INTERUNIVERSITY PROGRAMME
IN
WATER RESOURCES ENGINEERING

Katholieke Universiteit Leuven –
Vrije Universiteit Brussel, Belgium

Nitrate Pollution and Contaminant Transport to Groundwater Resources

(In Beit-Lahia Area- Gaza Strip - Palestine)

Promotor :
Prof.Dr.Ir. F.De. Smedt

Advisor :
Drs. P.v. Rossum

Master dissertation in partial fulfilment
of the requirements for the Degree of
Master of Science in
Water Resources Engineering
by : Adnan Aish

June/ 200

Table of Contents

CHAPTER 1

Introduction

Water is the most abundant substance on the earth, the principal constituent of all living things, and a major force constantly shaping the surface of the earth. It also key factors in conditioning the earth for human existence and in influencing the civilization process. The hydrosciences deal with the earth's water resources, their distribution and their circulation, their physical and chemical properties, and their interaction with the environment, including interaction with all living things, especially human beings.

The primary motivation for the study of groundwater has traditionally been its importance as a resource. In arid and semiarid countries such as Palestine, the demand for ground water resources is increasing due to rise in population especially after peace agreement. This is worsening by the fact that the water quality is also poor due to pollution from wastewater and fertilizers used in agriculture.

1.1 Problem description:

Nitrate is the most important pollutant of the groundwater all over the Gaza Strip, Palestine (figure 1.1). The concentration of nitrate in the range of 100 - 200 mg/l with extreme concentrations reaching 600 mg/l. These concentrations exceed the World Health Organization (WHO) standard of 50 mg/l of drinking water .The reason for drawing the attention to nitrate pollution is its toxicity to humans, especially for babies and pregnant women by the so called " blue babies " syndrome.

Figure 1.1: Location map of Palestine

Map source: political satellite

Beit-Lahia area, being a part of Gaza Strip, is suffering from the nitrate pollution of its groundwater. The nitrate concentration in the drinking water abstracted from the groundwater is increasing gradually and reaching to values in the range of 50 - 200 mg/l which are exceedingly higher than the WHO standards. The significant potential nitrate sources that pollute the groundwater are domestic and industrial wastewater, solid waste dumpsites and agricultural N-fertilizers. The produced leachate from different sources containing nitrogen infiltrates into the soil where it is converted to nitrate by the nitrifying bacteria.

1.2 Objectives

The main objective of this study is to investigate the nitrate pollution sources in Beit-Lahia area, Gaza Strip, and to investigate the pollutant transport from wastewater plant by means of a groundwater model **(MODFLOW).**

1.3 Implementation

The study was carried out during the period of August 1999 - May 2000. The first part comprised of a field study that was carried out in Beit-Lahia area during the period of 27 July- 25 September 1999 With Flemish student (Bert.B, Tom.D, and Sven.A). This was in order to collect local data on potential sources of nitrate pollution and to perform water and wastewater analyses in addition to other tasks related to the objectives of the study.

This is within the framework of UNESCO/ Flanders FIT project between the Water Research Center at Al-Azhar University - Gaza- Palestine and Inter-University Program in Water Resources Engineering (IUPWARE) at the Flemish Universities Katholieke University Leuven- (K.U. Leuven) and Vriie University- Brussel (VUB Brussel), Belgium.

The second part, which consists of the development of groundwater flow model and pollutant transport, was carried out at the Laboratory of Hydrology of Vrije University - Brussel.

This study consists of a general literature review in chapter 2. General description of Beit-Lahia area, the study area, is presented in chapter 3 in addition to a description of nitrate pollution problem in groundwater. Chapter 4 provides the methods and materials used to tackle the nitrate pollution problem and field research and analysis. Groundwater flow modeling chapter 5. Model application and results in chapter 6. The conclusions and recommendations are presented in chapter 7.

CHAPTER 2

Literature Review

2.1 Introduction

Groundwater contamination by nitrate is becoming a hot environmental issue in many countries in which groundwater is the main source for water supply. Concern arises when nitrate accumulates in groundwater, because of its toxicity to humans. The protection of nitrate pollution and its controls well as removal became important issues to water scientists all over the globe. But the problems of transport and transformation processes of nitrates are in their importance to contamination very different from one region to another. In many cases research is needed and continuos monitoring of the endangered areas is highly recommended.

2.2 The nitrogen cycle

Evaluation of sources of nitrate (NO_3^-) to ground water must consider the complicated series of chemical, biological and physical reactions of nitrogen (N), commonly termed the N-cycle. (Figure 2.1) outlines the inputs, reactions and losses of nitrogen compounds in the N-cycle. (Keeney, 1989). The primary processes involved in the N-cycle that influence the amount of available nitrate for leaching are shortly over viewed in the following paragraphs.

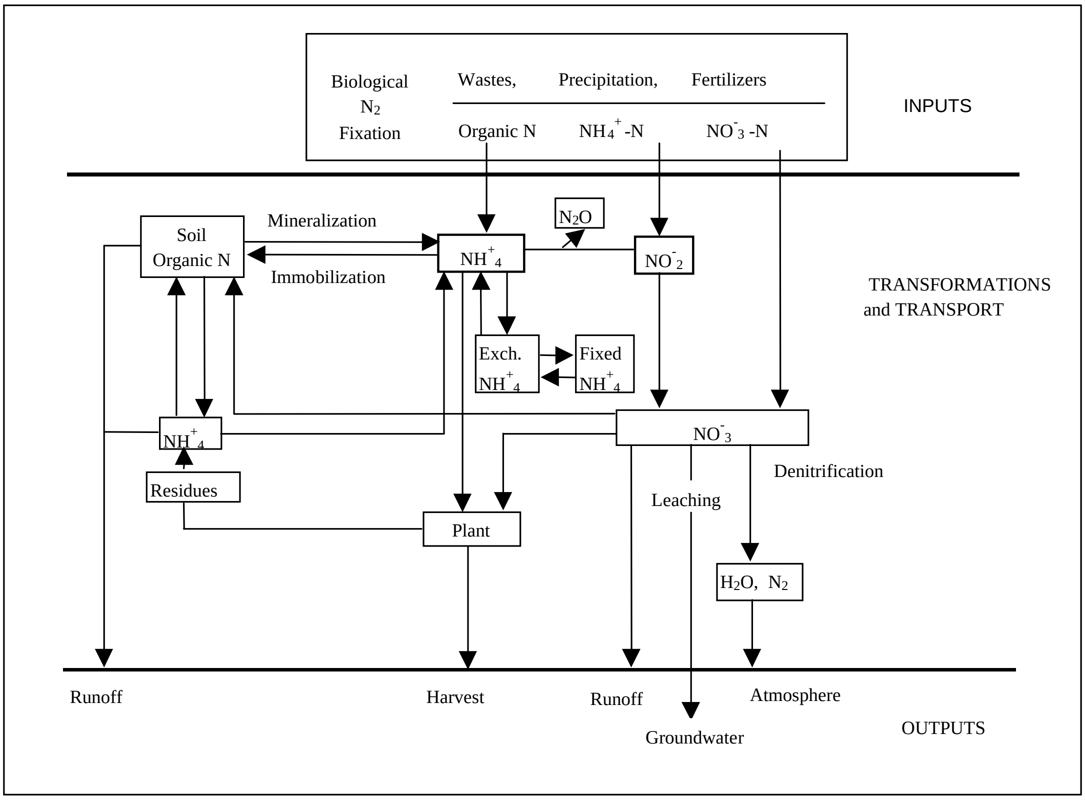


Figure 2.1 The nitrogen cycle (Keeney, 1989)

2.2.1 Mineralization - Immobilization

These two opposing processes are occurring continually in soil. Mineralization or ammonification is the decomposition of organic N with the release of ammonium (NH_4^+):

$$\text{Organic N} \xrightarrow[\text{Mineralization}]{} NH^+_{4(aq)}$$

$$\text{Organic N} \xleftarrow[\text{Immobilization}]{} NH^+_{4(aq)}$$

Some of the ammonium produced by the mineralization step will rapidly recycle through microbial biomas into the organic pool. This process is called immobilization. Part of the ammonium produced by mineralization step is immobilized and the remaining part is converted to nitrate if the appropriate conditions of nitrification are present. The rate of Mineralization is of great importance to estimate the amounts of nitrate leaching to the groundwater (Keeney, 1989).

2.2.2 Nitrification

Nitrification is the microbial oxidation of ammonium to nitrite (NO_2^-) and further to nitrate (NO_3^-). Two groups of microorganisms are involved in this process: *Nitrosomonas* and *Nitrobacter*

$$2\,NH^+_{4(aq)} + 3\,O_{2(aq)} \xrightarrow[\textit{Nitrosomonas}]{} 2\,NO_{2(aq)} + 2\,H_2O_{(aq)} + 4\,H^+_{(aq)}$$

$$2\,NO_2^- + O_2 \xrightarrow[\textit{Nitrobacter}]{} 2\,NO_3^-$$

Nitrification occurs in aerobic conditions only as oxygen (O_2) is needed. Each mg of ammonium requires 4.33mg of oxygen to be nitrified. That is why nitrification occurs in the unsaturated zone of soil only, with the exception of some atmospheric reactions. Nitrification is the sole source of nitrate to the biosphere. Hence, control of nitrification has received considerable attention. (Keeney, 1989)

2.2.3 Denitrification

Denitrification refers to the biological conversion of nitrate to gaseous nitrogen ($NO_{x,}$ N_2), which subsequently escape to the atmosphere. Denitrification primarily occurs under anaerobic conditions, thus, it is most likely to take place in moist soils with high water holding capacity (clay), and inside aggregates, which are water saturated. A organic source is also important for the denitrifying bacteria. Therefore it is usually assumed that denitrification does not occur in groundwater or in the deep vadose zone, (Keeney, 1989).

A relatively broad range of bacteria can accomplish denitrification, including *Pseudomonas*, *Arthrobacter* and *Bacillus* species. These groups accomplish nitrate reduction by a process called dissimilation, in which nitrate or nitrite replaces oxygen in the respiration process of these organisms under anoxic conditions.

2.2.4 Ammonia volatilization

Ammonia (NH_3) volatilization is an important process mainly in basic soil. NH_3 is volatilized following the dissociation of NH_4^+ to NH_3 and H^+ according to the following equation:

$$NH_4^+ \dashrightarrow NH_3 + H^+$$

The volatilization of NH_3 is determined by the percentage of free NH_3 present, which is a direct function of the pH.

$$[NH_3^-][H^+] / [NH_4^+] = K_{eq} = K_a$$

Where, K_a : acidity constant = 5.75×10^{-10}

p K_a = 9.24

2.2.5 Adsorption

Part of the NH4^{+} ions is adsorbed by the negatively charged clay and organic particles X^{-}, present as in the soil to form a cation -exchange complex.

$$NH_4^{+} + X^{-} \longleftrightarrow NH_4 \ldots\ldots X$$

The cation - exchange capacity (CEC) of the soil depends upon the amount and type of the clay and the amount of organic matter. The CEC may range from 10 meq to 20 meq / kg of soil for very sandy soils with little clay or organic matter to more than 1000meq / kg for soils high in clay or organic matter, or both. The fraction of the CEC that may be used to adsorb NH_4^{+} depends upon the concentration of other cations in the water applied because these cations (particularly, divalent cations such as $Ca^{2+}$and Mg^{2+}) compete with NH4^{+} for exchange sites. This fraction, called the exchangeable ammonium percentage, can be estimated if the CEC and the concentration of the principal competing divalent cations are known (Gabriel and Charles, 1990).

The NH_4^{+} adsorbed by the soil CEC is only temporarily immobilized because it can be readily remobilize or oxidized to NO^{-}_3 when oxygen is available. However this adsorption is extremely important because it retains nitrogen within the root zone for a time.

2.2.6 Biological nitrogen fixation

Biological nitrogen fixation is conversion of N_2 to organic N forms. Symbiotic and non-symbiotic fixation are the two types of biological nitrogen fixation in the soil plant system.

Symbiotic N fixation occurs when the bacteria in the root nodules of leguminous assimilate the elemental nitrogen from air.

Non-Symbiotic N fixation is carried out by the free-living microorganisms in the soil (Brady, 1990).

2.3 Nitrate leaching

Any source of N in the form of nitrate is subject to leaching downward with soil water, through soil, in response to gravitational forces until it reaches the groundwater.

Nitrate leaching is affected by:

(I) nitrification rate, (II) soil texture, (III) land use, (IV) rainfall and irrigation pattern and (V) fertilization practice, in addition to other factors .

Leaching occurs more readily from soils of coarse texture than from those of fine texture.

In general the amount of nitrate leached out of the upper zone is not equal to the input of nitrate into the groundwater. Due to the denitrification processes within the unsaturated zone. Therefore, any quantitative method for predicting nitrate leaching must take into account the effects of the amount of the percolating water and the hydraulic properties of soil and rocks.

2.4 Nitrogen balance

Sources of nitrate pollution to groundwater have a function in the nitrogen balance in the soil under different land usage. Major gains and losses of available soil nitrogen as indicated by Brady, 1990 are summarized in figure (2.3) and briefly discussed in the following:

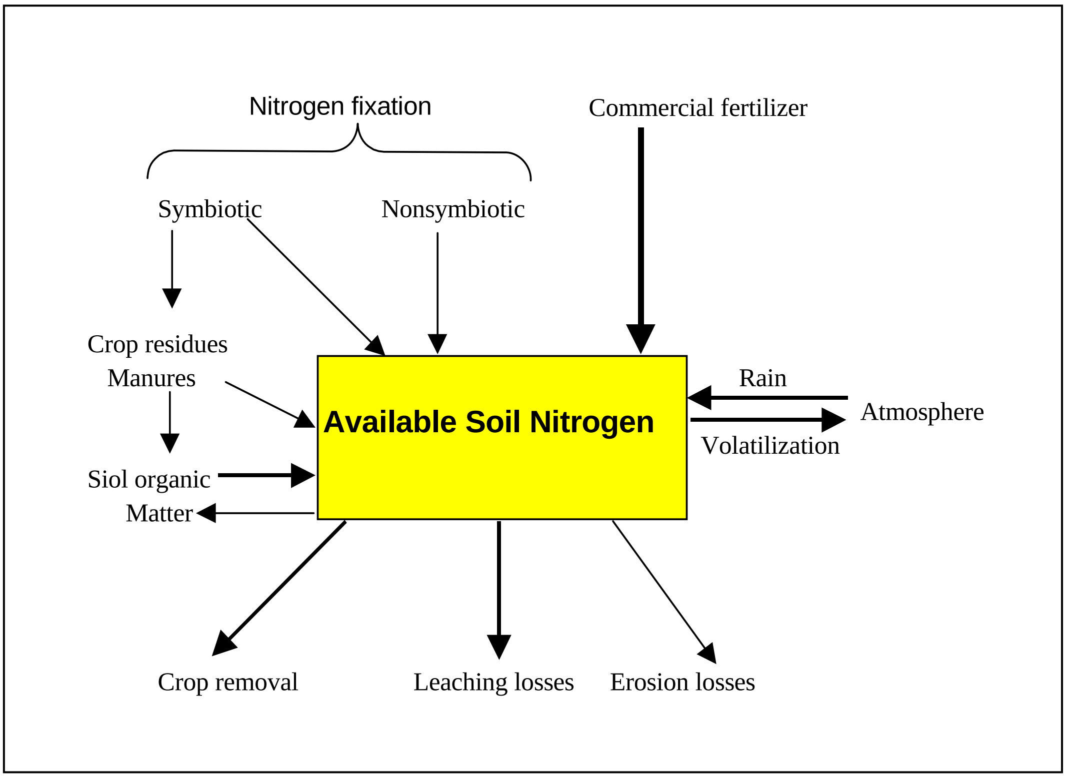


Figure 2.3 Major gains and losses of available soil nitrogen. The widths of the arrows indicate roughly the magnitude of the losses and the additions often encountered (Brady, 1990)

CHAPTER 3

Groundwater Nitrate in Beit-Lahia Area

3.1 Geography and demography

Geography

Gaza Strip is a part of the Palestinian plain in the south west of Palestine where its forms a long and narrow rectangle. Its area is about 365 km^2 and its length is approximately 45km. The location of the Gaza Strip is shown in (figure 3.1)

Demography

The population characteristics of the Gaza Strip are strongly influenced by political developments, which have played a significant role in the growth and population distribution of the Gaza Strip. The most reliable estimation was don by the Palestinian Bureau of Statistics as illustrated in (table 3.1).
Northern Governorate is one of the five Governorates in the Gaza strip. There are 180,000 inhabitants living on area of 60.5 km^2.

Table 3.1: Average population change in Gaza Strip (PBS, 1998)

End of period	1947-48	1948-67	1967-68	1968-80	1980-92	1992-94	1994-96	1997
Total Population	280000	454900	354700	449600	747200	842600	963000	1020000

3.2 Climate conditions

Temperature, humidity, and solar radiation

The Gaza strip is located in the transitional zone between the arid desert climate of the Sinai Peninsula and the temperate and the semi-humid Mediterranean climate along the coast.

The average daily mean temperature ranges from 25°C in summer to 13 °C in winter. Average daily maximum temperature range from 29 °C to 17 °C and minimum temperatures from 21 °C to 9 °C in the summer and winter respectively.

The daily relative humidity fluctuates between 65 % in the daytime and 85 % at night in the summer and between 60 % and 80 % respectively in winter. The mean annual solar radiation amounts 22MJ/m^2/day or (2200 J/cm^2 /day).

Rainfall and Evaporation

The average annual rainfall varies from 450 mm/year in the north to 200 mm/year in the south. Most of the rainfall occurs in the period from October to March, the rest of the years being almost completely dry (figure 3.2).

