pollution loading, groundwater flow and solute transport within the aquifer. They developed and applied a GIS based decision support framework that integrates field scale models of these processes for the assessment of the non-point-source pollution of groundwater. The GIS was used for representing the spatial variations in input data over the area and to map the output of the recharge and nitrogen balance models.

Babiker et al. (2004) carried out an assessment study of groundwater contamination by nitrate leaching from intensive vegetable cultivation using GIS technology. They investigated nitrate contamination of groundwater by agrochemical fertilizers in the Kakamigahara heights, Gifu

Prefecture, and central Japan. Thematic information and chemical data of groundwater from the heights were analyzed in a GIS environment to study the extent and variation of nitrate contamination and to establish spatial relationships with respect to land use types.

Almasri and Kaluarachchi (2003) applied GIS to historical nitrate concentration data from 1990 to 2000 to asses the spatial and temporal variability of nitrate data. The analysis was conducted for whole catchments as well as for individual catchments and for different land use classes. Their analysis was intended to evaluate regional long-term trends and occurrences of nitrate in the groundwater of agricultural watersheds in Whatcom County, Washington, US. Figure 10 shows the concept of nitrogen loading and soil transformations of their works.

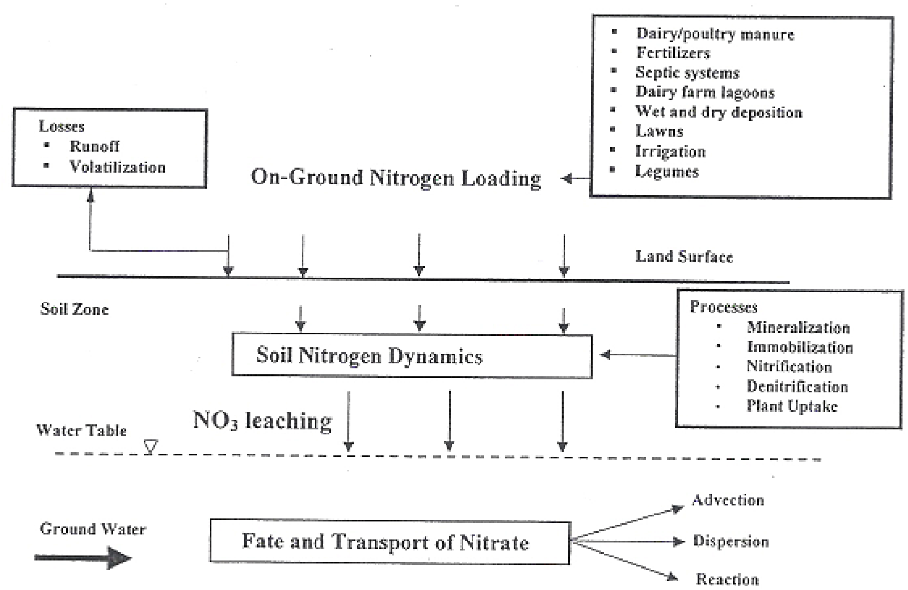


Figure 10: The concept of nitrogen loading and soil transformations (Almasri and Kaluarachchi, 2003)

Shamrukh et al (2001) studied the effect of chemical fertilizers on groundwater quality in the Nile valley aquifer, Egypt. Their study was conducted to investigate the contamination of groundwater by nitrogen and phosphorus chemical fertilizers, as well as the availability of groundwater for irrigation and public water supply for the next century. A groundwater modeling system (GMS) was used by them to simulate the three-dimensional groundwater flow and contaminant transport in the Tahta region of the Nile valley aquifer, and to predict the future concentration of chemical fertilizer species. They have concluded that best management practices should be employed to control and reduce the nitrate leaching and future impact of phosphorus and potassium fertilizer applications.

Jensen and Skop (1998) used two GIS-based models. The first is a distributed riverine nitrogen loading model for analysis of agricultural changes while the second is a linked-lumped model for lake restoration analysis. Two alternative strategies for reduction in nitrogen loading were analyzed where changes in agricultural production structure and lake creation/restoration where assessed. The former includes spatial redistribution of agricultural production, setting aside areas and changes in agricultural practice.

El-Sadek et al. (2003) carried out an analysis of fate and transport of nitrate in the soil and nitrate leaching to drains. The transport and fate of nitrate within the soil profile and nitrate leaching to drains were analyzed by comparing historic field data with the simulation results of the DRAINMOD model. In the analysis, a continuous cropping with maize was considered. Comparisons between experimental measurements and simulated state variables indicate that nitrate concentrations in the soil and nitrate leaching to drains are controlled by the fertilizer practice. The study reveals that the model used gives a fair description of nitrogen dynamics in the soil and subsurface drainage at field scale.

Lischeid and Langusch (2004) applied the process-oriented Integrated Nitrogen in Catchments (INCA) model and an artificial neural network to the data set from the forested catchment in south Germany. They simulated the mean nitrate concentration in the stream as well as seasonal fluctuation. They underestimated the short-term variance of the observed stream water nitrate concentration, especially the pronounced concentration peaks in late summer. In contrast, the artificial neural network matched the short-term dynamics using non-linear regressions with stream discharge and air temperature data.

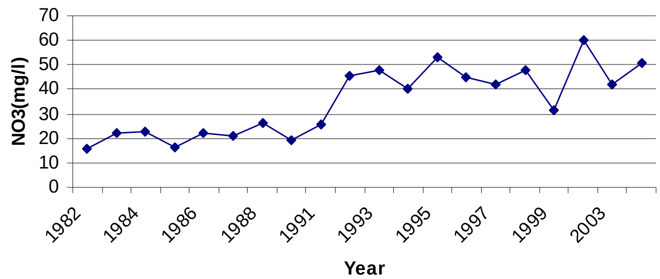
Vaughan and Corwin (1994) carried out a research study of modeling vertical fluid flow and solute transport in a GIS context. In their study a geographic information system (GIS) was used to store and manipulate a variety of data required for vertical transport modeling of water flow in the field area. A data classification scheme was developed consisting of four basic types of variables. Each specific variable was classified utilizing the classification scheme and a relational database was created for all the data. From the data included in this database, calculations of fluid and solute transport were made at selected locations by a capacity-based, one-dimensional transport model. The results of calculation were incorporated into the database for further manipulation and representation.

Kumar and Ratnoji (2002) used a software package, SWIM (Soil Water Infiltration and Movement) where known quantities of fertilizers were applied and field investigations were carried out for monitoring the chemical constituent (Nitrogen/Phosphorous/Potassium) at varying depths up to 120cm. Field observed and simulated (through SWIM) solute concentration (N, P and K) profiles after application of fertilizer were compared. The model can be used to predict the cumulative solute in the soil profile for different scenarios of fertilizer applications.

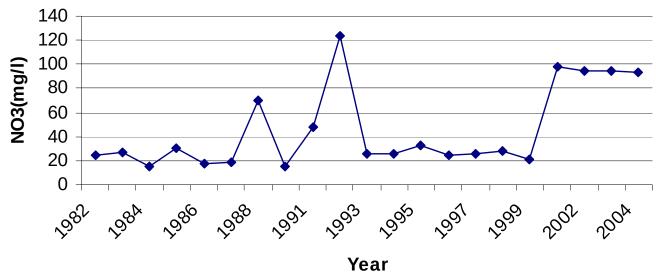
Kharmah (2007) used a MODFLOW and GWM models to develop a simulation model for groundwater in the Eocene Aquifer because this aquifer is heavily utilized for agricultural activities and it is believed that there is a potential for additional utilization of the aquifer through pumping. The groundwater model was constructed and calibrated under steady-state conditions. The simulation model was then utilized in the development of the GWM model optimization to find out the optimal pumping rates that the aquifer can sustain without depleting the aquifer.