The evaporation measurement have clearly shown, that the long term average open water evaporation for the Gaza Strip is in the order of 1300 mm/yr. Maximum values in the order of 140 mm/month are quoted for summer. While relatively low pan - evaporation values of around 70 mm/month were measured during the months December to January (table 3.2)

Table 3.2: Typical open water evaporation and rainfall values for the Gaza town (PWA, 1994)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rain. (mm)	83.3	55.3	41.2	8.9	3.7	0	0	0	0.7	15.6	70.9	91.8	**371**
Evap. (mm)	63.4	73.1	94.1	116.4	133.4	135.5	137.8	124.9	124.9	113.7	91.0	78.7	**1299**

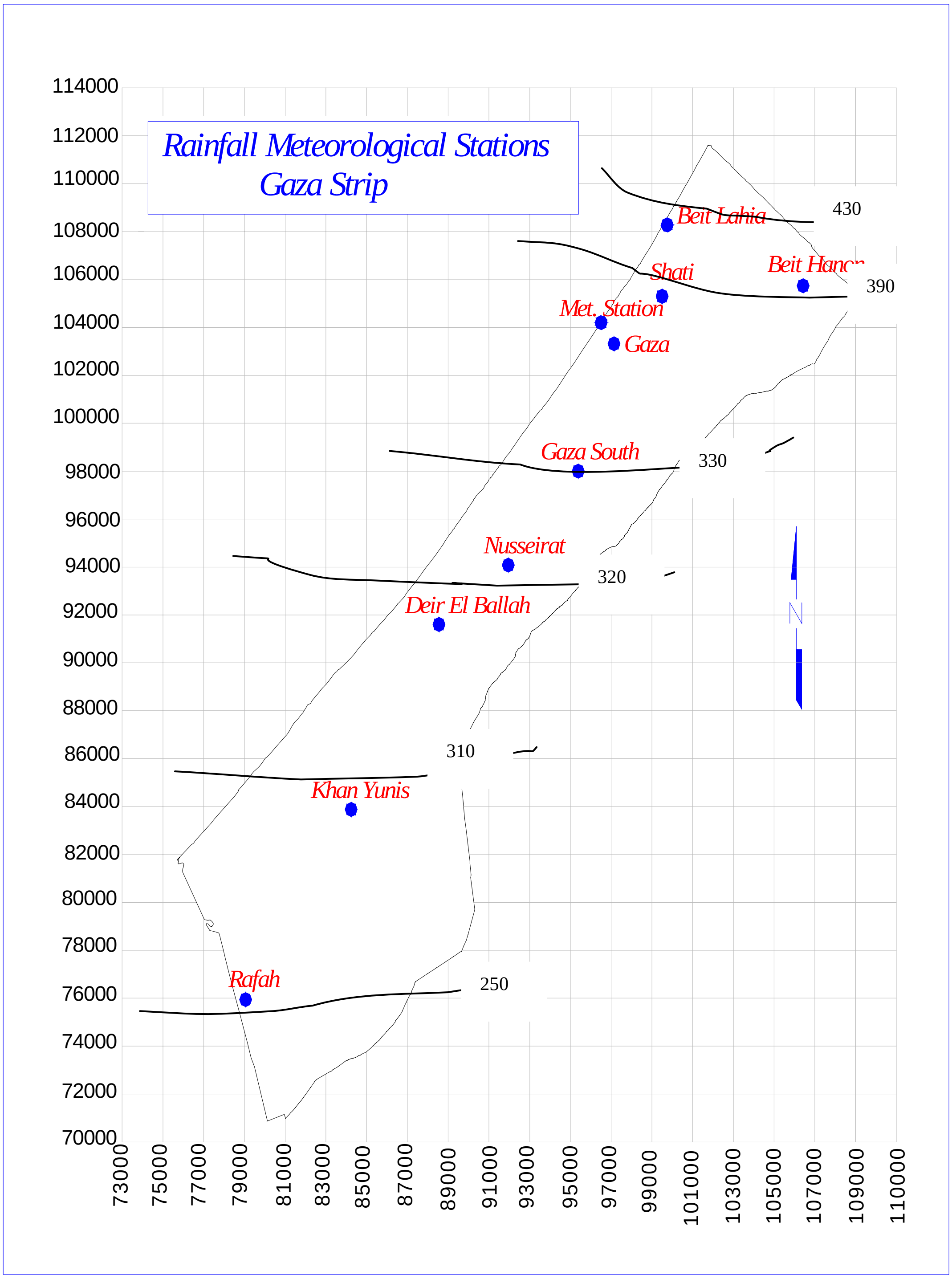


Figure 3.2: Average annual rainfall in the Gaza Strip (PWA, 1994)

3.3 Hydrological conditions and soil distribution

Hydrological condition

The ground water in Northern Governorate is confined in a coastal aquifer divided into three sub-aquifers and consists of sand, sandstone, poorly consolidated Shelly sandstone and pebbles of Quaternary - Pleistocene age. The sub-aquifers overlie each other and are separated by impervious and/or semi-impervious silt clayey layer. The lower intercalated clayey layers tend to be more thick and continuous towards the coast. It dips towards the coast and its thickness increases in the dipping direction to about 15 - 20 m thick and diminishes gradually to the east at a distance of about 4 - 5 km from the coast. The base of the aquifer consists of impermeable marly clay (Saqiah-Formation) of Pliocene age. (Appendix 1).
Groundwater level is more or less close to the mean sea level and its elevation ranges between 3 m above MSL in the northeast and about 1 m below MSL in the central area reflecting the highly intensive pumping (Figure 3.3). Depth to water level is controlled mainly by ground elevation and is ranging between 60 m in the highly elevated area and less than 5 m in the low land area along the shoreline.

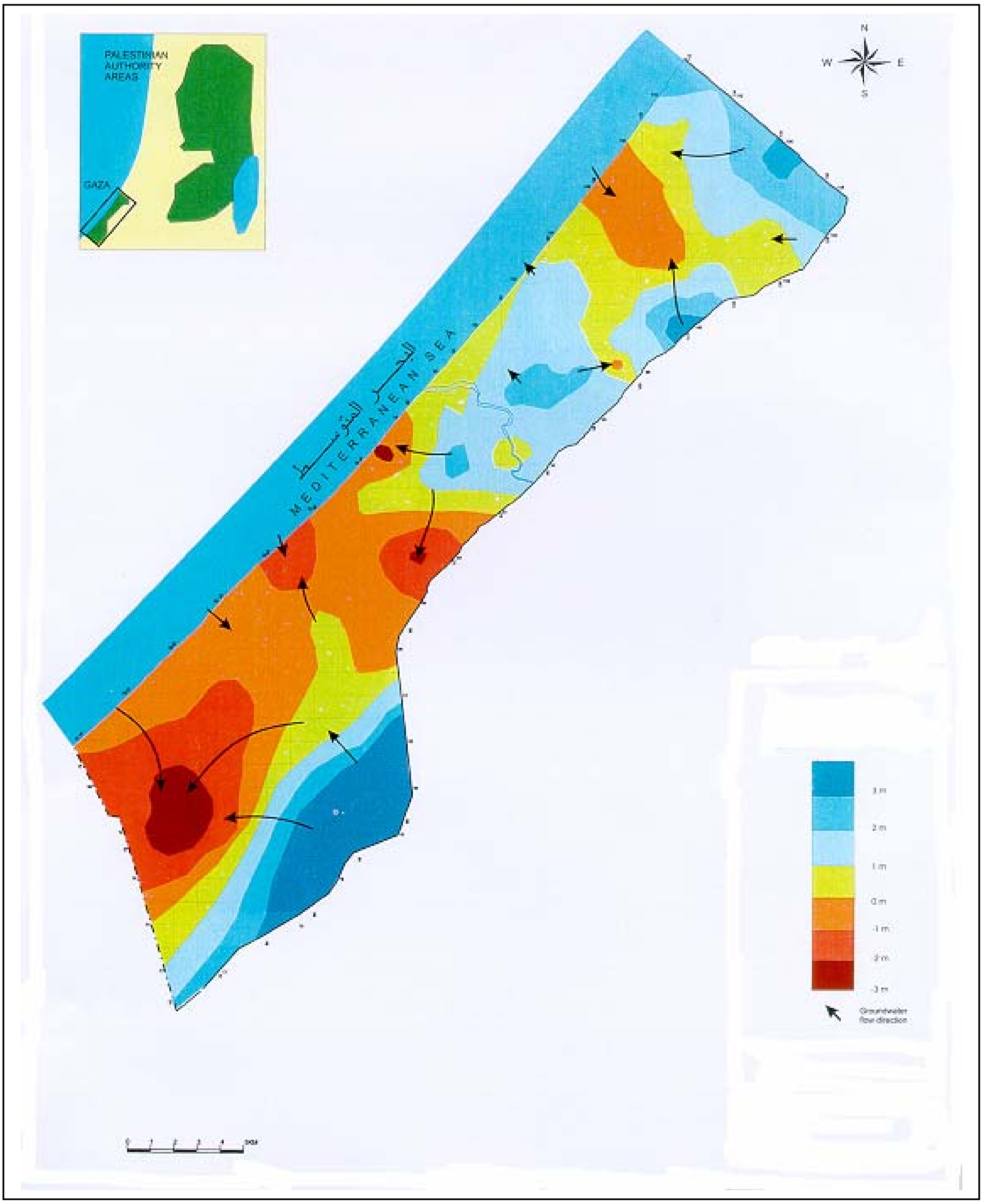


Figure 3.3 Groundwater table and flow direction of Beit-Lahia area in relation to the groundwater table of Gaza Strip. (Data source: Mopic, 1994-1995)

Soil distribution

The northern area is covered in sandy soils in the west and center, with dark brown clay loam soil in the east (Figure 3.4). The areas classified as having sandy soils are regosoils and effectively have no soil profile. A vertical cut through such areas normally shows sand continuing with no particular horizons or textures for several meters into the subsoil. They consist of medium to coarse quartz sand with a low water holding capacity. The subsoil is found to be on top of clay layers interspersed with more sand. Loamy clay soil areas largely result from the underlying clay being nearer the surface. Therefor the profile normally consists of the top 30 centimeters of clay soil, which rapidly becomes a solid layer of clay several meters thick.

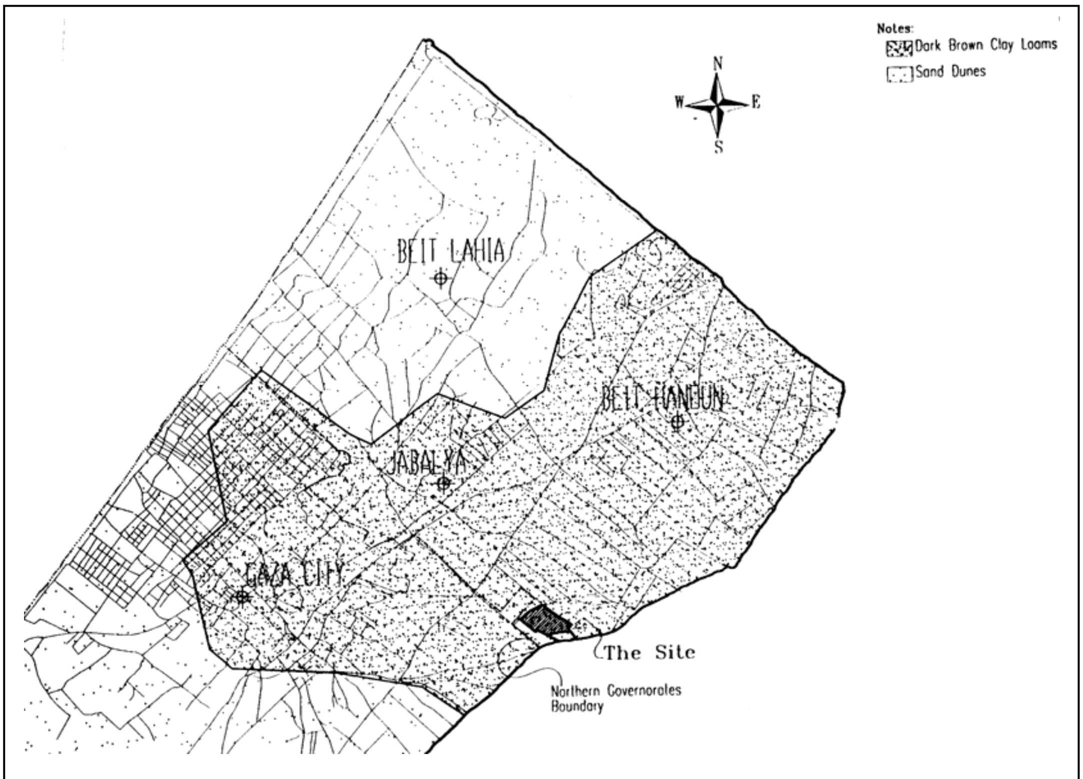


Figure 3.4 Topsoil classification in Beit-Lahia area. (PWA)

3.4 Wastewater treatment plant

The Beit-Lahia treatment plant was built in 1976, the system was designed as 4 aerated ponds of 5000 m^2 surface area each, with a capacity of 29000m^3 . Two more ponds were added in 1985 (no. 5 & no. 6) with a surface area of 10000m^2 each and with a capacity of 34000 m^3 for the first pond and 12000 m^3 for the second pond. In 1993 another 34000 m3 pond was added to the system (no. 7). The treatment plant serves about 60 % of the community in the northern governorate. The sewage flow to the treatment plant is estimated at approximately 7000 m^3 /day with a possible increase to 15000 m^3 /day in winter appendix 1.

Beit-Lahia treatment plant was constructed based on an idea of reuse of treated effluent in agriculture but farmers refused to use the effluent, as they were worried about the sociocultural acceptability of their products. In addition, the effluent quality does not fulfill the reuse requirements recommended by the (WHO) standard, that requires effluent with Biological Oxygen Demand (BOD) less than 20 mg/L and Suspended Solids (SS) less than 30 mg/L.

The final disposal from pond No. 7 is discharged directly to the sand duns where it is infiltrated into the ground. (Figure 3.5, Plate 1)

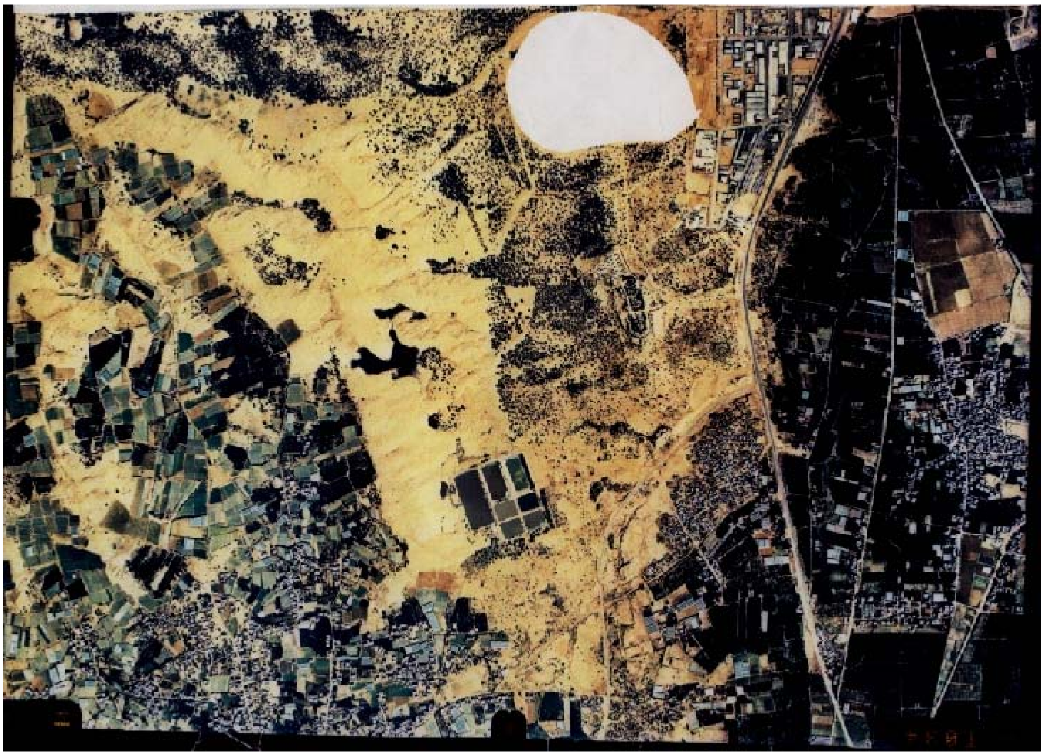


Figure 3.5 Arial photo of Beit-Lahia area (PWA,1998)

3.5 Nitrate in groundwater

Groundwater is the only source of potable water in Beit-Lahia area. Groundwater is abstracted from five municipality wells in addition to agricultural and private wells. The water quality of all these wells is continuously deteriorating. The concentration of nitrate range from 50 to 200 mg/l, which exceeds the WHO standards for drinking water. Figure 3.6 gives an idea about the distribution of nitrate concentration in northern governorate in relation with the entire Gaza Strip nitrate distribution. Figure (3.7) show the time series of nitrate concentration of four representative wells in Beit-Lahia area. More details on the nitrate concentration in different areas of Beit-Lahia in chapter four and in (appendix 1)

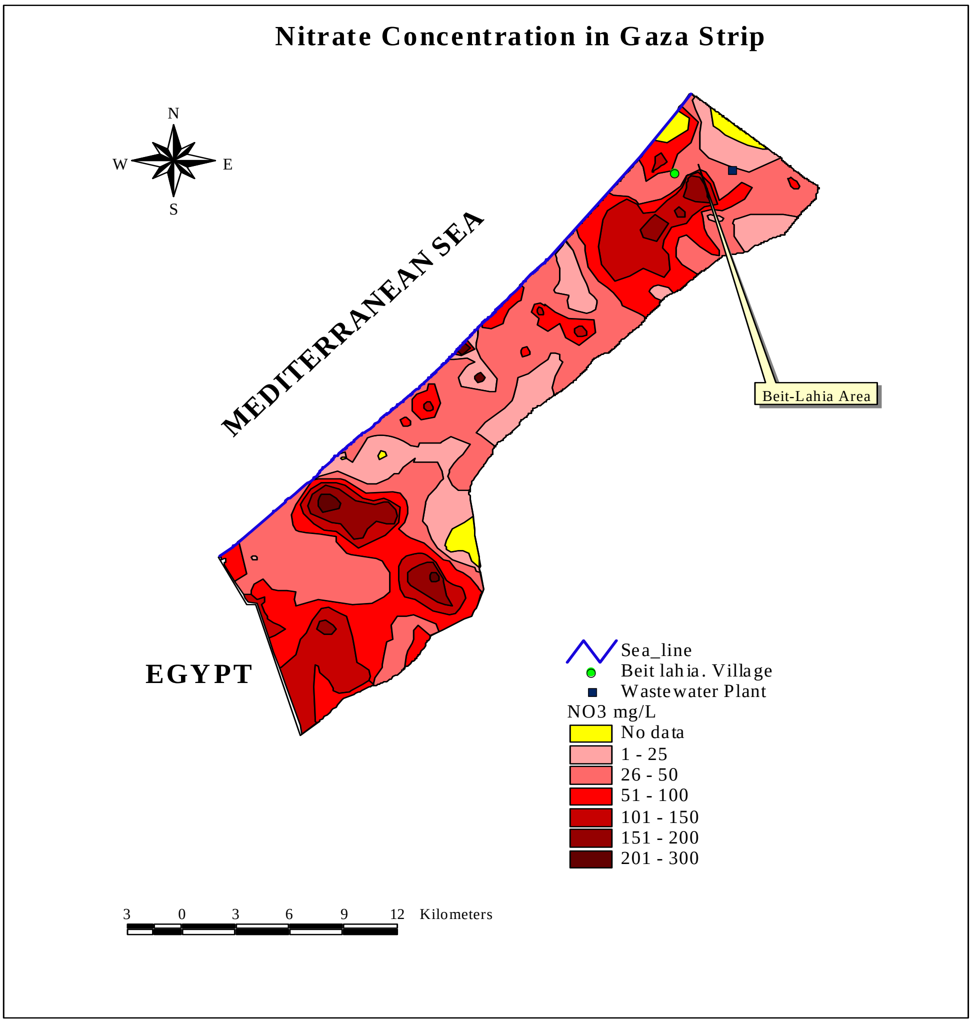


Figure 3.6 Nitrate concentration of Beit-Lahia area in relation to the nitrate concentration of the entire Gaza Strip (Data source: MOPIC, 1994- 1995).

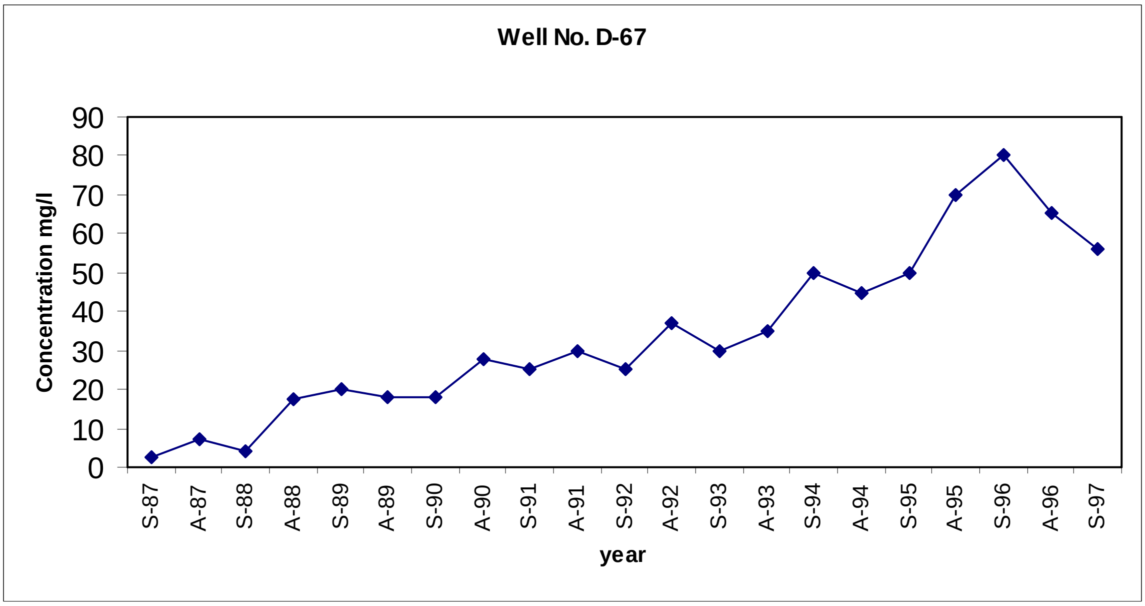


Figure 3.7.a Time series of nitrate concentration mg/l for well D- 67 in Beit-Lahia area

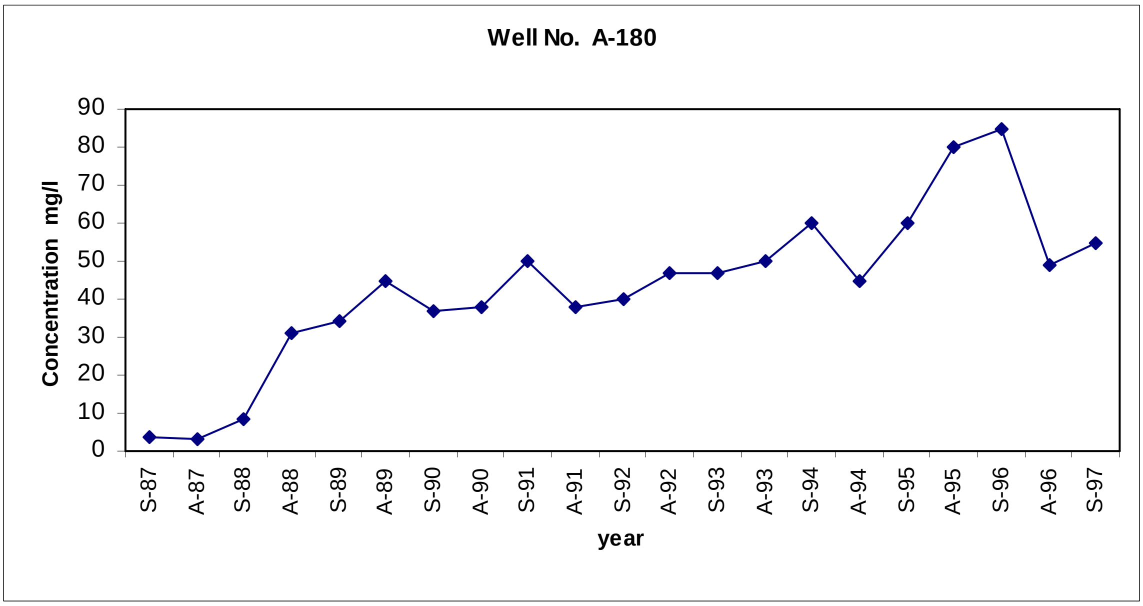


Figure 3.7.b Time series of nitrate concentration mg/l for well A-180 in Beit-Lahia area

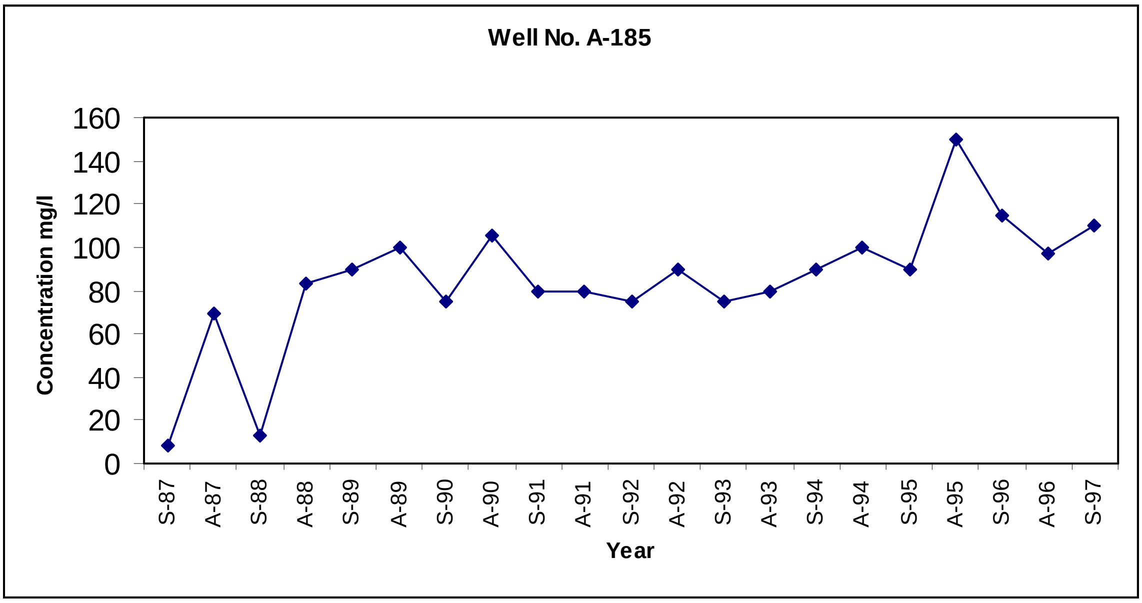


Figure 3.7.c Time series of nitrate concentration mg/l for well A- 185 in Beit-Lahia area

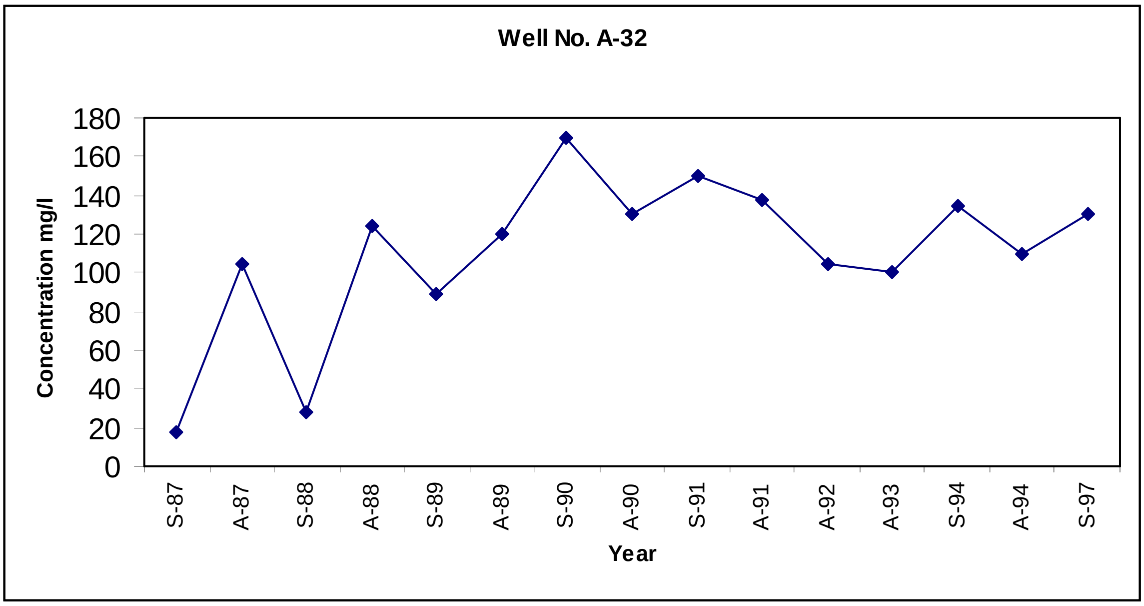


Figure 3.7.d Time series of nitrate concentration mg/l for well A- 32 in Beit-Lahia are

CHAPTER 4

Field Research and Analysis

4.1. Data collection and analysis in Beit-Lahia area

Field investigation of domestic activity as nitrate pollution source. Domestic activity investigation has been investigated in the following procedure:-

i) Interviews and Discussions:

Engineers of the sanitation office of the Beit_Lahia and Jabalia municipalities were interviewed on the varies issues relating to water and wastewater production, collection, treatment, disposal, and cesspits.

ii) Water and Wastewater Sampling and Analysis

Wastewater sampling and analysis program has been implemented. The samples were taken from the treatment plant at Beit-Lahia area. Water samples were collected from 5 municipal wells and 26 agricultural wells around wastewater plant. The water and wastewater samples were analyzed in AL-Azhar University- Water Research Center (WRC), water and wastewater Lab., and in the Ministry of Agriculture, Central Lab. for soil and water Gaza. The analysis and methods of preservation of samples followed the procedures in the Standard Methods for Examination of Water and Wastewater, 19^{th} edition (Greenberge et al, 1995). Wastewater parameters of interest to measure were: Chemical Oxygen Demand (COD: refers to the amount of oxygen required to oxidize the organic compounds in a water sample to carbon dioxide and water), Biological Oxygen Demand (BOD: is the quantity (mass) of oxygen consumed from a unit volume of water by microorganisms while they decompose organic matter, during a specified period of time). Ammonia ($NH4^+$), Kjeldahl nitrogen (TKN: this is a measure of both the ammonia and the organic forms of nitrogen) and Nitrate (NO_3^-).

Water Sampling and analysis is very important in this study it confirms the nitrate pollution problem claimed according to old records and gives the latest concentration in the groundwater of Beit-Lahia area. The water samples were analyzed for nitrate and ammonia in addition to chlorides and electrical Conductivity. The samples were taken after at least two hours of pumping from each well.

4.2 Results of Water Analysis

The results of the water analysis for nitrate concentration performed for 5 domestic wells and 26 agricultural wells, are given in (Table 4.1) and (Table 4.2). Nitrate concentration in the domestic wells is found at levels greater than the drinking water standard. The highest nitrate value found in the well E6 was 131 mg /L as nitrate due to high density of population and poorly sewerage system (figure 4.1) . The location of the domestic wells illustrated in (figure 4.2) comparing with nitrate concentration from year 1994-1995 according to (MOPIC) data.

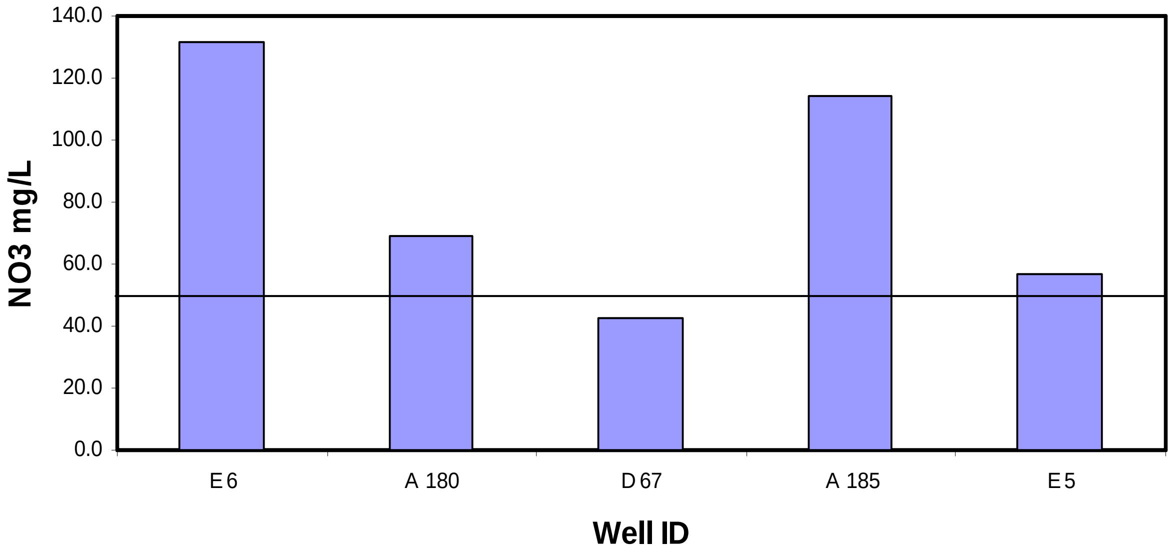


Figure 4.1 Nitrate concentration in domestic wells

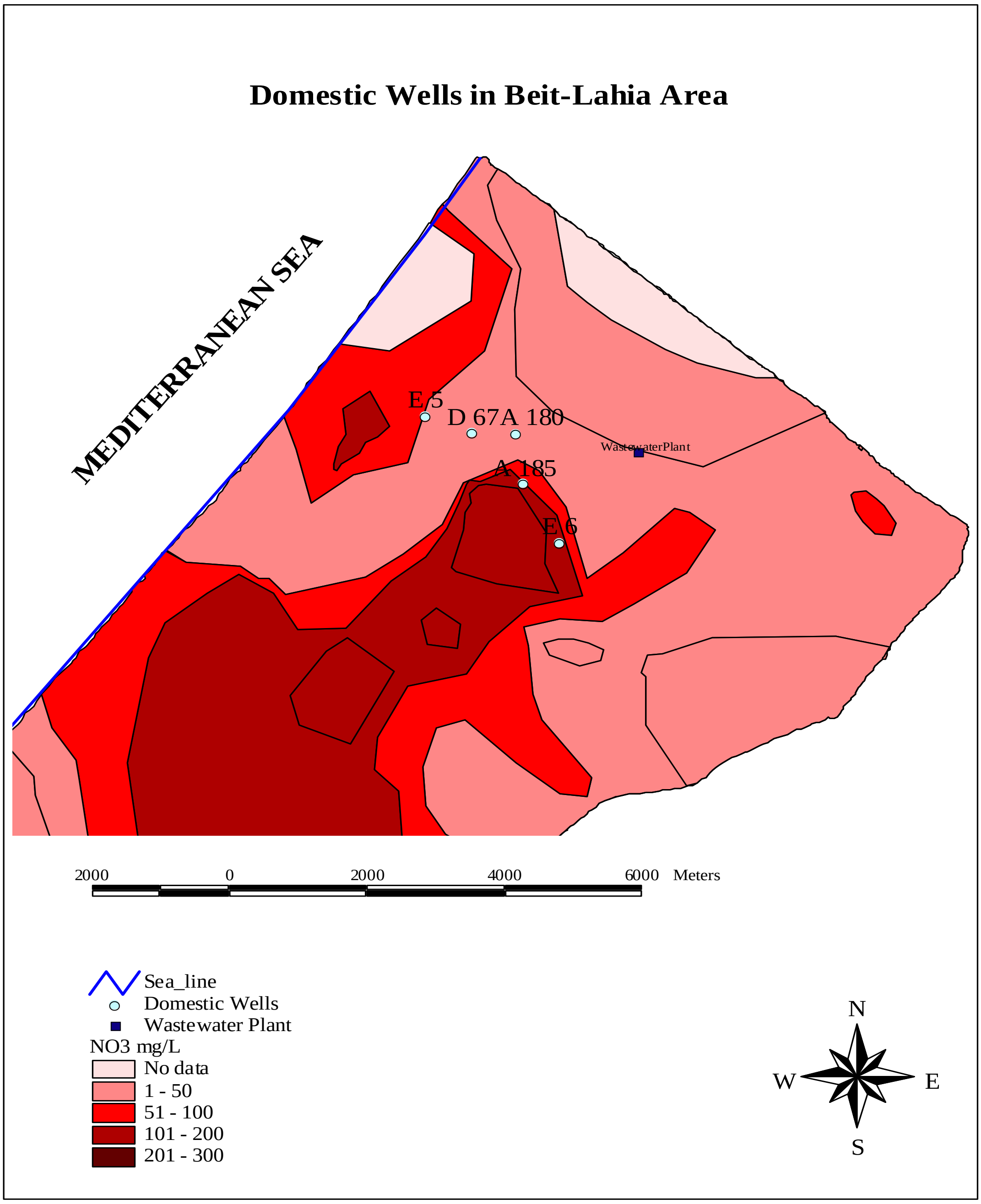


Figure 4.2 Location of domestic wells in beit-Lahia area

(Map source: MOPIC, 1994 – 1995)

Nitrate in the selected agricultural wells around wastewater plant is found at levels greater than the WHO standard. The highest nitrate concentration is found in wells A26, 165.7 mg /L, A31, 164.9 mg/L and A126, 119 mg/L (figure 4.3). The location of the agricultural wells in Beit-Lahia area is given on the map in (figure 4.4).