In the West Bank, the data available shows an increase in nitrate concentrations in wells located in the Eocene aquifer as evident by Figure 11. Apparently, these time series show elevated concentration at different well locations above MCL (plotted from the database of the PWA).

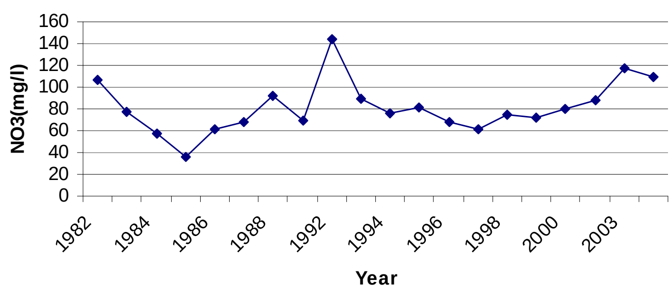
Domestic well in jenin-Fuad Abu Alrub



Agricultural well in jenin-Mohammad aref



Domestic well in jenin-Fuad abdel al hadi



Domestic well in jenin-Jenin municipality

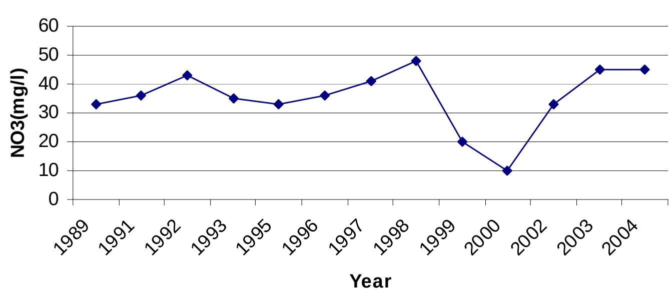


Figure 11: Annual nitrate concentration for domestic and agricultural wells in the Eocene aquifer

3.3 Health Impacts of Nitrate Contamination

Elevated nitrate concentrations in drinking water are linked to health problems such as methemoglobinemia in infants and stomach cancer in adults (Addiscott et al., 1991; Lee et al., 1994; Hall et al., 2001; Wolfe and Patz, 2002).

Clinical methemoglobinemia is associated with elevated levels of methemoglobin (metHb) in the blood stream. When ingested, NO_3 is absorbed in the blood stream from the stomach and upper intestines. Most is excreted in the urine but some can be reduced, especially in the intestines, to nitrite (NO_2). Nitrite oxidizes the iron in hemoglobin to form metHb. If less than 10% of the hemoglobin has been converted to metHb, the oxygen-carrying capacity of the blood is sufficiently lessened that symptoms of the anoxia develop. Higher metHb levels may lead to brain damage and death. The main source of NO_3 in the adult diet is food, with only about 1% from water unless the water supply is exceptionally high in NO_3. People on solid foods are not susceptible to NO_3 toxicity at commonly occurring exposure levels, but infants under 3 to 6 months are at risk because the activity of the enzyme system that reduces metHb is lower, and the pH of the stomach and intestines is higher than in older humans.

Higher pH promotes bacterial activity that leads to reduction of NO_3 to NO_2. Numerous environmental, heredity, and diet factors affect the toxicology of NO_3. Citrus fruits or vitamin A seem to provide protection against toxicity, while illness, particularly diarrhea, enhances toxic effects. The symptoms of methemoglobinemia are easily recognized and treated. Public health authorities in high risk areas are usually aware of the potential health hazard. Most common advice is to provide an alternate water source for infants and expectant mothers (Follett et al 1991).

Blue-baby syndrome is the health problem in children caused by nitrites. Symptoms include shortness of breath and blue skin. In the long term, nitrite can produce diuresis and haemorrhaging of the spleen (WHO, 2007)

As for animals and although there are no drinking water standards for livestock, it is recommended not to allow animals to drink water of concentration more than 10 mg/l NO_3-N. This is especially true of young animals. They are affected by nitrates the same way as human babies. Older animals may tolerate higher levels of nitrate in drinking water (Self and Waskon, 1998).

3.4 Management Practices to Reduce Nitrate Contamination in Groundwater

Management alternatives developed to protect groundwater quality are improvements to agricultural practices and land use patterns (Latinopoulos, 2000). In-field management practices consist of those related strictly to the source or concentration term in the loss equation (such as the rate, method/placement, form/additives, and timing of N application) and those related to both the concentration and transport, or volume of drainage, terms (such as tillage and cropping). In the following sections the management related parameters are discussed.

3.4.1 Rate

The rate of N application has a very direct effect on NO_3-N concentrations in subsurface drainage water (Baker, 2001). One component of a comprehensive nutrient management plan is to determine proper fertilizer application rates. The goal is to limit fertilizer to an amount necessary to achieve a realistic yield goal for the crop. Soil sampling and crediting other sources are also parts of the concept (EPA, 2001).

3.4.2 Method/Placement

The method of application or placement of applied N is receiving increased attention because the location in/within the soil relative to zones of higher water movement influences the degree of anion concentration (including NO_3-N) leaching (Baker, 2001).

Fertilizer application equipment should be inspected at least once annually. Application equipment must also be properly calibrated to insure that the recommended amount of fertilizer is spread (EPA, 2001).

3.4.3 Timing

Better timing of N application relative to crop needs reduces the opportunity for NO_3- N leaching. The corn plant's need for N is not that great until at least four weeks after plant emergence which generally means the greatest uptake period in mid-June through July. Fall application, while sometimes having advantages in the way of N pricing or time to do field work, exposes the applied N to leaching losses over an extended period.

3.4.4 Form/Additives

Because of soil adsorption of ammonium-nitrogen (NH_4-N), additions of ammonical N (or N that will form NH_4-N) will significantly reduce the N leaching potential for the time the N stays in the NH_4-N form. One approach to extend the “life” of NH_4-N is to add a nitrification inhibitor, such as nitrapyrin to the ammonical-N being applied to reduce the conversion rate to NO_3-N (Baker, 2001).

3.4.5 Tillage

The degree of tillage has the potential to affect both NO_3-N concentrations and the volumes of surface and subsurface drainage, where tillage can range from complete inversion with the moldboard plow to no tillage at all. Mineralization of N in soil organic matter and crop residue will affect the amount of NO_3-N available for leaching. Increased aeration of surface soils with increased tillage is expected to increase mineralization. Furthermore, the destruction of structure, including macropores, in surface soil with tillage affects both the rate and route of infiltrating water. The tillage system used also influences the options available for N application; in particular, the degree of incorporation possibly decreases with the decreased severity of tillage (Baker, 2001).

3.5 Point and Non-point Sources of Nitrate Contamination

Groundwater pollution due to point and non-point sources is caused mainly by agricultural practices (noticeable is the use of inorganic fertilizers, pesticides, and herbicides), localized industrial activities (organic pollutants and heavy metals), and inadequate or improper disposal of wastewater and solid waste (including hazardous materials) (Wishahi and Awartani, 1999; UNEP, 2003; Almasri and Kaluarachchi, 2003).

Nitrate is the most common pollutant found in shallow aquifers due to both point and non-point sources (Postma et al., 1991). Agricultural activities are the main source of elevated nitrate concentrations. Agricultural practices can result in non-point source of nitrogen pollution of groundwater (Hall et al., 2001; Delgado and Shaffer, 2002).

With non-point sources, groundwater quality may be depleted over time due to the cumulative effects of several years of practice (Addiscott et al., 1991; Schilling and Wolter, 2001).

Non-point sources of nitrogen from agricultural activities include fertilizers, manure application, and leguminous crops (Hubbard and Sheridan, 1994).

Elevated nitrate concentrations in groundwater are common around dairy and poultry operations, barnyards, and feedlots (Hii et al., 1999; Carey, 2002).