From the results of water analysis, it's concluding that the concentrations of nitrate in the domestic wells are in the range of 42 - 131mg/L and in the range of 30 - 166 mg/L in the agricultural wells, it is clear no difference so much in concentration.. The variation of nitrate concentration between different wells is due to the location of each well relative to the pollution sources.

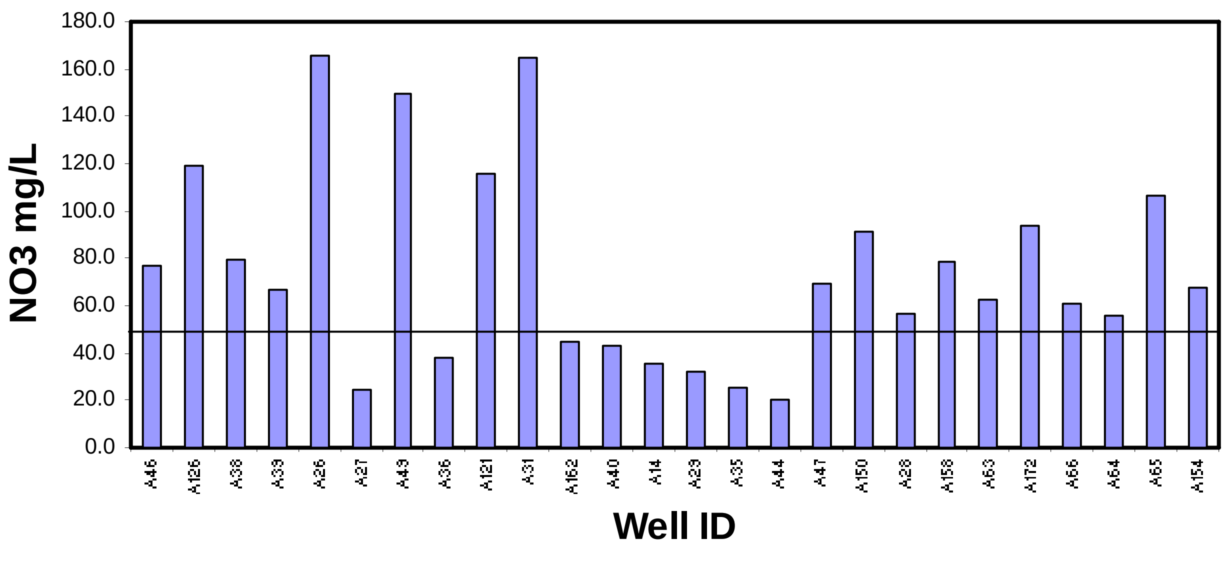


Figure 4.3 Nitrate concentration in selected agricultural wells

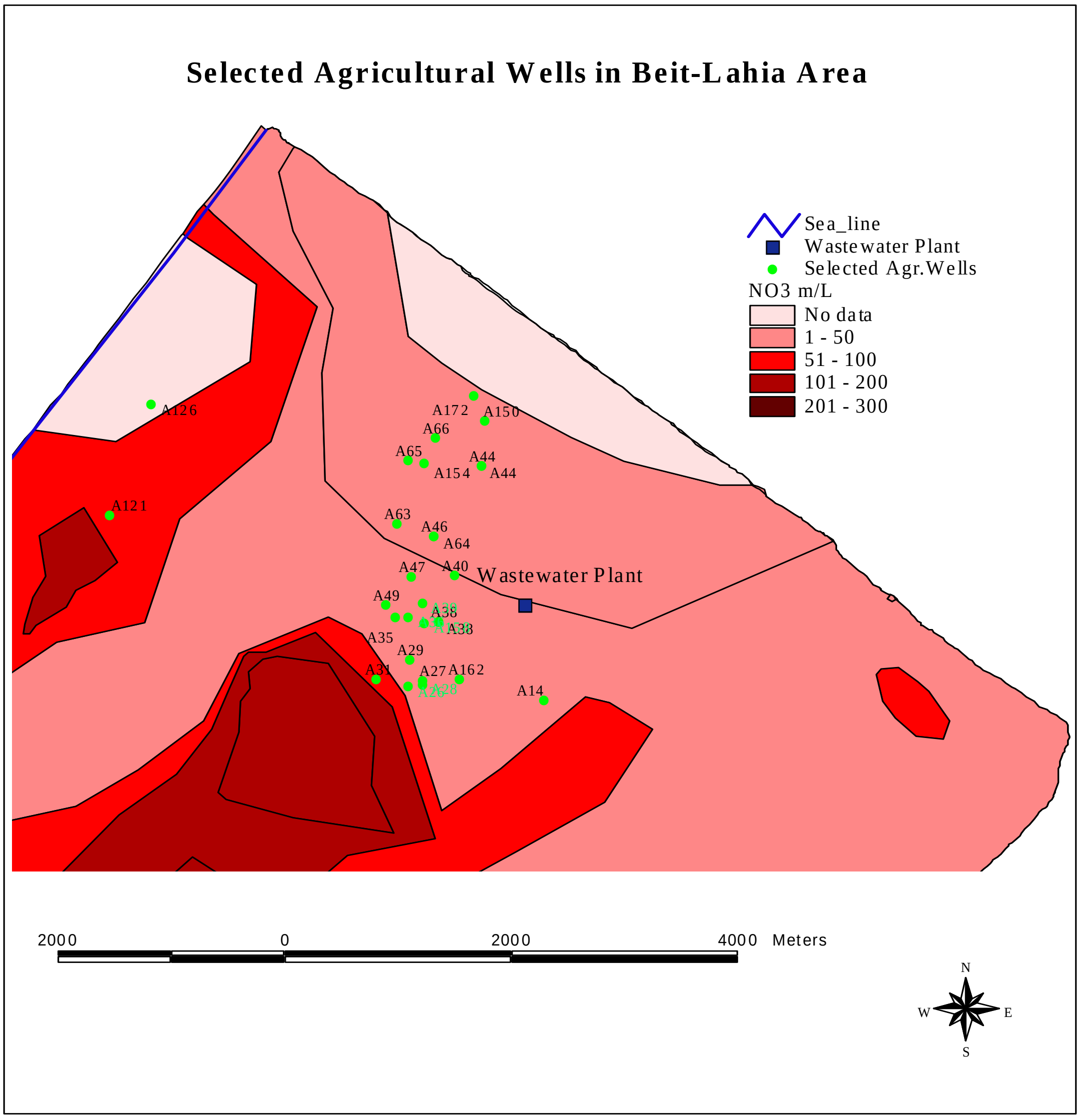


Figure 4.4 Location of selected agricultural wells in Beit-Lahia area

(Map source: MOPIC, 1994 – 1995)

4.3 Wastewater Characteristics

The samples were taken from the treatment plant on different times is presented in (table 4.3), (table 4.4),and (plate 2, 3.and 4) were measured in tow laboratories, at Al-Azhar University-WRC (water and wastewater Lab.) and Ministry of Agriculture-Central Lab. for soil and water.

The average Concentration of TKN is 52 mg/L. The efficiency of the treatment plant to remove nitrogen is limited as nitrification and denitrification processes are not occur in the plant where these two processes required a significant amount of artificial aeration with a considerable residence time respectively.

The average concentration of ammonia in the effluent is 34 mg/L .The average concentration of COD is 160 mg/L and average BOD concentration is 41 mg/L (plate 5). This high concentration in effluent limits the possibility of reuse of wastewater in agriculture.

The poorly treated wastewater is pumped to wastewater pond in sand duns area and infiltrate to the groundwater.

Table 4.3 Influent and Effluent Wastewater Quality

(Beit-Lahia Wastewater Treatment Plant)

Lab Measurements

Location	Date	Time	Temp.	pH	EC	TDS	Turbidity	NO3	T.S.S	COD	BOD
		hh:mm	C°		μS/cm	mg/l	NTU	mg/l as No_3	mg/l	mg/l	mg/l
Influent	21/08/99	10:30	N/D	7.43	2120	1125	67	20	412	730	N/D
Effluent	21/08/99	10:45	N/D	7.80	2082	984	52	16	42	140	N/D
Influent	30/08/99	10:30	29.6	7.79	1950	1034	52	24	374	485	400
Effluent	30/08/99	11:00	28.9	7.99	2210	1042	32	15	40	140	45
Influent	04/09/99	10:30	28.7	7.90	2050	1087	72	30	572	530	520
Effluent	04/09/99	11:00	29.6	8.15	2150	1160	17	15	31	140	35

Ministry of Agriculture
Central Lab. for Soil and Water

CHAPTER 5

Groundwater flow modeling

5.1 General groundwater flow equations

Differential equations that govern the flow of groundwater flow can essentially represent the groundwater flow system derived from the basic principles of groundwater flow hydraulics. The main flow equation for saturated groundwater flow is derived by combining a water balance equation with Darcy's law, which leads to a general form of the 3-D groundwater flow governing equation:

$$\frac{\partial h}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) - R(x, y, z) = S_s \frac{\partial h}{\partial t} \qquad (5.1)$$

Where K_x ,K_y and K_z, are the hydraulic conductivity of the x,y and z direction (making x, y and z- axes parallel to main axes of hydraulic conductivity), h is the hydraulic head (L), R is the local sources and sinks of water per unit volume (T^{-1}), S_s is the specific storage coefficient (L^{-1}) and t is the time (T).

Darcy's law

In differential form, Darcy's law is expressed as:

$$q = K_x \frac{\partial h}{\partial x} \qquad (5.2)$$

Where q is the groundwater flux (LT^{-1}).
This equation clearly shows that the cause of groundwater movement is the difference in the hydraulic potential. The potential can be generalize to a function of all three-space coordinates, that is, h= h (x,y,z) , the rate of change of head with position , to

three dimensions, giving the three components of the groundwater flux.

$$q_x = -K \frac{\partial h}{\partial x} \tag{5.2.1}$$

$$q_y = -K \frac{\partial h}{\partial y} \tag{5.2.2}$$

$$q_z = -K \frac{\partial h}{\partial z} \tag{5.2.3}$$

We know that the space derivatives are partial derivatives because head is now function of all three –space coordinates.

Equation (5.2) can be written the shorthand of vector notation as:

Q = -K grad **h** (5.3)

The left-hand side of equation represents the net change in the volume rate flow per unit volume. q has components q_x, q_y and q_z and the gradient has components:

$$\frac{\partial h}{\partial x}; \frac{\partial h}{\partial y} \, and \, \frac{\partial h}{\partial z}$$

Because each component of q is the same scalar multiple K of the corresponding component of (-grad h), the vectors q and (- grad h) both point in the same direction. This conclusion follows from the assumption of isotropy.

Continuity equation for steady state flow: Law of conservation of mass

Darcy's law, equation (5.2) summaries much of physic of groundwater flow by relating the velocity vector to gradient of potential. Continuity or conservation is a second important law. For steady state condition, continuity requires that the amount of water flowing in to representative elemental volume be equal to the amount flowing out.

The existence of steady – state condition implies that head is independent of time. We make two other simplifying assumptions:

First, we assume water is incompressible, second, the elemental volume contains no source of sinks. The sign convention is that if the derivative is positive, there is a net out ward flow of water.

The net change in the discharge rate in the x direction is $(\frac{\partial q_x}{\partial x})\Delta v$, the net change in the discharge rate in the y direction is $(\frac{\partial q_y}{\partial y})\Delta v$, and the net change in the discharge in the z direction is $(\frac{\partial q_z}{\partial z})\Delta v$

The sum, $(\frac{\partial q_x}{\partial x}\Delta v + \frac{\partial q_y}{\partial y}\Delta v + \frac{\partial q_z}{\partial z}\Delta v)$, must be equal zero.

We can divide through by Δv and be left with the continuity equation for steady state conditions.

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \qquad (5.4)$$

In most analyses the general flow equation is formulated by applying the law of conservation of mass over an elemental volume of an aquifer situated in the flow field. Continuity requires that, the net inflow into the elemental control volume must be equal to the rate which water is accumulating within the volume under investigation, that is, outflow minus inflow equals change in storage. However, this applies as long as variable is considered on macroscopic level, in which the flow is in the y-direction, the net inflow into the volume on volumetric basis can be expressed as:

$$\frac{(q_x)out-(q_x)in}{\Delta y}(\Delta x\Delta y\Delta z) \tag{5.5}$$

Where $(\Delta x\Delta y\Delta z)$ is the volume of the elemental control volume. In differential form, Equation (5.5) can be written as:

$$\frac{\partial q_y}{\partial y}(\Delta x\Delta y\Delta z) \tag{5.6}$$

Similar expressions can be formulated in the x – and y directions, thus yielding the total change in flow rate equal to change in storage as:

$$(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z})\,\Delta x\Delta y\Delta z \tag{5.7}$$

By introducing a sink or source term within the elemental control volume represented as R, the volumetric inflow rate becomes R $(\Delta x\Delta y\Delta z)$. Putting this term in Eq. (5.7) yields:

$$(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\text{-R})\,\Delta x\Delta y\Delta z=\Delta s \tag{5.8}$$

Where ($\Delta x\Delta y\Delta z$) is the change in storage. The change in storage is represented by the specific storage, or specific storage coefficient, Ss as explained in Eq. (5.1) which is defined as the volume of water a unite of saturated aquifer release from storage for a unit decline in hydraulic head. That is:

$$S=\frac{\Delta v}{\Delta h\Delta x\Delta y\Delta z} \tag{5.9}$$

Where $\Delta x\Delta y\Delta z$ is the volume of water released from storage. The rate of change in storage is then given by:

$$\frac{\Delta v}{\Delta t} = -S_s \frac{\Delta h}{\Delta t} \Delta x \Delta y \Delta z \qquad (5.10)$$

Combining Eq. (5.4) and Eq. (5.7) and dividing by $\Delta x \Delta y \Delta z$ yields the general form of the mass balance equation as:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = S_s \frac{\partial h}{\partial t} + R \qquad (5.11)$$

Eq.(5.1) is obtained by combining Eq. (5.11) and Darcy's law.

For steady state flow, the term $\frac{\partial h}{\partial t}$ in eqn (5.1) is zero and the equation thus reduces to

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) = 0 \qquad (5.12)$$

If we at the same time neglect the source/sink term Eqn(5.12) expresses the general form of the equation describing steady state flow through an isotropic saturated porous medium.

If the source and sink term in Eq.(5.1) is neglected , the equation can conveniently be used for transient flow.

Laplace's combine Darcy's law and continuity equation in to a single second –order partial differential equation.

Darcy's law is submitted component by component in to equation (5.4) to give

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z})$$

Where K= k(x,y,z) if is assumed to be independent of x,y and z that is the region is assumed to be homogeneous as well as isotropic. The equation becomes:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \qquad (5.13)$$

Equation (5.13) is the Laplace's equation, the governing equation for groundwater flow through an isotropic, homogeneous aquifer under steady state conditions.

In most cases for field applications, it is convenient to work in two dimensions since thickness of strata is often insignificant in comparison to lateral extent. For a confined aquifer (thickness, b, the hydraulic conductivity may be replaced by T= Kb; and two dimensional form of Eq.(5.1) becomes:

$$\frac{\partial}{\partial x}(T_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(T_z \frac{\partial h}{\partial z}) = S\frac{\partial h}{\partial t} - R(x, y.z) \qquad (5.14)$$

Where T is the transmissivty (L^2), S is storage coefficient given by, S = Ss b
For steady state conditions Eq. (5.14) becomes:

$$\frac{\partial}{\partial x}(T_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(T_z \frac{\partial h}{\partial z}) + R(x, y.z) = 0 \qquad (5.15)$$

Which is an equation of the Poisson type.

The Darcian approach in formulating the general flow equation is based on replacing the actual aquifer with a representative continuum in order to use macroscopic lax to describe flow at microscopic scale. Groundwater flow is expressed by simple relationship ignoring the complex flow configuration at pore scale.

5.2 Numerical methods

Overview

Groundwater flow equations are usually difficult to solve analytically, because either the flow is governed by partial differential equations that are complicated (e.g., non-linear), or the medium properties are heterogeneous.
In such cases, numerical solution techniques can be used to obtain an approximate solution. The following numerical methods are used in groundwater modeling:

- Finite differences method (FDM).
- Finite elements method (FEM).
- Integrated finite differences method (IFDM).
- Finite volume method (FVM).
- The boundary integral equation method.
- Analytical and semi-analytical solutions.

As FDM and FEM techniques are more commonly used to solve flow problems, the discussion in this paragraph focuses on these two numerical methods.

A computer program or code solves an algebraic equation method by approximation the partial differential equations (governing equation, boundary condition and initial condition) that form the mathematical model.

Approximating techniques such as the finite difference and the finite element methods operate on a mathematical model in a form that can be solved quickly by a computer. The set of algebraic equations produced in this way can be expressed as a matrix equation.

5.2.1 Finite element techniques

The main idea of the finite element method is to have a greater freedom in the position of the nodes. For instance nodes can be placed in interesting locations, the density of the nodes can be chosen according to the expected variations of the variables, and the geometry of the flow domain can be better approximated.

-General considerations

The basic concept of the finite element method is to subdivide a series of finite elements that are connected at a discreet number of modal points N. Each element is identified by its element number and the lines connecting the modal point located on the element boundary. The idea of the finite element method is to represent the unknown variable within each element by an interpolating polynomial that is continuous along with its derivatives to a specified order within the element.
Consider a flow equation, which is a partial differential equation of this form:

$$F(h) = 0$$

Where:
F: differential operator
h: dependent variable

In order to arrive at N algebraic equations, we have to know the potential values in points that are not nodes because these are unknown. Hence, an interpolation method is needed.