In addition to agricultural practices, nonpoint sources of nitrogen involve precipitation, irrigation with groundwater containing nitrogen, and dry deposition. Point sources of nitrogen are shown to contribute to nitrate pollution of groundwater (Almasri and Kaluarachchi, 2003). The major point sources include septic tanks and dairy lagoons.

Many studies have shown high concentrations of nitrate in areas with septic tanks (Cantor and Knox, 1984; Keeny, 1986; Amade, 1999; MacQuarrie et al., 2001). Nitrate contamination of groundwater is caused by infiltration of fertilizers and raw sewage, and elevated concentrations are found throughout the West Bank (UNEP, 2003).

3.6 Nitrogen Cycle

Nitrate leaches to groundwater from the unsaturated zone. This is a complex interaction of many factors such as land use practices, on-ground nitrogen loading, groundwater recharge, soil nitrogen dynamics, soil characteristics, and depth to water table. Figure 12 is a Schematic presentation of the integrated three-zone approach. The approach has been conceptualized by Almasri (2006) to model the increasing nitrate occurrences in groundwater.

Regardless of the source, the amount of nitrate that enters groundwater is controlled by a complex set of hydrologic and biochemical processes that occur largely in the soil and the unsaturated zone through a series of chemical transformations, most of which are mediated by bacteria,

The soil nitrogen cycle largely controls the amount of nitrogen in the soil column that is available for leaching to groundwater. Two hydrologic conditions that most affect the leaching of nitrate to groundwater are the availability of water to transport the nitrate and the hydraulic conductivity of the soil and unsaturated zone medium that control the rate of movement of soil moisture and groundwater (Almasri, 2006).

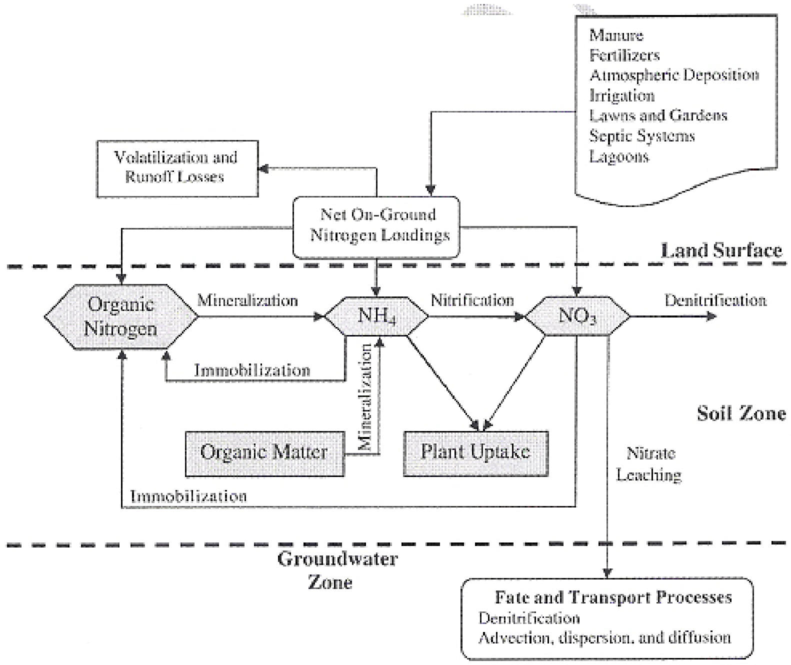


Figure 12: Schematic presentation of the integrated three-zone approach to conceptualize the increasing nitrate occurrences in groundwater (Almasri, 2006)

The major soil transformation processes in the soil that greatly affect nitrate leaching are (Almasri, 2003).

a. Ammonification: microbial decomposition of organic matter resulting in the production of ammonia.

b. Assimilation: incorporation into organic forms of nitrate, nitrite and ammonia into microorganisms and plant tissues.

c. Nitrogen fixation: microbial reduction of nitrogen gas to ammonia and organic nitrogen.

d. Nitrification: microbial oxidation of ammonia producing nitrite and nitrate.

e. Denitrification: microbial reducing of nitrate producing nitrous oxide or nitrogen gas.

f. Mineralization: the breakdown of organic compounds to their inorganic forms.

These reactions depend on pH, temperature, soil water content, and soil biological characteristics and oxygen.

CHAPTER FOUR

MODEL DEVELOPMENT

4.1 Introduction

A conceptual model of groundwater fate and transport is an idealization of the real world that summarizes the current understanding of site conditions and how the groundwater flow and transport system works (Spitz and Moreno, 1996).

The conceptual model of the nitrate fate and transport in groundwater for the Eocene Aquifer is intended to include the following:

1. Estimation of the spatial distribution of on-ground nitrogen loading;
2. Assessment of all nitrogen sources in the aquifer;
3. Approximate description of the soil nitrogen dynamics in the surface soil;
4. Realistic estimation of the nitrate available for leaching and nitrate leaching to groundwater depending on the available data; and
5. Description of fate and transport of nitrate in groundwater.

In this research GIS is employed for better visualization and assessment of the spatial distribution of nitrogen data.

4.2 On-ground Nitrogen Loading

A major step in modeling the nitrate contamination of groundwater is the estimation of the on-ground nitrogen loading from several nitrogen sources in the study area. There are many sources of nitrogen in the Eocene Aquifer including the application of inorganic nitrogen fertilizers, cesspits, precipitation, and mineralization of soil organic mater.

The developed conceptual model of fate and transport of nitrate consists of the following three integrated phases:

(i) Estimation of the spatial distribution of on-ground nitrogen loading;

The procedure for computing the nitrogen loading from on-ground sources can be summarized as follows:

1. Identify the spatial distribution of nitrogen sources in the model domain by using GIS maps;
2. Estimation of nitrogen loading for each source depending on available studies and data collected form the field; and
3. Compute the monthly on-ground nitrogen loading from each source.

(ii) Estimation of net nitrate mass recharge to the groundwater after allowing for the transformations in the soil; and

(iii) Modeling of the fate and transport of nitrate in groundwater.

In the following sections, nitrogen sources and corresponding magnitudes are summarized.

4.2.1 Cesspits

Cesspits are point sources of nitrogen that contribute to nitrate pollution of groundwater. To estimate the nitrogen loading from cesspits in the Eocene aquifer for communities that have no sewage collection system, the following procedure was used:

1. Obtain the population size for each uncovered community by the sewerage system or the communities that are partially covered;
2. Assume a 6 kg annual nitrogen production rate per capita (Cox and Kahle, 1999);
3. By multiplying the population size with the per capita annual nitrogen production, the total nitrogen obtained from cesspits can be known;
4. Obtain the amount of nitrogen per unit area for each community by dividing annual nitrogen production to the community area.

Figure 13 shows the mass of nitrogen loading from cesspits in the Eocene Aquifer. Table 2 summarizes the calculations of the nitrogen produced by the inhabitants in each of the local communities within the study area.