- **The interpolation method: Residual minimization methods**

The main goal of residual interpolation techniques (e.g., Galerking) is to obtain an algebraic equation, called a finite element equation, that will make it possible to calculate the potentials in the nodes (the figure 5.1 gives some 3D finite elements used in finite element modeling)

A criterion is needed for making an approximate solution (h*) as close as possible to exact solution. There are several techniques, the most popular of which are residual minimization methods. These methods are based on the fact that when the approximate solution is introduced in the flow equation, the result will not equal zero. This non-zero value is called the residual, E, function defined over the total flow domain.

The residual interpolation contains:

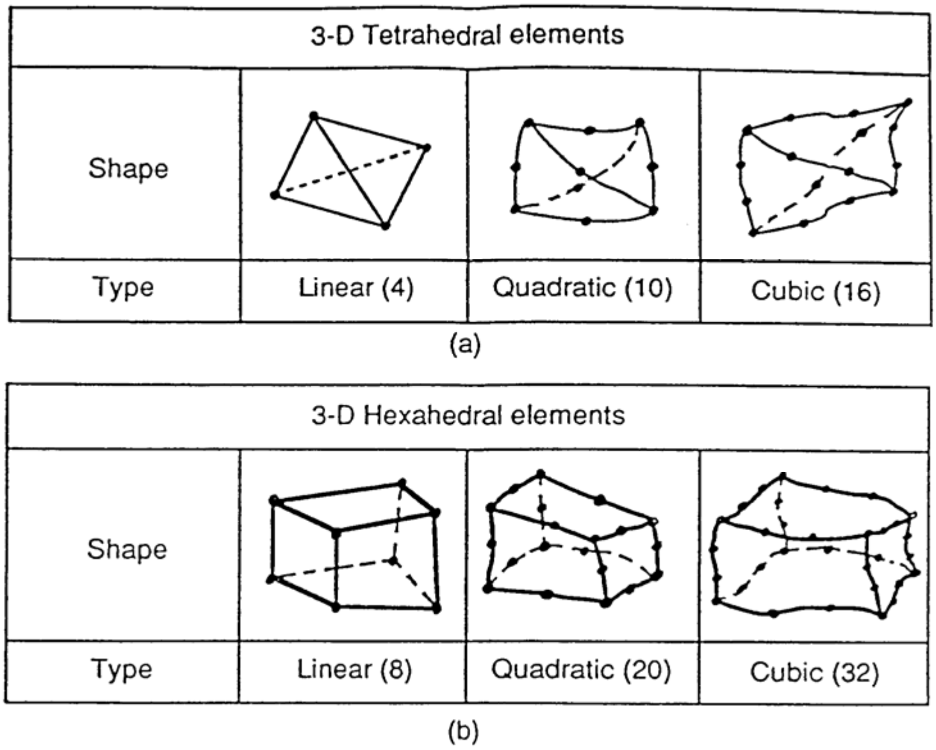
- Allocation techniques
- Zone techniques
- Mean squared residual method
- Galerking Method

The last method is the most used of all these residual methods.(for a more detailed explanation, see: Numerical modeling of groundwater flow , chapter 3:Finite element techniques, by F.De.Smedt)

Figure 5.1: 3D Finite element used in groundwater modeling

(a) Tetrahedral elements

(b) Hexahedral elements



5.2.2 Finite difference techniques

A partial differential equation is complicated to solve. Numerical solution techniques can be used to obtain an approximate solution. The oldest and most popular numerical technique is the finite difference method.

The basic idea of the finite difference method is to replace partial derivatives in the flow equation by finite differences, which are ratios of the chance of the variable over a small but finite distance, such as:

$$\frac{\partial h}{\partial x} = \lim_{\Delta x \to 0} \frac{\Delta h}{\Delta x} \approx \frac{\Delta h}{\Delta x} \tag{5.14}$$

To satisfy the flow equation, a finite number of points can be calculated approximately. The distance between these nodes points need not to be constant, but unless there is a specified need for changing the distances, a constant value is preferred.

For time –dependent problems, the time is divided into increments, which need not be all equal. The solution obtained is only approximate, the resulting error, that is to say the difference between the time (analytical) solution and the exact solution of the finite difference equation, is termed the truncation error. The use of computer is to make the task easier, but also if there is an error between the true value and the calculated value, this error is termed the round of error (F. De. Smedt , 1999)

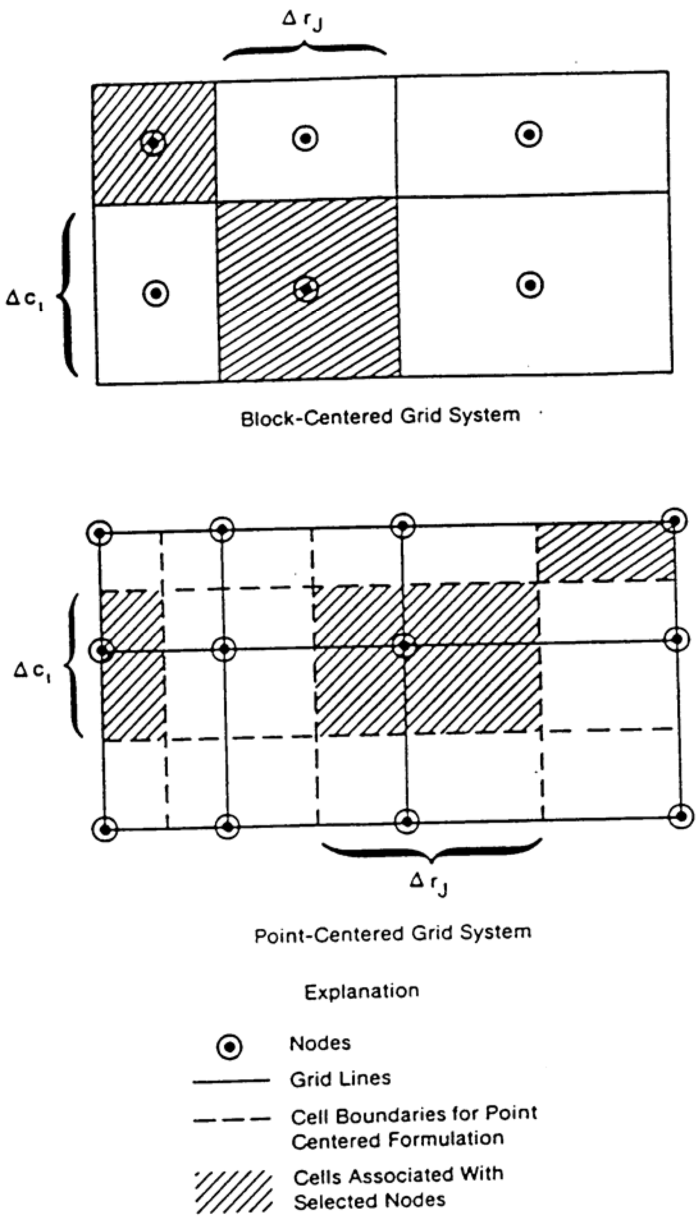
Finite difference convictions

Within each cell there is a point called a node, at which the potential is to be calculated in two dimensions, two conventions for defining the configuration of the cells with respect to the location of the nodes:

- the block – centered formulation
- the point – centered formulation

Both systems start by dividing the aquifer with two sets of parallel lines that are orthogonal (see figure 5.2)

Figure 5.2: Block-centered and point-centered grid systems



In fact, in the block-centered formulation, the blocks are formed by the sets of parallel lines and the cells; the nodes are at the intersection points of the set of parallel lines, and the cells are drawn around the nodes with faces halfway between the nodes. In the point –centered formulation, the spacing of the nodes should be closer so that the hydraulic properties of the system are generally uniform the extent of a cell.

- **Backward, forward and central finite difference approximations**

The accuracy of the finite difference approximation is very crucial in the model. Different possibilities exist. Consider the Taylor series expansion of the potential function h(x) by taking a small step forward to x :

$$h(x+\Delta x) = h(x) + \Delta x \frac{dh}{dx} + \frac{(\Delta x)^2}{2I}\frac{d^2h}{dx^2} + \frac{(\Delta x)^3}{3I}\frac{d^3h}{dx^3} + ... \qquad (5.17)$$

A finite difference approximation results for the first order derivative:

$$\frac{dh}{dx} \approx \frac{h(x+\Delta x) - h(x)}{\Delta x} \qquad (5.18)$$

If Δx is very small, the forward finite difference approximation will be accurate consider the Taylor series expansion by taking a step backward to x- Δx :

$$h(x-\Delta x) = h(x) - \Delta x \frac{dh}{dx} + \frac{(\Delta x)^2}{2I}\frac{d^2h}{dx^2} - \frac{(\Delta x)^3}{3I}\frac{d^3h}{dx^3} \qquad (5.19)$$

Solving the first order derivative gives :

$$\frac{dh}{dx} = \frac{h(x) - h(x-\Delta x)}{\Delta x} + \Delta x(....) \qquad (5.20)$$

Which yields a backward finite difference approximation:

$$\frac{dh}{dx} \approx \frac{h(x) - h(x - \Delta x)}{\Delta x} \tag{5.21}$$

Subtracted the forward from the backward finite difference equation to obtain:

$$h(x + \Delta x) - h(x - \Delta x) = 2\Delta x \frac{dh}{dx} + \frac{2(\Delta x)^3}{3I} \frac{d^3 h}{dx^3} + ... \tag{5.22}$$

or

$$\frac{dh}{dx} = \frac{h(x + \Delta x) - h(x - \Delta x)}{2\Delta x} + (\Delta x)^2 (....) \tag{5.23}$$

Which yields a central finite difference approximation:

$$\frac{dh}{dx} \approx \frac{h(x + \Delta x) - h(x - \Delta x)}{2\Delta x} \tag{5.24}$$

Having an error proportional to $((\Delta x)^2)$, which is smaller than the error of forward and backward approximations. Hence, the central finite difference approximation is superior in accuracy and should be preferred whenever it is possible.

- **Solution for steady state flow**

Let us begin by a simple Laplace equation in two dimensions and by a central finite difference approximation in the second derivative of the equation in the node (i.j):

-The second derivative versus x:

$$\frac{\partial^2 h}{\partial x^2} = \frac{h_{i-1,j} - 2h_{i,j} + h_{i+1,j}}{(\Delta x)^2} \tag{5.25}$$

-The second derivative versus y:

$$\frac{\partial^2 h}{\partial y^2} = \frac{h_{i,j-1} - 2h_{i,j} + h_{i,j+1}}{(\Delta y)^2} \tag{5.26}$$

The LAPLACE equation becomes:

$$\frac{h_{i-1,j} - 2h_{i,j} + h_{i+1,j}}{(\Delta x)^2} + \frac{h_{i,j-1} - 2h_{i,j} + h_{i,j+1}}{(\Delta x)^2} = 0 \tag{5.27}$$

$$h_{i-1,j} + h_{i,j-1} - 4h_{i,j} + h_{i+1,j} + h_{i,j-1} = 0 \tag{5.28}$$

This equation is used for all inside nodes, but not for the nodes on the boundary. For the boundary condition, its seems to approximate as follows (see figure 5.3)

$$q_x^0(x_i, y_{i)} = -K\frac{h_{i+1,j} - h_{i,j}}{\Delta x} \tag{5.29}$$

Where:

q_x^0 : Boundary flux in the x direction.

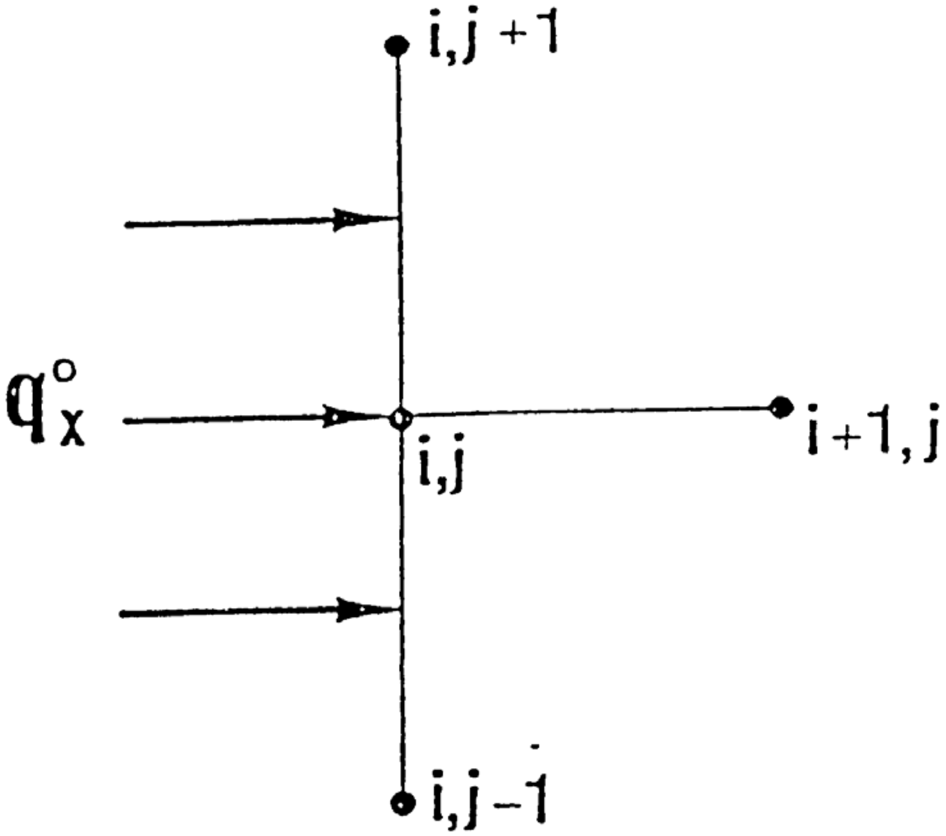


Figure 5.3: Boundary conditions in the nodes

This is a forward finite difference approximation, which is not as accurate as a central finite difference approximation.

To apply this method, an imaginary node (i-1,j) must be introduced (see figure 5.4) and the central finite difference approximation becomes possible:

$$q_x^0(x_i, y_{i)} = -K \frac{h_{i+1,j} - h_{i-1,j}}{2\Delta x} \tag{5.30}$$

Which will make it possible to calculate the potential at the imaginary node:

$$h_{i-1,j} = h_{i+1,j} + 2q_x^0(x_i, y_i)\Delta x / K \tag{5.31}$$

This yields a correct central finite difference approximation of the flux boundary conditions (in x direction):

$$h_{i,j-1} - 4h_{i,j} + 2h_{i+1,j} + h_{i,j+1} = -2q_x^0(x_i, y_i)\Delta x / K \tag{5.32}$$

In order to obtain reliable finite difference models, it is necessary to use correct accurate finite difference approximations, considering a more complicated equation as horizontal flow in an aquifer:

$$\frac{\partial}{\partial x}\left[T(x.y)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[T(x.y)\frac{\partial h}{\partial y}\right] + R(x,y) - W(x.y) = 0 \tag{5.33}$$

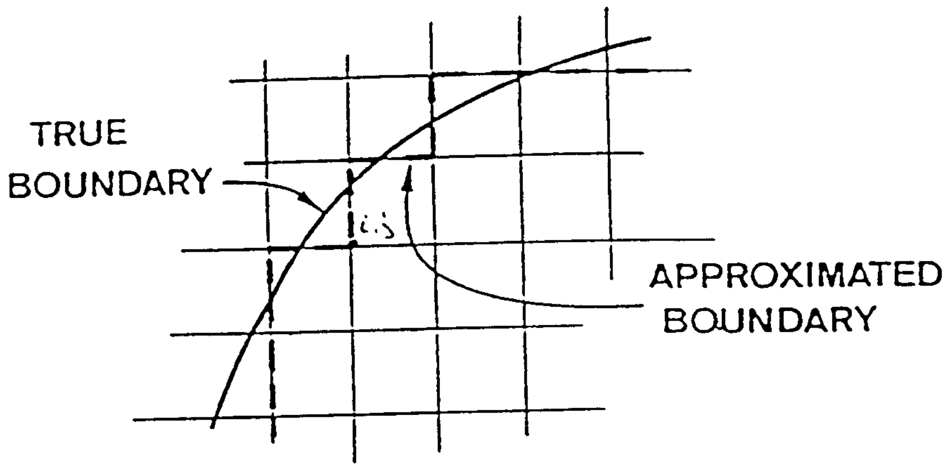
Where:

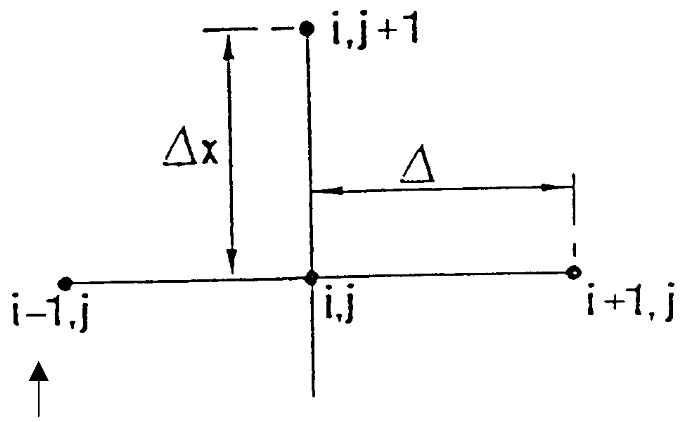
W: total pumping rate

T: transmissivity

R: recharge (varying within the position)

Figure 5.4: The imaginary node (i-1,j) for the FD boundary approximation





Imaginary node

The following relaxation equation is obtained:

$$h_{i,j} = \frac{T_{i+1/2,j}h_{i-1,j} + T_{i,j-1/2}h_{i,j-1} + T_{i+1/2,j}h_{i+1,j} + T_{i,j+1/2}h_{i,j+1} + R_{i,j}(\Delta x)^2 - W_{i,j}}{T_{i-1/2,j} + T_{i,j-1/2} + T_{i+1/2,j} + T_{i,j+1/2}} \quad (5.34\text{-a})$$

This is a central finite difference approximation inside a domain:

$$h_{i,j} = \frac{Q_i \Delta x + (T_{i,j-1/2}h_{i,j-1/2}/2) + T_{i+1/2,j}h_{i+1,j} + (T_{i,j+1/2}h_{i,j+1}/2) + (R_{i,j}(\Delta x)^2/2) - W_{i,j}}{(T_{i,j-1/2}/2) + T_{i+1/2,j} + (T_{i,j+1/2}/2)}$$

(5.34-b)

Where:

Q_i: boundary condition

This is a correct central finite difference approximation.