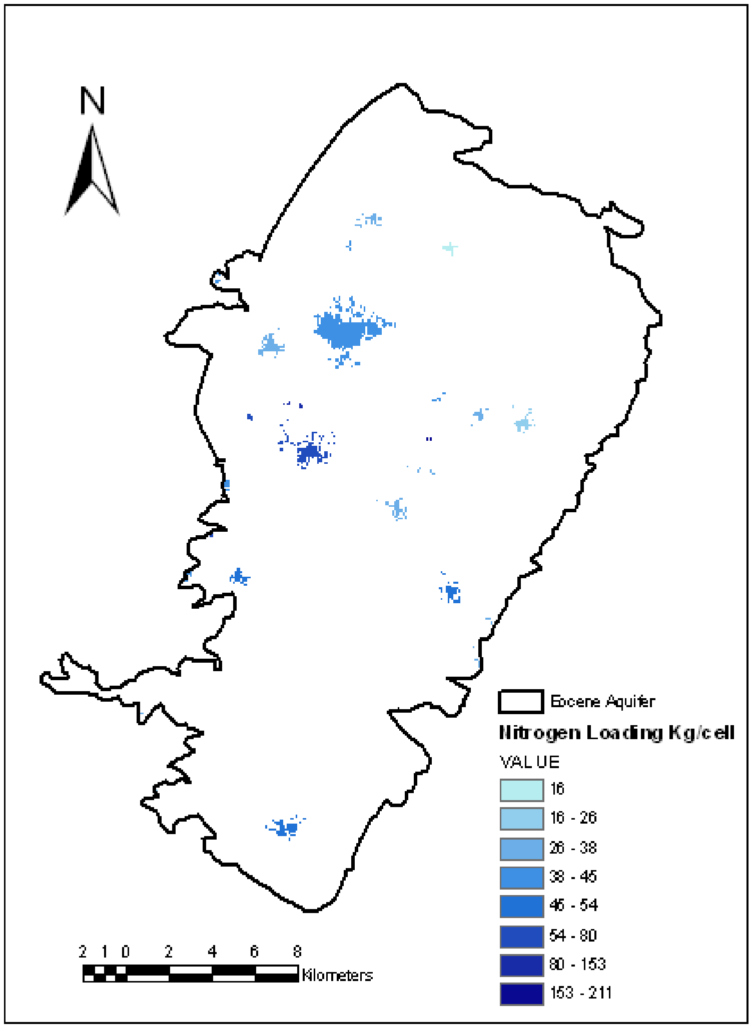


Figure 13: Mass of nitrogen loading from cesspits in the Eocene Aquifer

Table 2: Computations of nitrogen loading from cesspits for each community in the Eocene Aquifer

Name	population (2006)	Community area (km^2)	Total Load (Kg/year)	Total Load (kg/m^2)
Al Jalama	2471	0.26	14826	0.038
Deir Ghazala	916	0.19	5496	0.019
Al Yamun	17851	1.34	107106	0.054
Jenin City and Jenin Camp	51450	4.06	308700	0.051
Birqin	6328	0.63	37968	0.040
Umm at Tut	1075	0.09	6450	0.048
Ash Shuhada	1864	0.06	11184	0.126
Jalqamus	2002	0.18	12012	0.045
Al Mughayyir	2402	0.32	14412	0.030
Tannin	621	0.1	37260	2.53
Qabatiya	21123	1.1	126738	0.078
Telfit	596	0.053	3576	0.045
Mirka	1668	0.13	10008	0.052
Az Zababida	4143	0.39	24858	0.043
Az Zawiya	753	0.037	4518	0.083
'Anza	2152	0.18	12912	0.048
Sanur	4573	0.29	27438	0.064
Jaba'	9335	0.23	56010	0.165
Al Fandaqumiya	3607	0.08	21642	0.183
'Aqqaba	6512	0.41	39072	0.064
Tubas	17254	1.78	103524	0.039
Bizzariya	2098	0.14	12588	0.061
Burqa	3930	0.43	23580	0.037
Beit Imrin	2840	0.12	17040	0.096
An Naqura	1617	0.22	9702	0.029
'Asira ash Shamaliya	7568	0.54	45408	0.057
Total	**176,749**	**13.36**	**106,049,4**	**4.125**

4.2.2 Atmospheric Deposition

Atmospheric deposition of nitrate corresponds to nitrate dissolved in precipitation and dry deposition (Schepers and Mosier, 1991).

To estimate the nitrogen loading from atmospheric deposition in the Eocene aquifer, the following procedure was employed:

1. Obtain values of rainfall in the Eocene aquifer depending on the rainfall stations located in the area;
2. Find out the values of the rainfall per unit area by using the Theisen polygon method;
3. Calculate the volume of rain water over each unit area by multiplying rainfall depth with area;
4. Finding the amount of leaching water to groundwater from rainfall;
5. Assume a 4 mg/l concentration of nitrogen in precipitation (WESI); and
6. Multiply the volume of water over each unit area with the concentration of nitrogen in rainfall, and then the total nitrogen loading from atmospheric deposition is obtained.

Figure 14 shows the mass of nitrogen loading from atmospheric deposition in the Eocene Aquifer.

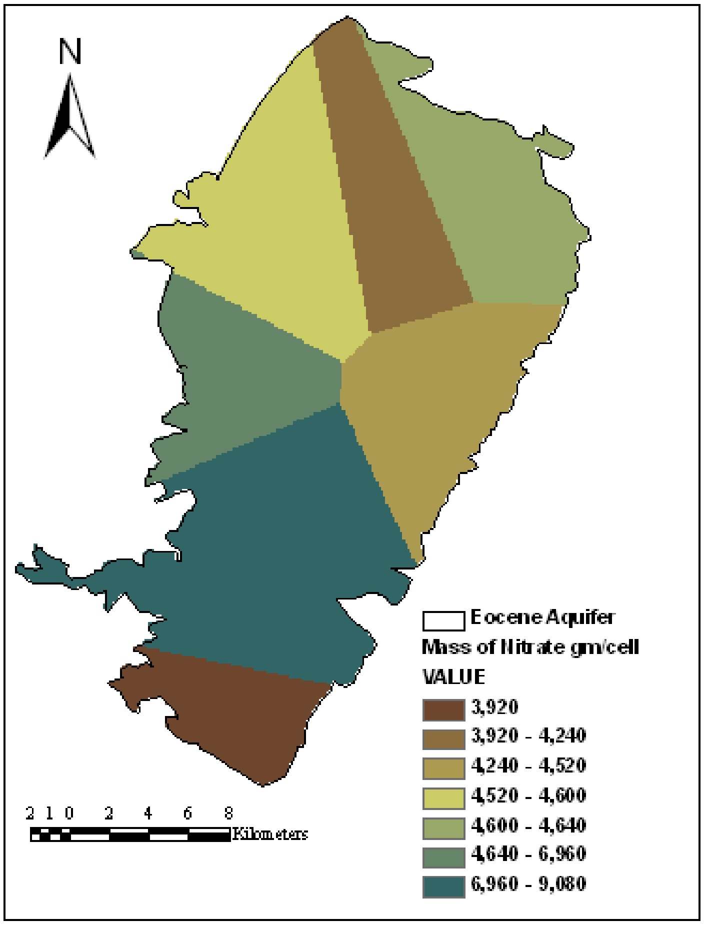


Figure 14: Mass of nitrogen loading from atmospheric deposition in the Eocene Aquifer

4.2.3 Fertilizer Application

In general, agricultural activities are the main source of elevated nitrate concentrations in groundwater and fertilizer application is considered as an agricultural practice that results in non-point source pollution of groundwater (Hall et al., 2001; Delgado and Shaffer, 2002).

After carrying out field visits to the farmers in Marj Sanour in the study area, the outcome from these visits and the interviews is the acquisition of information regarding the monthly rates of fertilizers applied. The agricultural lands have been classified according to the times of cultivation during year and the use of water for irrigation. According to this classification, the amount of fertilizers is applied. The types of crops grown in the non-irrigated lands are wheat, barley, and clover. The crops that are planted in the irrigated lands are vegetables.

Figure 15 depicts the irrigated and non-irrigated areas within the Eocene Aquifer.

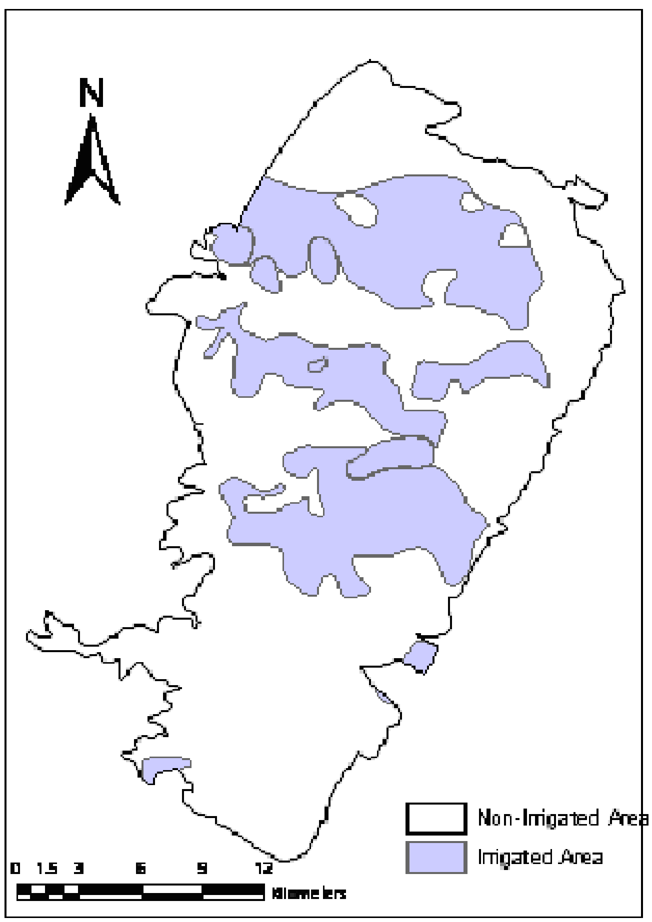


Figure 15: The irrigated and non-irrigated areas in the Eocene Aquifer

Table 3 summarizes the monthly amounts of applied fertilizers in the irrigated areas in the Eocene Aquifer.

For non-irrigated lands, application rate is 25 kg/donum for one time in January. There are three types of fertilizers used by farmers in the Eocene Aquifer and these are Urea, NH_4SO_4, and $CaNO_3$.

Table 3: Applied fertilizers in the irrigated areas in the Eocene Aquifer

Month	Applied fertilizers (Kg/donum)
January	15
February	35
March	10
April	15
May	35
June	10
July	15
August	35
September	10
October	15
November	35
December	10

4.2.4 Nitrogen Mineralized From Soil Organic Matter

To estimate the mineralized nitrogen from soil organic matter in the Eocene aquifer, the following procedure was used:

1. Define the soil type in the Eocene Aquifer;

2. Determine the organic content which ranges from 1.5% – 2%;

3. Assume that the mineralization process occurs in the first 30 cm of the soil;

4. Calculate the volume of soil per unit surface area;

5. Assume a soil density of 2.65 gm/cm^3 ; and

6. By multiplying the unit volume of the soil with the concentration of nitrogen in soil with soil density, the total nitrogen obtained from mineralization of organic matter can be obtained.

4.3 Nitrate Leaching to Groundwater

Based on a previous study (Shamruch et al., 2001), Table 4 summarizes the percentage of nitrate leaching into groundwater from the different sources.

After calculating the on-ground nitrogen loading from all the sources, the percentage of nitrate was used to calculate the NO3 leaching to groundwater without getting into a detailed analysis for losses and transformations of nitrate in the soil zone. Figure 16 shows the spatial distribution of nitrate leaching to groundwater for the month of January; this has been obtained by using GIS analysis.

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Table 4: Nitrate leaching to groundwater for the different sources (Shamruch et al., 2001)

Nitrogen sources	NO_3 leaching to groundwater
Precipitation	50%
Fertilizes	25-35%
Mineralization of soil organic matter	5%
Cesspits effluent	68%

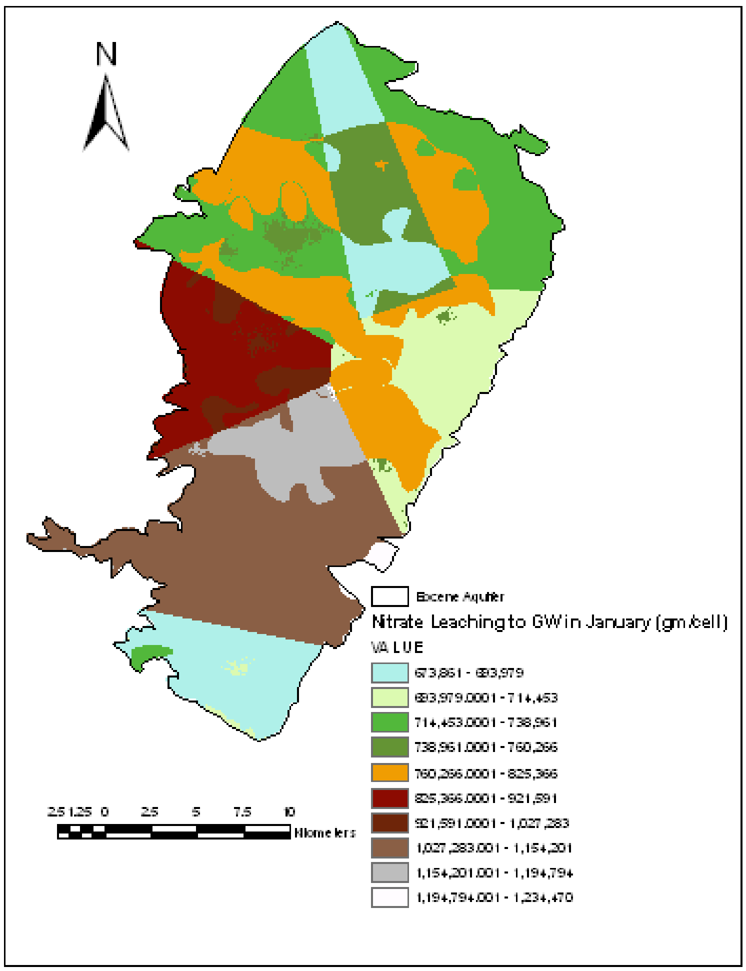

Figure 16: The spatial distribution of nitrate leaching to groundwater for the month of January

4.4 Model Setup

In this section the groundwater fate and transport model of nitrate is developed.

The reactive mass transport model (MT3D) is linked to the available groundwater flow model that was developed by Kharmah (2007).

In order to use the MT3D model, the model domain was discredited into a finite-difference grid. A uniform cell size of 100 m×100 m was chosen to match the cell of the groundwater flow model. The model domain contains 288 columns and 386 rows. One layer with a total of 111,168 cells was created that includes all active and inactive cells.

4.5 The Model

Mathematical model development is the step that follows the completion of the conceptual model where the physical and chemical processes that are taking place in the system are represented by a system of mathematical expressions. The solution to the system of mathematical equations will provide the output, which is in this case the temporal and spatial distribution of nitrate concentration in groundwater. The well-known groundwater flow model, MODFLOW, and the reactive mass transport model, MT3D, are used for this study.

4.5.1 The Fate and Transport Processes

The advection-dispersion partial differential equation that governs the three-dimensional transport of a single chemical constituent in groundwater, considering advection, dispersion, fluid sinks/sources, equilibrium-controlled sorption, and first-order irreversible rate reactions is described in the following (Zheng and Bennet, 1995):

$$R \frac{\partial C}{\partial t} = \frac{\partial}{\partial xi} D_{ij} \times \frac{\partial C}{\partial xj} - \frac{\partial}{\partial xi} \times Vi\ C + \frac{qs}{\theta} \times Cs - \lambda \left(C + \frac{\rho b}{\theta} \right) C^{-}$$

Where C is the dissolved concentration (ML^{-3}); C^{-} is the adsorbed concentration (ML^{-3}); t is time (T); D_{ij} is the hydrodynamic dispersion coefficient tensor ($L^{2}T^{-1}$); Vi is the pore water velocity (LT^{-1}); q_s is the volumetric flow rate per unit volume of aquifer and represent fluid sources and sinks (T^{-1}); Cs is the concentration of the fluid source or sink flux (ML^{-3}); λ is the reaction rate constant (T^{-1}); R is the retardation factor (L^{0}); ρ_b is the bulk density of the porous medium (ML^{-3}); and Θ is the porosity (L^{0}).