5.3 Visual MODFLOW Interface

Visual MODFLOW, first released in 1994, is being widely used by consultants, regulators and educators in many countries around the world. It is being the proven standard software package for professional, three- dimensional groundwater flow, pathline and contaminant transport modeling (Waterloo Hydrogeologic Inc.). It combines the USGS MODFLOW, MODPATH and MT3D with the most powerful and intuitive graphical interface available. It allows the user to graphically assign all necessary flow and transport parameters, run the simulation using the Win32 MODFLOW Suite (wherein MODFLOW, MODPATH and MT3D are included), calibrate the model using calibration statistics and graphical results, and visualize full –color, high-resolution results in plan view or full- screen cross sections.

5.3.1 MODFLOW code

An Overview

MODFLOW, simulates flow in three dimensions, the modular structure consists of main program and a series of highly independent subroutines called " modules ". The modules are grouped into " packages ". Each package deals with a specific feature of the hydrologic system to be simulated. The division of the program into modules no only permits the user to examine specific hydrologic features of the model independently but also facilitates development of additional capabilities by introducing new packages to the program without making major modifications , to the existing package .

Groundwater flow within the aquifer is simulated using a block-centered finite difference approach. Layer can be simulated as confined, unconfined, or a combination of confined and unconfined. Flow associated with external stresses, such as wells. Recharge, evapotranspiration, drains and streams, can also be simulated through the use of specified head, specified flux, or head –dependent flux boundary condition. The implicit finite –difference equations can be solved using either the strongly implicit –procedure (SIP) or slice-successive over relaxation (SSOR) methods. Newer packages offer several additional solution algorithms, including a preconditioned conjugate – gradient solver (Hill, 1990), a direct solver (Harbaugh, 1995), the WHS solver (Waterloo Hydrogeologic Inc., 1998). Although the input and output systems of computer program were initially designed to permit maximum flexibility, usability and ease of interpretation of model results can be enhanced by using one of several commercially available preprocessing and postprocessing packages.

Mathematical model and finite –difference analog

The three –dimensional movement of groundwater of constant density through porous earth material may be described by the partial-differential equation:

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]-W=S_s\frac{\partial h}{\partial t} \qquad (5.35)$$

Where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x,y and z coordinate axes , which are assumed to be parallel to the major axes of hydraulic conductivity; h is the potentiometric head W is a volumetric flux per unit volume and represents sources and/or sinks of water Ss is the specific storage coefficient of the porous material; and T is time (t). In general, Ss, K_{xx},K_{yy} and K_{zz} may be functions of space (S_s = S_s (x,y,z), K_{xx} = (K_{xx}(x,y,z), etc.) and W may be a function of space and time (W = W(x,y,z,t)) ; Equation (5.35) describes groundwater flow under non equilibrium conditions in a heterogeneous and an isotropic medium, provide the principal axes of hydraulic conductivity are aligned with the coordinate directions.

Equation (5.35), together with specification of flow and/or head conditions at the boundaries of an aquifer system and specification of initial –head conditions, constitutes a mathematical representation of a groundwater flow system. A solution of such an equation, in an analytical sense, is an algebraic expression giving h (x,y,z,t) such that, when the derivatives of h with respect to space and time are substituted into

Equation (5.35) , the equation and its initial and boundary conditions are satisfied. A time –varying head distribution of this nature characterizes the flow system, in that it measures both the energy of flow and the volume of water in storage, and can be used to calculate directions and rates of movement.

Packages

The MODFLOW packages, at the present, include basic, Block- Centered Flow, River, Recharge, Drain, Evapotranspiration, General –Head Boundary, and Horizontal-Flow Barriers (Wall) packages.
Explanations are provided, only very briefly. Interested readers are encouraged to refer to McDonald and Harbaugh (1988), Harbaugh and McDonald (1996) for full documentation and more explanations on physical and mathematical concepts on which the development of the packages is based and how those concepts are incorporated in the modular structure of the computer program.

5.3.2 MODPATH code

MODPATH is a particle – tracking post-processing package used to compute 3D pathlines based on output from steady state simulations, and recently transient simulations, obtained with the MODFLOW code. The package consists of two FORTRAN 77 computer programs: MODPATH, which calculates pathlines; and MODPATH-PLOT, which presents results graphically (Pollock, 1989). MODPATH uses a semi-analytical particle-tracking scheme and is based on the assumption that each directional velocity component varies linearly with a grid cell in its own coordinate direction. Given the initial position of a particle anywhere in a cell, the coordinates of any other point along its path line within the cell, and the time of travel between them, can be computed directly.
MODPATH-PLOT is a graphics interface package that visually displays the results of MODPATH (Pollock, 1994). The particle tracking procedure implemented in

MODPATH is based on a specific set of assumptions (Pollock, 1989,1994) that need to be understood and obeyed in order to obtain meaningful results.

5.3.3 MT3D: modular three- dimensional transport model

MT3D is a modular three- dimensional transport model for simulation of advection, dispersion and chemical reactions of dissolved constituents in groundwater systems. The model program uses a modular structure similar to that implemented in MODFLOW. This modular structure makes it possible to simulate advection; dispersion, sink/source mixing, and chemical reactions independently without reserving computer memory space for unused options. New transport processes and options can be added to the model readily without having to modify the existing code.
The MT3D transport model uses a mixed Eulerian-Lagrangian approach to the solution of the three-dimensional advective- dispersive equation, in three basic options: the method of characteristics (MOC), the modified method of characteristics (MMOC), and a hybrid of these two methods (HMOC). This approach combines the strength of the method of characteristics for eliminating numerical dispersion and the computational efficiency of the modified method of characteristics. The availability of both MOC and MMOC options, and their selective use based on an automatic adaptive procedure under the HMOC option, make MT3D uniquely suitable for a wide range of field problems.
The MT3D transport model is intended to be used in conjunction with any block-centered finite difference flow model such as MODFLOW and is based on the assumption that changes in the concentration field will not affect the flow field measurably. This allows the user to construct and calibrate a flow model independently. MT3D retrieves the hydraulic heads and the various flow and sink/source terms saved by the flow model, automatically incorporating the specified hydrologic boundary conditions.

CHAPTER 6

Model Application and Results

6.1 The conceptual model and grid design

The purpose of the conceptual model is to simplify the field problem and organize the associated field data so that the system can be analyzed more readily. The non-feasibility of complete reconstruction of the field system paves the way for introduction of simplification of the complex system, of course to a certain level, thereby making the latter not an alternative but rather a necessity.

For the purpose of model construction, the aquifer system is one layer as an unconfined-confined aquifer. (figure 6.1)

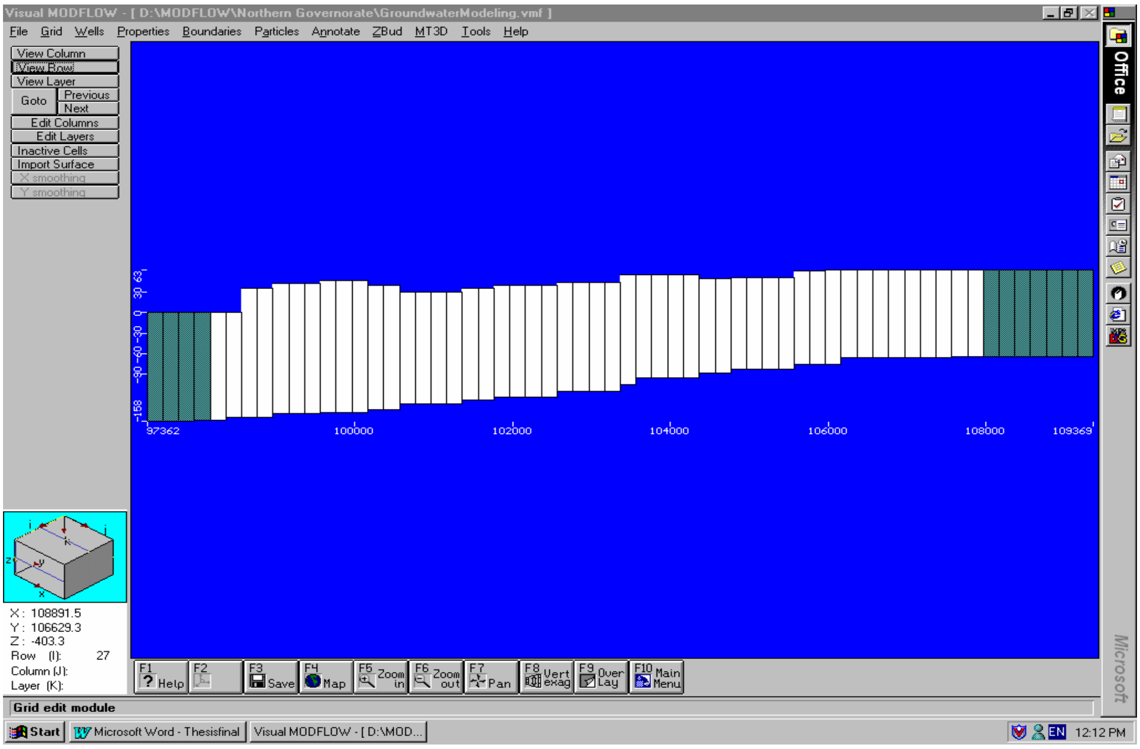


Figure 6.1 W-E cross-section of the conceptual model.

The grid is chosen to be regular with a cell size of 200m by 200m. The whole aquifer system is discretised with square grids as shown in figure 6.2. The model area is subdivided into 60 columns and 55 rows.

The boundary condition in the model is a constant head from the north and the east. The data was taken from a contour map of groundwater head (PWA). The western boundary is designed as a zero constant head formed by the Mediterranean Sea. The outer area is an inactive cell.

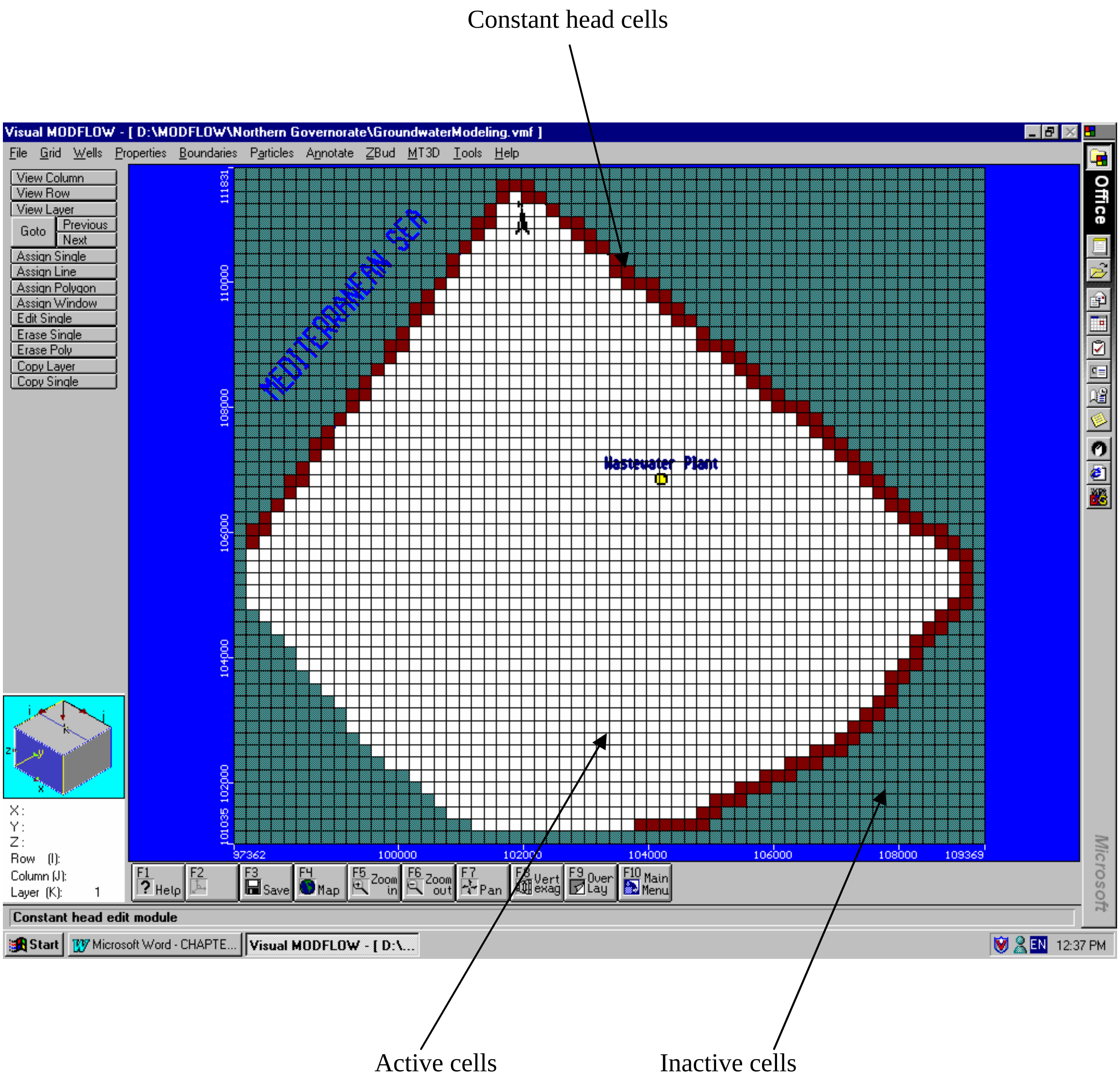


Figure 6.2 Design of grid and boundary conditions

6.2 Model input

The process of building the input data file for a groundwater flow and /or transport model is often the most time – intensive and tedious task associated with groundwater modeling projects.

Properties

All model properties including hydraulic conductivity (K_x, K_y, and K_z), specific storage (S_s) ,specific yield (S_y), and porosity (n) were also assigned. Of course, the fact that each different property zone color – coded in visual MODFLOW interface greatly helped in differentiating layers and/or zones with different property values. The same facility enabled to change such properties like hydraulic conductivity based on the information we had at our disposal regarding the conductivity characteristics of the underground layer. Table 6.1 shows the properties, assigned, together with their values.

Parameter	Value
Hydraulic conductivity (m/day)	
K_x	30
K_y	30
K_z	3
Specific storage (S_s)	0.00015
Specific yield (S_y)	0.21
Effective porosity	0.25
Total porosity	0.35

Table 6.1 Aquifer properties in northern governorate

Pumping wells

Pumping wells was added using the intuitive well editing tools. Out of a total of 512 wells, (25 domestic wells (municipal wells) and 487 agricultural wells), as shown in figure 6.3 and (appendix 2)

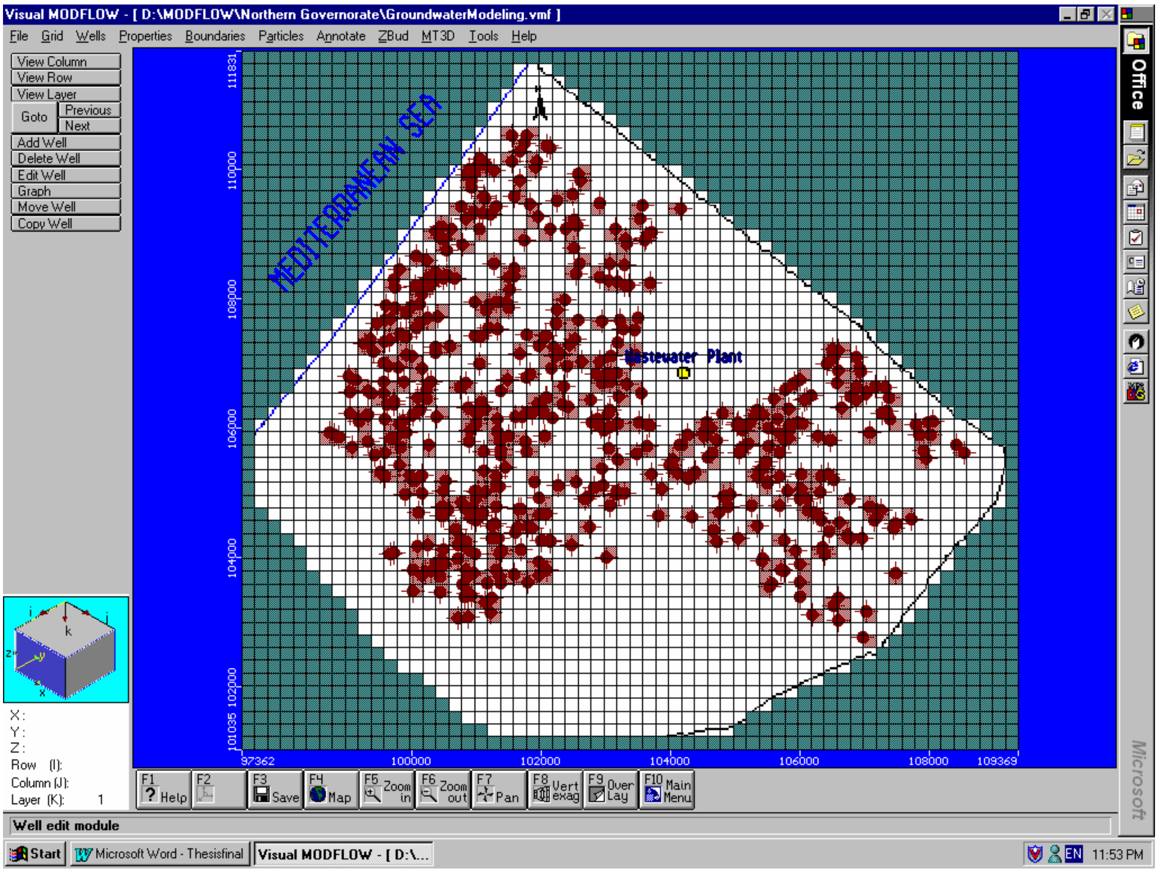


Figure 6.3 Domestic and agricultural wells in northern governorate

According to Palestinian water authority data, the total abstraction from domestic wells 6.6million m^3/year and abstraction from agricultural wells 24.9million m^3/year. Accordingly, average pumping rates from each domestic well is 723.3 m^3/day and from each agricultural well is 140 m^3/day. As all the simulations were done under steady-state conditions.

Recharge

The groundwater recharge was taken from the data of aquifer water balance used in feasibility study for wastewater treatment plant for northern Gaza Strip, August, 1999). In which the rainfall recharge is 165 mm/year, recharge from irrigation drainage returns 124 mm/year and recharge from sewage effluent returns 82 mm/year.