Modeling nitrate fate and transport requires several processes among these are;

Advection is the process by which the moving groundwater carries dissolved solutes at the same velocity as the groundwater (Almasri, 2003);

Hydrodynamic dispersion is the cumulative effect of molecular diffusion and mechanical dispersion. Mechanical dispersion along the longitudinal and lateral directions can be represented through the dispersivity and the pore water velocity.

Denitrification is the only dominant chemical reaction that affects nitrate concentration in the groundwater under anaerobic conditions (Almasri, 2003). Denitrification can be expressed using first-order kinetics with a first-order decay coefficient. The first-order decay coefficient, λ, is related to the half-life, $t_{1/2}$, as follows:

$\lambda = 0.693/t_{1/2}$ (Almasri, 2003).

The half-life of nitrate is in the range of 1 to 2.3 years (Frind et al, 1990).

Although sorption of chemicals on the solid matrix is common, nitrate is a highly mobile species with little sorption on the solid matrix. Hence, sorption is neglected and the retardation coefficient, R, was assumed to be one (Almasri, 2003).

4.5.2 Initial and Boundary Conditions

The governing equation of nitrate fate and transport describes the transient changes of nitrate concentration in groundwater. Therefore, initial and boundary conditions are necessary to obtain a solution to the governing equations. Initial conditions represent nitrate concentration for the entire model domain at the beginning of simulation.

It is necessary to specify the concentration of nitrate at pollution sources. Nitrate leaching to the aquifer from the on-ground nitrogen loadings was applied as mass per month (kg/month) over the model cells after considering the soil transformations. For sinks, the nitrate concentration equals to the nitrate concentration of groundwater at the sink location and need not to be specified (Almasri, 2003).

4.6 Model Development

Rana Kharmeh (2007) in her MSc thesis developed the MODFLOW model for the Eocene Aquifer to simulate groundwater flow. Her simulation results are used here in developing the nitrate fate and transport model by linking MODFLOW to MT3D. This was developed under a quasi-steady state condition. In order to utilize MT3D model for the study area, initial conditions, decay rate, dispersion coefficient and stresses data are needed. All must be specified for the entire model domain.

MODFLOW and MT3D models consist of a main program and a large number of highly independent subroutines, called modules, which are grouped into a series of packages. Each of these package deals with a single aspect of the transport simulation. The similarity between MT3D and MODFLOW in the program structure and design facilitated the development of the model by linking MT3D transport model in conjunction with MODFLOW. The main packages of the MT3D model are summarized in Table 5 (Zheng, 1990).

Table 5: The Packages of the MT3D model

Package Name	Description
Basic Transport (BTN)	Specification of the boundary and initial conditions, determination of the step size, and preparation of mass balance information, and printout of the simulation results.
Flow Model (FMI)	Interfaces with flow model and reads its contents and prepares heads and flow terms in the form needed by the transport model.

Advection (ADV)	Solves the concentration change due to advection.
Dispersion (DSP)	Solves the concentration change due to dispersion.
Sink & Source Mixing (SSM)	Solves the concentration change due to fluid sink/source.
Chemical Reactions (RCT)	Solves the concentration change due to chemical reaction.
Utility (UTL)	Contains a number of utility modules that are called upon by primary modules to perform such general-purposed tasks as input/output of data arrays.

4.7 Model Calibration

Calibration is the process where the model parameters are modified such that the simulated values of nitrate concentration meet the observed ones. The model is calibrated under quasi steady-state conditions. A set of observation wells are selected and their nitrate concentration where obtained. Figure 17 shows these wells and their nitrate concentration that is used in the calibration process. These are based on the PWA data for 2004.

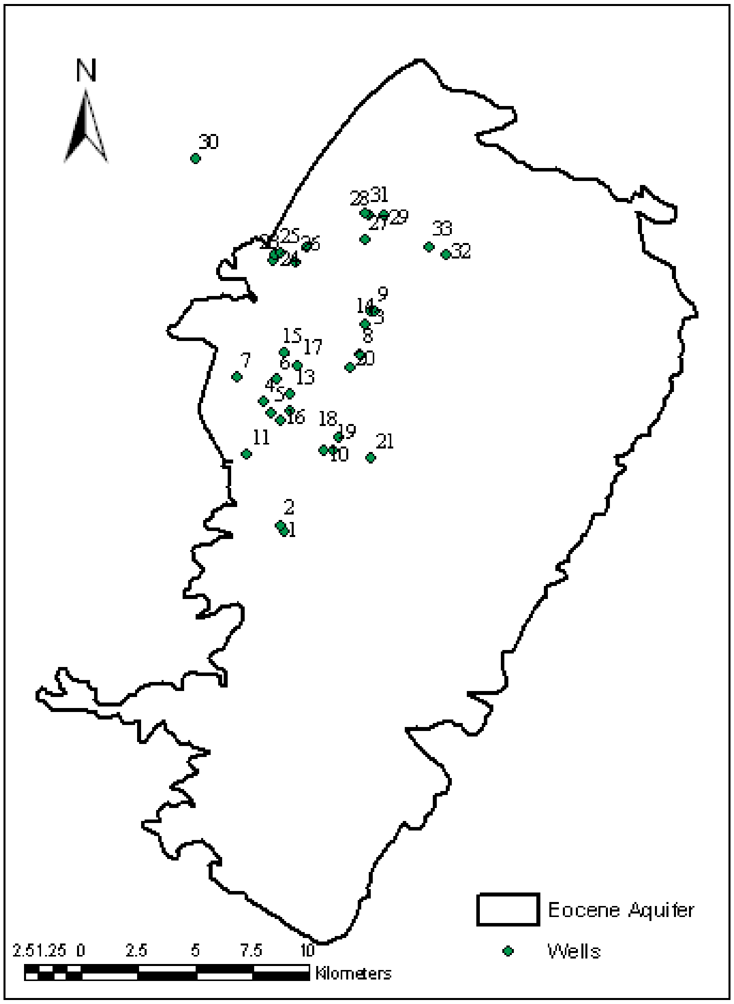

Figure 17: The wells and their respective IDs used in model calibration

The traditional method of calibrating a model is based on the trial-and-error approach. The simulated concentrations resulting from the model at the selected wells are compared to the observed ones. This method was carried out sequentially by adjusting the model parameters until the simulated values are approximate to the observed values. Figure 18 shows the observed and simulated nitrate concentrations at the calibration points.