6.3 Model results

The ability to visualize the simulation results is almost as important as creating the model in the first place. In order to get the most out of the model built; it is critical we have the tools necessary to properly analyze and interpret the results. The visual MODFLOW output module automatically reads the results files from each successful simulation and provides a comprehensive selection of graphical formats for displaying full-color results in plan view and cross-sectional views.

Contours

The contouring menu selection allows contouring the results of the modeling simulation in either plan view or cross-section. The contouring selections include heads, Drawdown, Water table, Elevation and Concentration.

Simple calibration

Calibration of the model was carried out on a trial and error basis by changing the hydrogeological parameters until the simulated groundwater heads agree with actual heads to an acceptable degree.(figure 6.4)

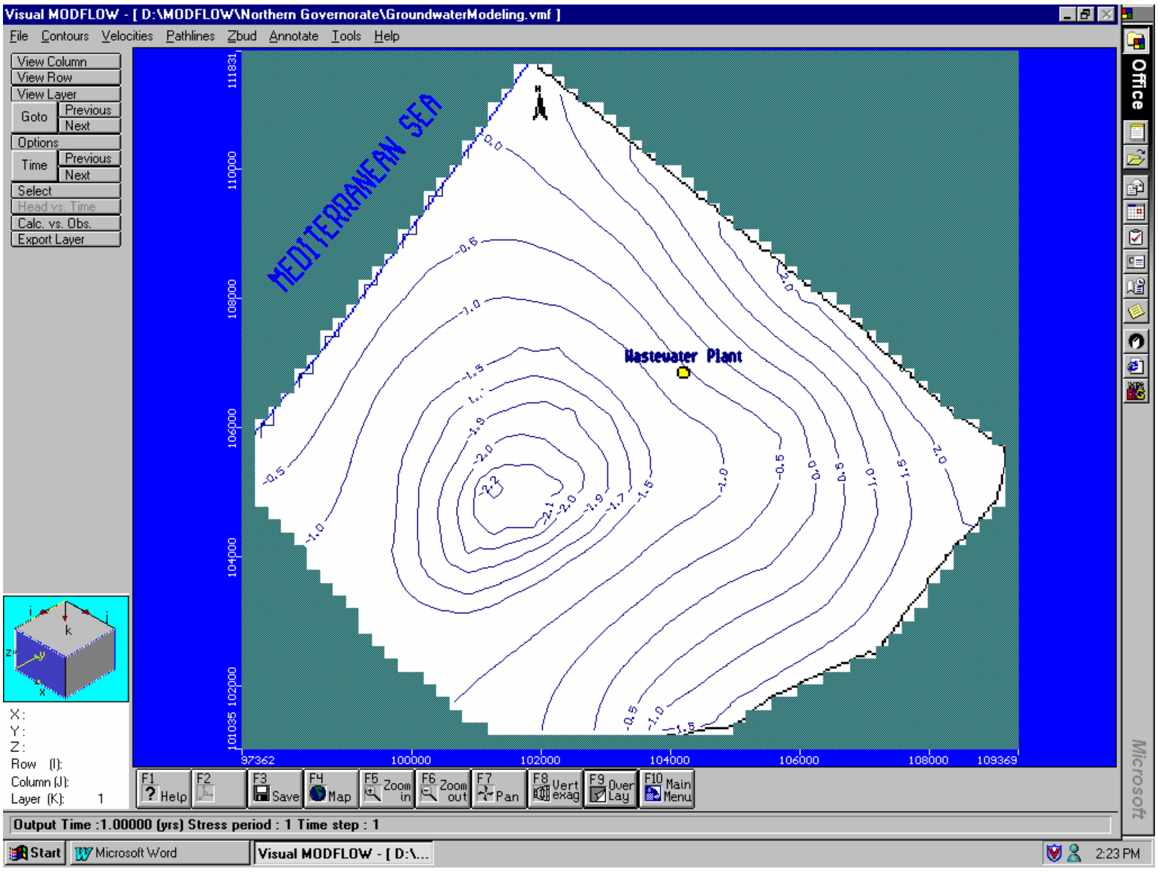
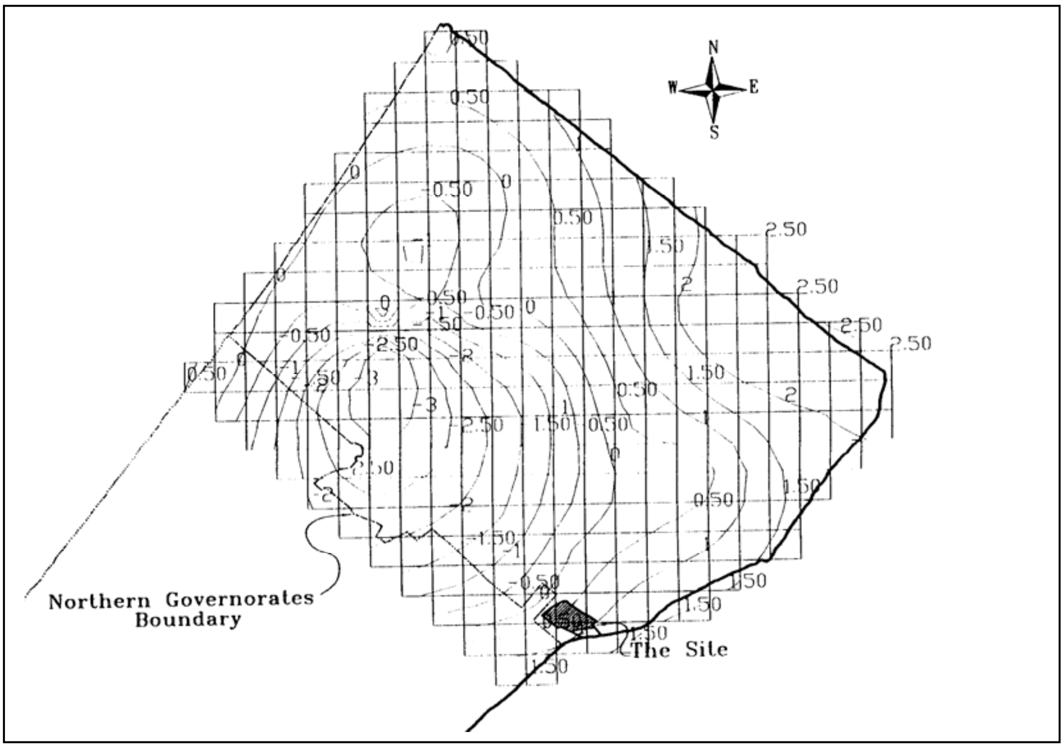


Figure 6.4.a Groundwater heads (**Simulation results**)

Figure 6.4.b Groundwater heads (**PWA measurements**)



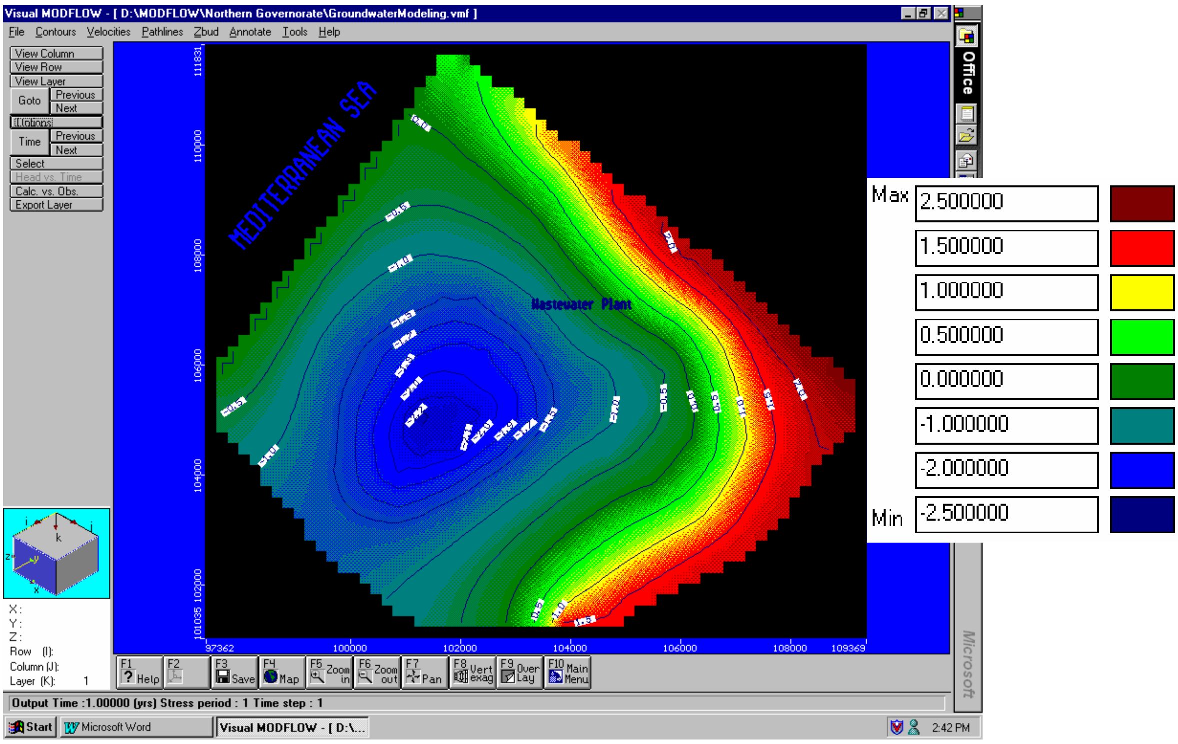


Figure 6.4.c Distribution of simulated groundwater heads.

Velocities

The flow velocity vectors provide an important representation of the groundwater flow direction. Each velocity vector color – coded to indicate whether it is flowing up or down relative to the plane being displayed. The max velocity of groundwater flow found from the model is 0.21 m/day.

The groundwater flow direction is from north to south and from east to west. The flow direction has been influenced by ground water abstraction especially within areas of intensive pumping as shown in figure 6.5. There is a major cone of depression due to the well field between Jabalia and Beat-Lahia. The water table in this area is approximately 2.2 m below sea level. This cone of depression forces the water to flow from all sides towards the lowest point.

Pathlines

The flow Pathlines provides an important representation of the flow direction and the path that the groundwater will follow from specific location.

Backward particle tracking can also be used to indicate where the groundwater is coming from. Display options include viewing all Pathlines as a projection through the entire model. The Pathlines option allows to plot Pathlines for a specified time period. If steady state is chosen the Pathlines will be continuous until they exit the system at sink.

The same fact also supported by the Pathlines of the groundwater (figure 6.5). The particles were placed around wastewater plant and near the Mediterranean coast, and were back-tracked so as to help detecting the origin or source of nitrate pollutant from the wastewater plant to the agricultural wells and of sea water intrusion to the aquifer.

Seawater intrusion

The co-existence of fresh water and seawater is a well-known phenomenon in most coastal aquifers. The driving force behind seawater can be explained as follows. Firstly, the permeable formation must be in hydraulic continuity with seawater.

Secondly, there must be an inland gradient or a tendency for water to move from the sea toward the pumping area.

From figure 6.5 the flow occurs from the west creating the possibility of saline water from the sea entering the aquifer.

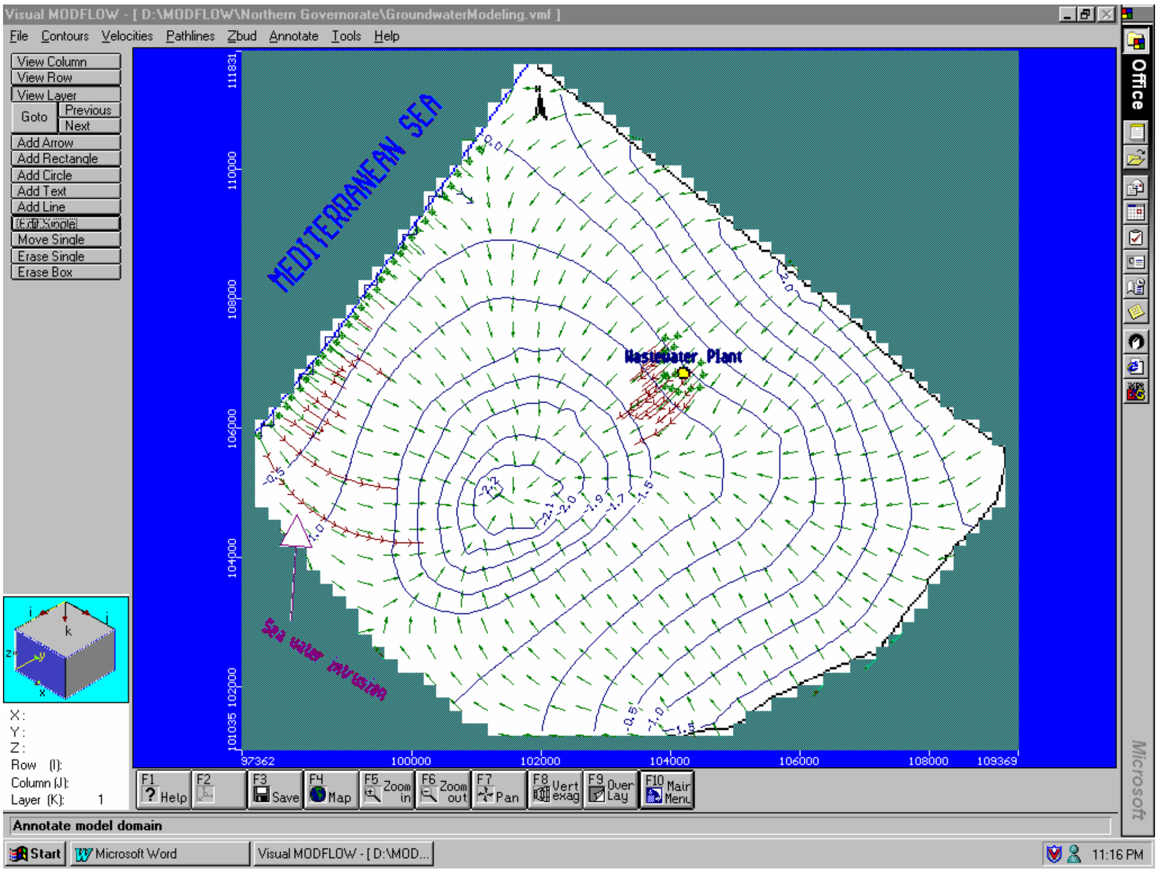


Figure 6.5 Ground water flow direction in northern governorate.

Mass balance

From the mass balance calculation, figure 6.6, it was observed that the total recharge is 9.3 million m^3/year and lateral flow is 22.7 million m^3/year.

The total abstraction from the wells is 31.4 million m^3/year and lateral flow to the sea in the N-W part around 0.54 million m^3/year.

To mansion the balance between the input and output from the system is 31.98 million m^3/year.

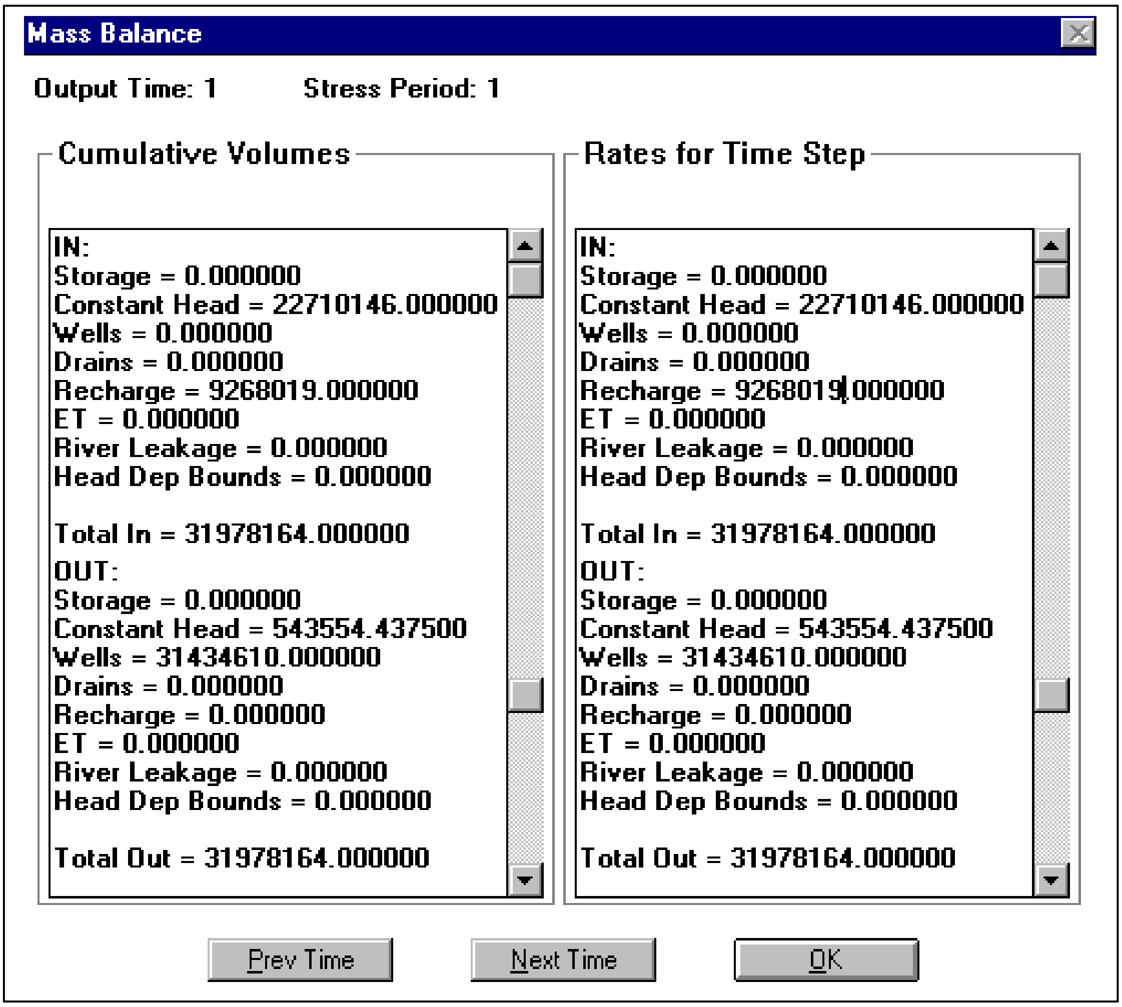


Figure 6.6 Mass balance in northern governorate.

6.4 MT3D Results

MT3D is a computer model for simulation of advection, dispersion and chemical reactions of contaminants in three-dimensional groundwater flow systems. The model was designed to be used in conjunction with a block – centered finite difference flow model such as MODFLOW and is based on assumption that changes in the concentration field will not measurably affect the flow field.

In MT3D simulation model, we need to introduce some parameters values as Longitudinal dispersivity is about 100m, horizontal dispersivity ratio 0.1, vertical transverse dispersivity ratio 0.1, molecular diffusion coefficient 10^{-4} m^2/day and nitrate concentration is 267 mg as NO_3/L.

Calibration

The process of calibration requires adjustments of the model input parameters that influence the output in MT3D are specially the recharge concentration value and the characteristics of soil parameters like Longitudinal dispersivity, horizontal dispersivity and vertical transverse dispersivity. Those alters values were adjusted and refined throughout the trial and error calibration process until an improved agreement between the simulated and observed value.

Nitrate concentration values was obtained from analysis of agricultural wells and wastewater plat during the fieldwork on months August and September, (Chapter 4). The input nitrate concentration from wastewater plant in the model was 267mg as NO_3/L. Figure 6.7 shows the pollutant movement from wastewater plant to agricultural wells in direction N-E to S-W to agricultural wells as A40, A39, A36, A38, A29, A27, A162 and A14 around wastewater plant.

Figure 6.7 Pollutant movement from wastewater plant

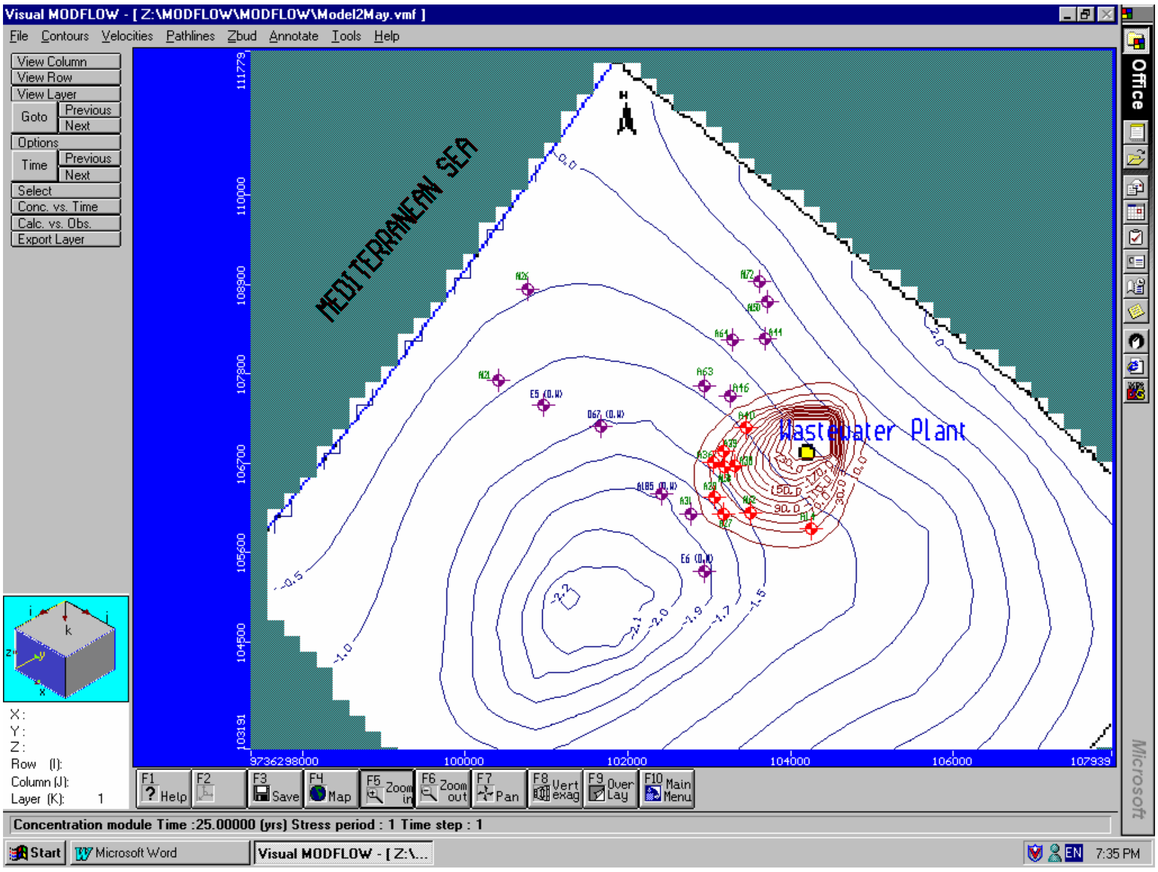


Figure 6.8 shows the calculated nitrate concentration versus the observed concentration values with mean absolute error 2.78 mg/L , it means a small error between calculated and observed concentration.

The calibration procedure is performed under steady state groundwater flow conditions. As it can be observed in the calibration, the simulated conditions don't differ significaly from field conditions.

The agricultural wells far from the wastewater treatment plant are polluted by the high use of nitrate fertilizers. The wells in the urban area are contaminated by nitrate due to high population density in the area and lack of sewerage system.

Assuming that pollution from the wastewater plant started in 1975 when the plant was built, then we have 25 years of simulation.
Figure 6.9 shows the increasing nitrate concentration with time in agricultural wells.

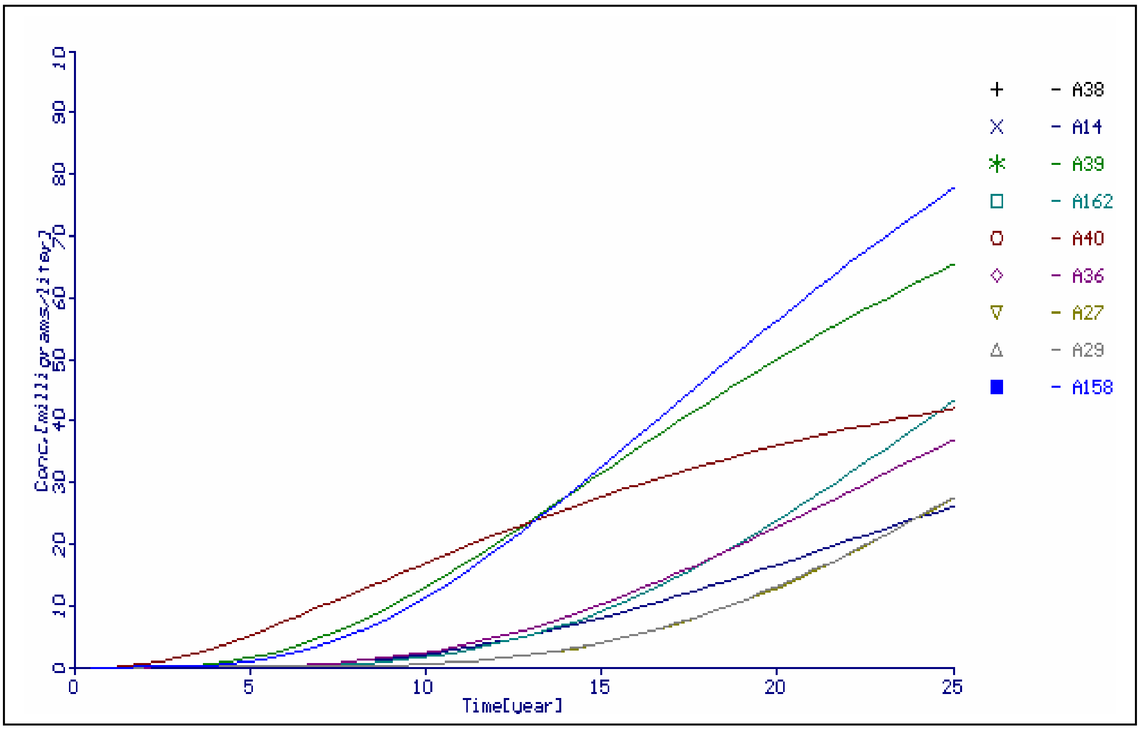


Figure 6.9 Nitrate concentration versus time in selected agricultural wells

CHAPTER 7

Conclusions and Recommendations

7.1 Conclusions

☐ Groundwater is the only resource for agriculture and drinking demand.

☐ Groundwater level in Northern Governorate is more or less close to the mean sea level

☐ Nitrate concentration in most of the wells is exceeding the recommended WHO limit (50 mg as NO_3 /L) reflecting the effect of the sewage water and high use of fertilizers.

☐ Nitrate pollution in Northern Governorate is a human-made pollution while natural nitrate sources are of negligible influence.

☐ Cesspits are the pollutant source in the urban area of Northern Governorate and their effect is expected to increase rapidly with the high rate of population growth.

☐ Over flow wastewater pond located on Sand dunes soil in Beit-Lahia area, which are above the best groundwater reservoir in Gaza Strip is a serious point source of pollution.

☐ The use of visual MODFLOW in the steady state simulation of groundwater flow in the present area, provided satisfactory results, especially for locating the damage caused by the presence of the wastewater pond, monitoring groundwater and locating the extend of concentration plumes.

7.2 Recommendations

- Decreasing the abstracted groundwater for the different purposes where possible, to minimize and/or stop the groundwater degradation in terms of quality and quantity in Northern Governorate.

- The recent overflow ponds has to be replaced by water tight concrete ponds or by lining their bottoms with a polyethylene membrane to prevent leakage to groundwater

- Developing the treatment plant to have a higher treatment capacity and to re-use its effluent in agriculture.

- Cesspits should be replaced by a sewerage collection system.

- An agricultural guiding and monitoring program has to be initiated to guarantee the farmers participation in the fertilization program and to develop their awareness to the pollution issue and the water scarcity.

- A better solution might be to pump the overflow of wastewater to the Sea until a new wastewater treatment plant has been built.

References

- Bardy, N. 1990. The nature and properties of soils. Tenth Edition. PP 315-338
- F. De. Smedt. Numerical modeling of groundwater flow.
- Fahid Kh.1997. Quantification of nitrate pollution to groundwater resources of Rafah (Gaza Strip). M.Sc. Thesis. PP 3-9 IHE -Delft
- Follett, R.F. Keeney.D.R. 1991. Managing nitrogen for groundwater quality and farm profitability. PP 12-29
- Follett.R.F. Walker, D.j. 1989. Groundwater quality concerns about nitrogen. In.R.E. Follet (ed): Nitrogen management and groundwater protection. Elsevier, New York PP 1-19
- Gabriel, B, and Charles, P.G., 1990. Groundwater pollution microbiology PP 202-212
- Gaza Environmental profile, phase II, Nitrate pollution study, September,1995
- Greenberge et,al, 1995, 19th edition. Standard Methods for Examination of water and wastewater.
- Harbaugh, A.W. and McDonald, M.G. 1996. User's Documentation for MODFLOW- 96, an update to U.S. Geological Survey Modular three-dimensional finite- difference groundwater flow model U.S.Geol. Survey open file reports 96-485.
- Hill M.C. 1990 preconditioned conjugate- A computer program for solving groundwater flow equations. U.S. Geol. Survey Water –Res. Invest. Report 90-404.
- IWACO-EUROCONSULT, 1995, Gaza environmental profile, phase II, Environmental series No.3, Gaza Palestine.

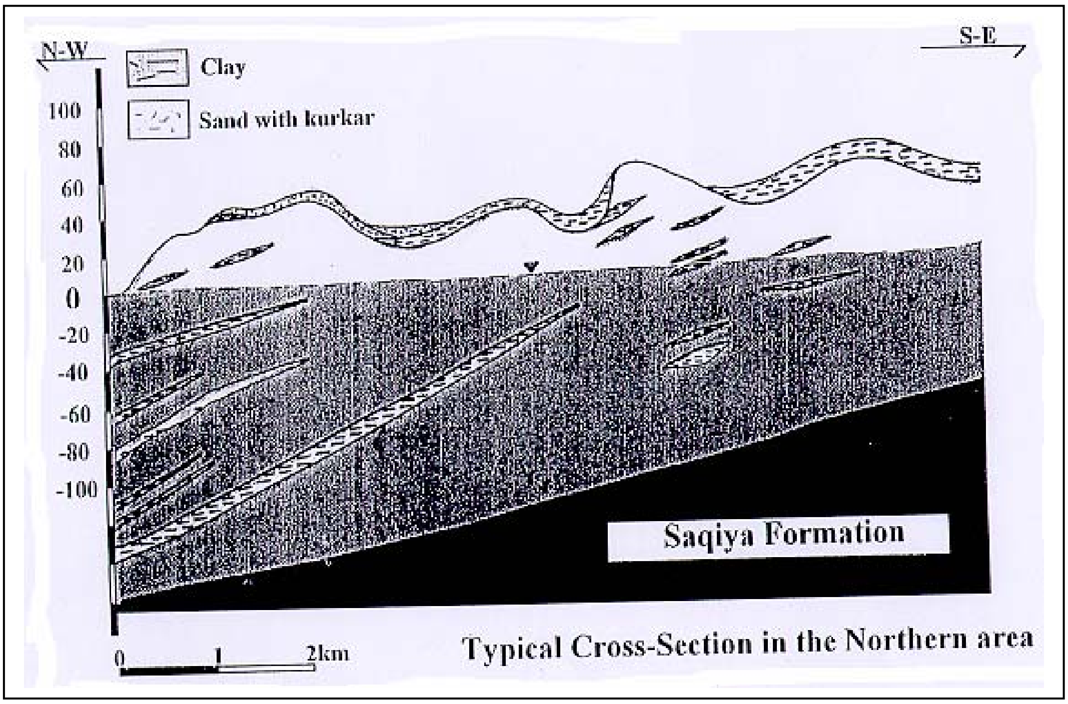
- Keeney DR. 1989. Sources of nitrate to groundwater. In: R.E.Follet (ed). Nitrogen management and groundwater protection. Elsevier, New York. PP 23-32.

- McDonald, M.G. and Harbaugh, A.W. 1988. A modular three- dimensional finite-difference groundwater flow model. Techniques of water resources investigation of the U.S. Geol. Survey book 6.
- MOPIC-EPD, 1996.Gaza water resources, policy directions in groundwater protection and pollution control, Gaza, Palestine.
- MT3D a modular three- dimensional transport model version 1.5 Documentation and User's guide.
- Pollock, D.W. 1994. User's guide for MODPATH/MODPATH-PLOT; version 3: A particle tracking post- processing package for MODFLOW, the U.S. Geol. Survey finite- difference groundwater flow model:U.S. Geol. Survey open-file report 94- 464
- Swedish International Development Co-operation Agency - Palestinian National Authority, PWA. Feasibility study for wastewater Treatment plant for Northern Gaza, August 1999.

E R A	EPOCH	AGE (M.Y.)	FORMATION	ENVIRONMENT OF DEPOSITION	LITHOLOGY	MAX THICKENS (M)	WATER BEARING CHARACTER
Quaternary	HOLOCENE	0.01	Alluvial	Terrieesial eollain Estuerine/ fluvial	Sand, loess calcareous silt and gravel	25	Locally pheratic aquifer
	PLEISTOCENE	1.8	Continental Kurkar	Elaine Fluvial	calcareous sandstone and loamy sand	100	Main aquifer
			Marine Kurkar	Near shore	calcareous sandstone and limestone	100	Main aquifer
TERTIARY	PLIOCENE	12	Conglomerate	Near shore		20	Base of the coastal zone aquifer
			Saqiya	Shallow marine	Clay, marl, shale	1000	Aquiclude
	MIOCENE	25		Marine	Marle, limestone, sandstone, and chalk	500	Aquiclude alternating permeable layers with saline water

Geology and geological history of the Gaza Strip. (Gaza Environmental Profile, 1994)

Hydrogeological cross section (SE-NW)(PWA)



Geological cross section of the coastal aquifer zone

Source: LYSA[17]

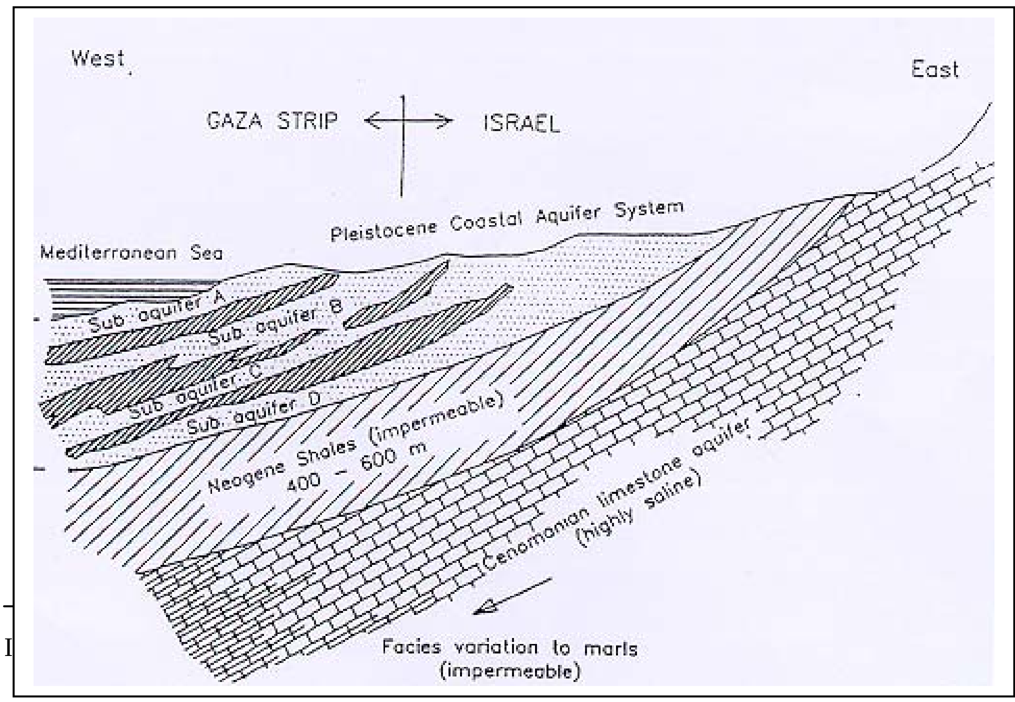


Plate 1: Wastewater plant in northern governorate.

Plate 2: Wastewater treatment lagoon

Plate 3: Wastewater influent, sampling and field analysis

Plate 4: Wastewater Effluent, sampling and field analysis

Plate 5: BOD analysis of influent and effluent from Wastewater plant