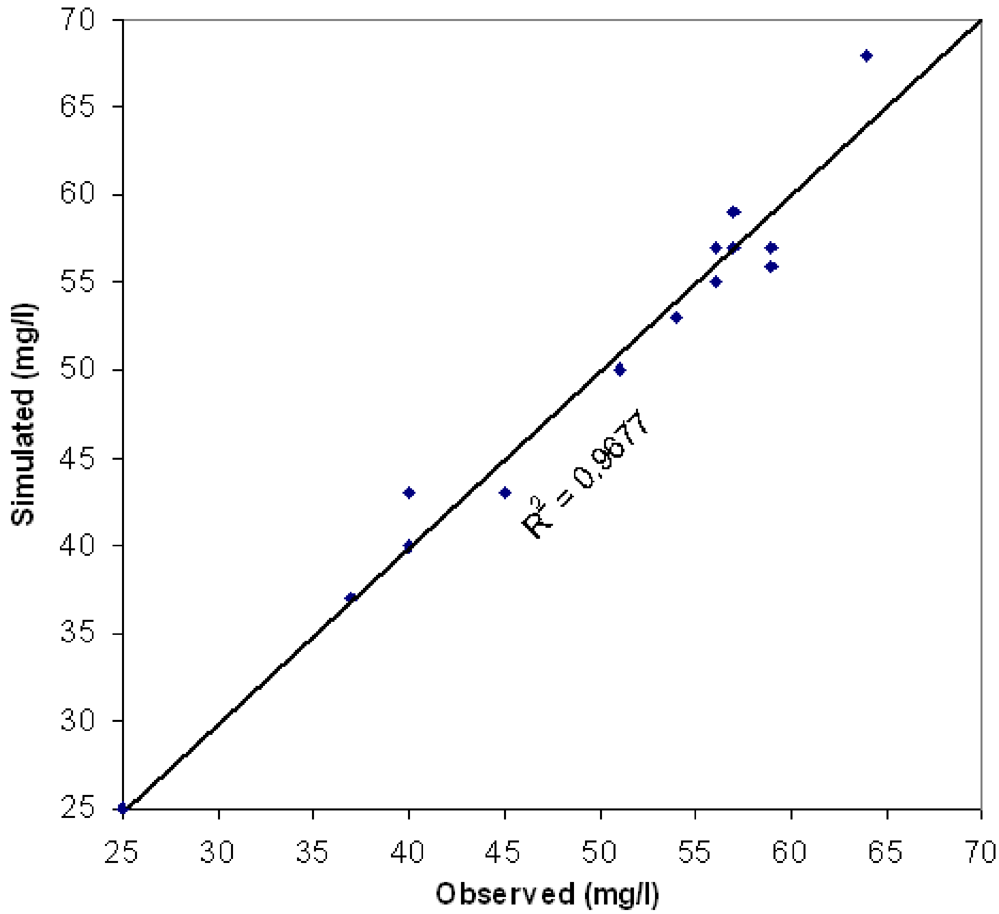

Figure 18: Observed versus simulated nitrate concentrations at the calibration points

The results proved very good matching between the observed and simulated nitrate concentrations and a regression coefficient of 0.97 was obtained.

4.8 Sensitivity Analysis

The purpose of the sensitivity analysis is to demonstrate the sensitivity of the model output to the uncertainty in the values of the model input parameters. The parameters tested in the sensitivity analysis are the decay rate and the applied mass of nitrate.

4.8.1 Model Sensitivity to Decay Rate

Model output was found to be sensitive to changes in decay rate where an increase in the decay rate causes the lowering of the total mass of estimated nitrate. Figure 19 shows the effect of changing the decay rate by specific fractions on the nitrate concentration at selected locations in the Eocene Aquifer.

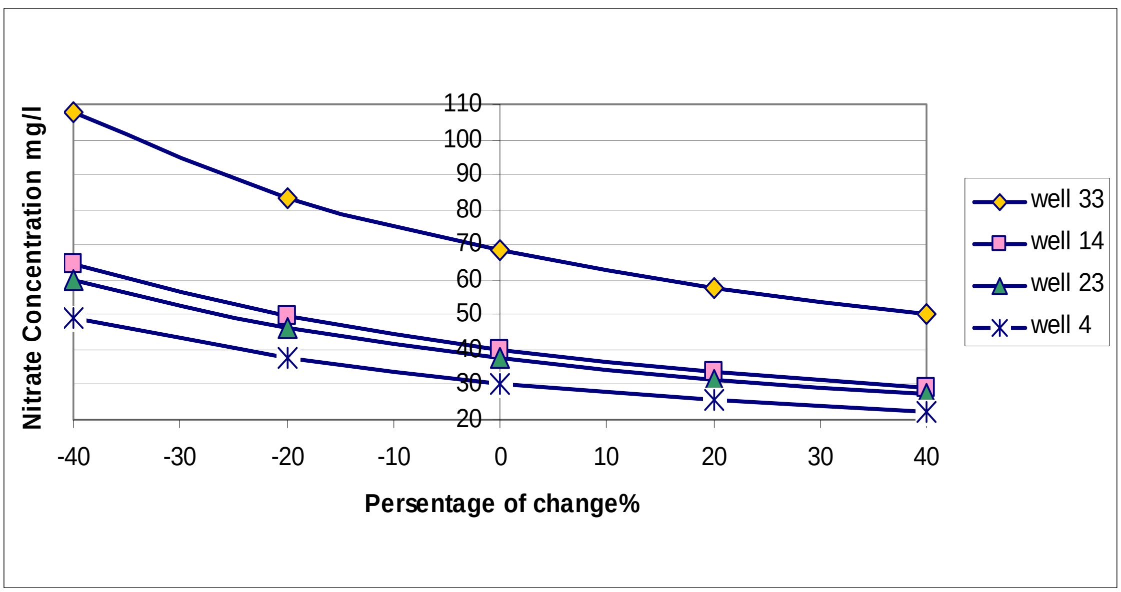

Figure 19: Sensitivity of nitrate contamination to increase and decrease of the decay rate

It is clear from Figure 19 that the model is sensitive to the decay rate. The graphs of the changes in the concentrations due to the changes in the decay rates are almost identical. This indicates that the sensitivity of changing the decay rate is the same in all wells. Well # 4 shows a slightly higher sensitivity as the percentage of change in the nitrate concentration is higher than other wells for the same increase or decrease in the decay rate.

4.8.2 Model Sensitivity to the Mass of Nitrate

Model output was found to be sensitive to the change in mass of applied nitrate at sources. It is obvious that an increase in the mass of nitrate causes an increase in nitrate concentration in the wells.

Figure 20 shows that the increase in the amounts of applied nitrogen leads to an increase in the nitrate concentration in the wells. This trend differs from well to well depending on proximity of the well to the nitrogen source. However, the figure shows that for well # 33, due to a reduction in the mass of nitrogen applied by almost 25%, the concentration becomes less than the MCL.

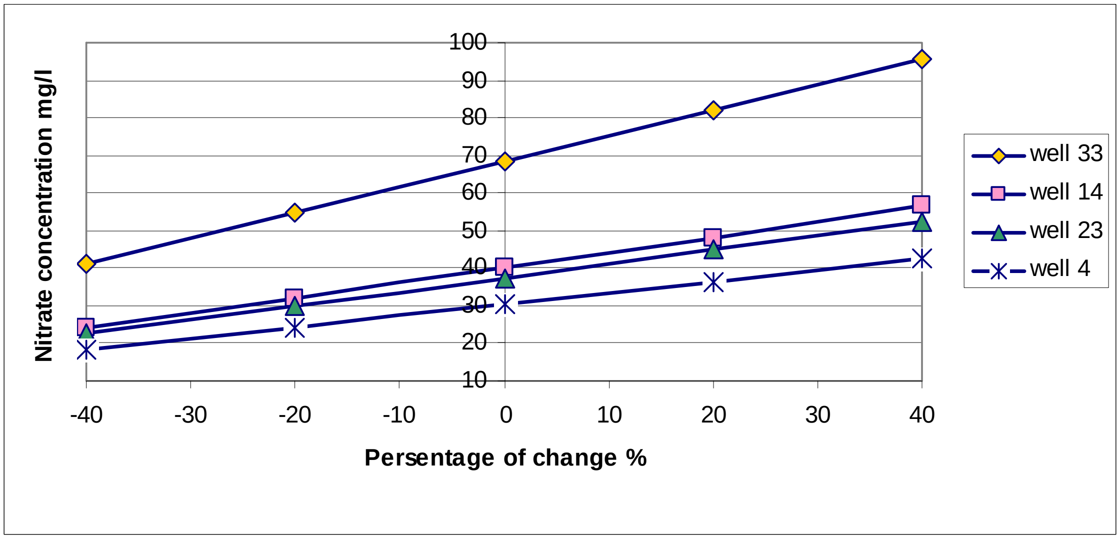

Figure 20: Sensitivity of nitrate contamination to mass of nitrate at sources

4.9 Further Modeling Considerations

This section presents further analysis and discussion of nitrate mass balance in the Eocene Aquifer. The main output from the model is the nitrate concentration in the groundwater at monthly time steps at a certain location under current conditions.

Figure 21 shows the spatial distribution of nitrate concentration in the Eocene Aquifer. Upon comparing figure 21 with figure 16, it is apparent that high nitrate concentrations are greatly correlated with high nitrate leaching to groundwater.

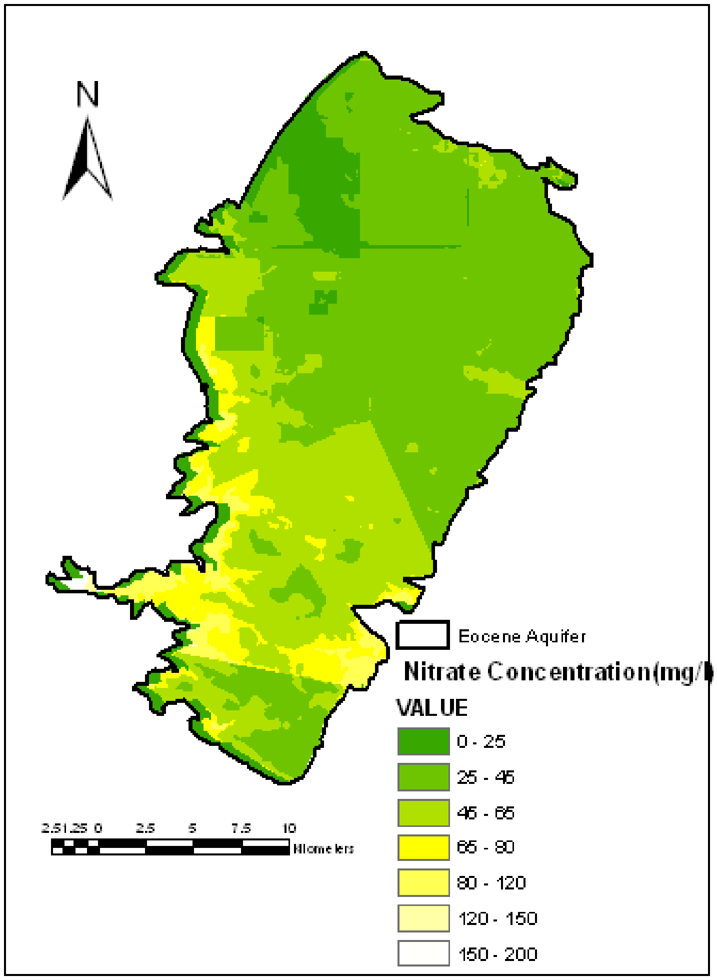

Figure 21: The spatial distribution of nitrate concentration in the Eocene Aquifer

Table 6 summarizes the simulated nitrate mass budget for the Eocene Aquifer under quasi steady-state conditions. The average mass of nitrate that enters the aquifer is approximately 2.42×10^{14} kg. About 7.27×10^{9} Kg leaves the model domain with lateral out flow. The mass of nitrate that leaves the aquifer is taking place through the pumping wells and through the drains.

Table 6: Nitrate budget in the Eocene Aquifer

Component	**In (Kg)**	**Out (Kg)**
Mass loading	$10^{14}\times2.37$	0
Mass storage (solute)	$10^{12}\times4.8$	$10^{12}\times5.83$
Wells	0	$10^{9}\times2.3$
Springs	0	$10^{9}\times3.2$
Head -dependent Boundary	0	$10^{9}\times7.27$
Denitrification	0	$10^{14}\times2.36$
Total	$\mathbf{10^{14}\times2.42}$	$\mathbf{10^{14}\times2.42}$

4.10 Management of Nitrate Contamination in the Eocene Aquifer

As mentioned earlier the Eocene Aquifer undergoes a nitrate contamination problem. The developed model provides us with an idea regarding the aquifer response to the potential management options. It is to present the related management options aimed at reducing nitrate concentration in the Eocene Aquifer. Consequently two management options are discussed:

1. Restriction on the use of fertilizers; and

2. Full coverage of the sewerage system.

In order to see the effect of nitrate reduction of the source, the developed model was applied. A reduction percentage in nitrate sources was set at 20% for 10 years. The model was run to find out the spatial distribution of nitrate concentration under combined management options of the above mentioned two options.

Chapter Five

Conclusions and Recommendations

5.1 Conclusions

In this thesis, a nitrate fate and transport model for the Eocene Aquifer was developed. The MT3D model was linked to a MODFLOW model to simulate the fate and transport of nitrate in the aquifer. GIS tools were utilized for data pre and post processing. The following are the key conclusions:

1. There is an on-going problem of nitrate contamination in the Eocene Aquifer. The high levels and continuous increase of nitrate concentration above the MCL is the main indicator of this problem.

2. According to the calculations made, the excessive applications of fertilizers for agriculture and the seepage of untreated wastewater from cesspits are the main causes of the high concentrations of nitrate.
3. The developed model after calibration showed that Nitrate contamination is very sensitive to the decay rate and source loading.
4. The applied nitrate fate and transport model mapped the spatial extent of nitrate contamination in the Eocene Aquifer and enabled the development and examination of the management options of the nitrate contamination in the aquifer.

5.2 Recommendations

The importance of the Eocene Aquifer as a source of potable water is highly important to the Palestinians. The recommendations listed herein support the future studies and address the following issues regarding the management of nitrate contamination in the Eocene Aquifer:

1. Since nitrate concentration of the Eocene Aquifer has been modeled, other pollutants can be considered.

2. It is recommended to set up management policies for the aquifer. Policies that control the use of fertilizers promoting the construction of wastewater collection systems and control of the use of cesspits.

3. Management practices should be considered to control and reduce the nitrate leaching to groundwater from the agricultural fields.

4. There is a strong need to establish a groundwater quality monitoring system in the Eocene aquifer to observe the contamination levels and their spatial and temporal distributions.

5. It is important to carry out an economic analysis to assess the potential impacts of the proposed management options on the local economy.

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جامعة النجاح الوطنية

كلية الدراسات العليا

تطوير نموذج رياضي لتمثيل تلوث الحوض الجوفي الايوسيني بالنيترات، فلسطين

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

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الملخص

يعتبر الحوض الجوفي الايوسيني من اهم احواض الضفة الغربية والذي أثبتت الفحوصات المخبرية لنوعية المياه في ابار هذا الحوض أن هناك زيادة في مستويات تركيز النيترات، ان التلوث المتواصل للمياه الجوفية في هذا الحوض دون تنفيذ وتطبيق أي إجراءات حماية ووقاية ستؤدي إلى تدهور نوعية المياه.

يركز هذا البحث على تطوير نموذج رياضي لتمثيل انتقال النيترات في الحوض الجوفي الايوسيني باستخدام نموذجين رياضيين هما MODFLOW و MT3D، ان تطوير هذا النموذج يتطلب بداية تحديد مصادر النيتروجين المختلفة المسببة للتلوث في الحوض الجوفي، حيث شمل البحث على خرائط لتوضيح توزيع وتغير تركيز النيترات في ظل النشاطات والاستخدامات الحالية للحوض، أظهرت الحسابات أن استخدام الأسمدة النيتروجينية بمعدلات عالية من أهم اسباب تسرب النيتروجين للمياه الجوفية، وتجدر الاشارة الى ان هناك اسباب اخرى يعزى اليها ارتفاع تركيز النيترات تتعلق باستخدام الحفر الامتصاصية للتخلص من المياه العادمة. شمل البحث ايضا تحديد معالم نظام رقابة لنوعية المياه الجوفية في الحوض الجوفي الايوسيني. تبين من تحليل حساسية النموذج لبعض المتغيرات أن هنالك تأثير كبير لمعدل تحلل النيترات وكمية النيترات المتسربة الى المياه الجوفية على تراكيز النيترات.