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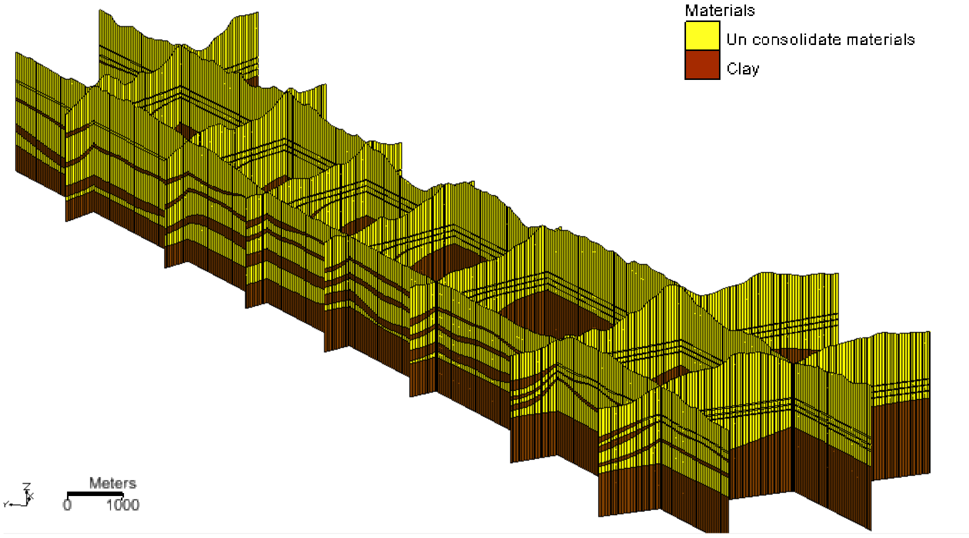
Doctor of Philosophy in Earth Sciences

WATER MANAGEMENT AND MODELLING OF A COASTAL AQUIFER – CASE STUDY (GAZA STRIP)



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Dedication

This PhD thesis is dedicated to my husband and children.

with all my love.

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Abstract

Groundwater resource is critical to the future of the Gaza Strip, as it is the only water resource available to satisfy the daily water needs. As future population growth will place increased stress upon water supplies, the need for effective water management is greater than ever. To plan for the sustainable use of groundwater resources in Gaza Strip, an understanding of the natural hydrologic system and quantitative of the natural hydrologic budget, are required.

This thesis addresses the problems facing the groundwater management in Gaza Strip, through development of a 3D groundwater flow model and the natural hydrologic budget of the Gaza aquifer. By applying the groundwater model to future scenarios, the impacts of variable pumping and recharge on the groundwater level in order to control sea water intrusion has been quantified and assessed. Based on the results, recommendations are made regarding optimal solutions to control sea water intrusion in the Gaza aquifer.

In order to study the aquifer behavior and the depth and extent of groundwater decline, the historical changes in groundwater levels were analyzed for the 1935 and 2009 period. For this, the kriging interpolation method was used to estimate the groundwater level based on available well data collected for the entire study area. Results show that groundwater levels

dropped by as much as 18 meters between 1935 and 2009. This drop is very important in the north and south due to over exploitation of groundwater.

Chemical analyses were carried out to study the salinization process and to identify the salinity sources in the Gaza aquifer. Results show that the groundwater in Gaza aquifer is characterized by Na-Cl-SO_4 and Ca-Mg-HCO_3 facies. The occurrence of salinity in different parts of the aquifer is related to the presence of the seawater in the western side, and lateral inflow from the eastern border due to the hydraulic connection with brackish aquifer.

This thesis discusses the vulnerability of Gaza aquifer to sea water intrusion by applying the GALDIT index method. Different thematic maps were prepared for seawater intrusion indicators and overlaid to develop the vulnerability map. The vulnerability map can be used as an additional tool to determine areas of potential saltwater intrusion and to identify the favorable zones to artificial recharge in the management model presented in this thesis.

For the realization of the 3D numerical flow model, the MODFLOW code (finite difference method) was selected. The used graphical interface is GMS 6.0 (Groundwater Modeling System). The groundwater flow model was developed in order to understand and simulate the aquifer behavior and to control sea water intrusion. A careful calibration of the model was performed, in which the simulated piezometric levels are compared with field measurements to determine the validity and reliability of the model.

Based on the developed transient model, 3 management scenarios were applied in order to study the impact of pumping rates and additional water resources on the groundwater level for the next 20 years. These scenarios are conceived to support coastal aquifer management plan adopted by Palestinian Water Authority for the control of the sea water intrusion. The results of the first management scenario show that the ground water level is strongly influenced by the over pumping. Two large depression zones are observed in the northern and southern Gaza Strip. Results of the second management scenario show an increasing ground water level, by several meters above mean sea level, under the effect of decreasing abstraction rates. Results of the third management scenario show an increasing ground water level, by several meters above mean sea level, under the effect of increasing the aquifer recharge. Using treated waste water to remediate the groundwater level and control the sea water intrusion in the Gaza aquifer appears as the most practical and suitable solution for saltwater intrusion control, since the other solutions require the use of fresh water resources, which are costly and unpractical in view of the Gaza Strip situation. Therefore, using treated wastewater represents an additional renewable and reliable water source for the management of water resources in the Gaza Strip.

Symbols and Abbreviations

MCM	Million Cubic Meter
WHO	World Health Organization
EQA	Palestinian Environmental Quality Authority
PWA	Palestinian Water Authority.
MSL	Main Sea Level
PoA	Palestinian Ministry of Agricultural
CMWU	Coastal Municipalities Water Utility
US	United State
DEM	Digital Elevation Model
WWTP	Waste Water Treatment Plant
GMS	Groundwater Modeling System
CAMP	Coastal Aquifer Management Plan
GIS	Geographic Information System
K	Hydraulic Conductivity
TDS	Total Dissolved Solids
PCBS	Palestinian Central Bureau of Statistics
ESDA	Exploratory Spatial Data Analysis
EC	Electrical Conductivity
ET	Evapotranspiration
yr	Year
Cl	Chloride
Na	Sodium
NO_3	Nitrate

Ca	Calcium
Mg	Magnesium
HCO3	Carbonate
SO4	Sulfate
B	Boron
Br	Bromide
Fe	Iron
m/d	Meter per day
m/y	Meter per year
mg/l	Milligrams per Liter
ppm	Part per Million
C°	Celsius
µmhos/cm	Micromhos per centimeter
µS/cm	Microsiemens per centimeter

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CHAPTER 1

GENERAL INTRODUCTION

CHAPTER 1: General introduction

1.1 Introduction

Saltwater intrusion is a very important concern issue in coastal zones. These zones are the most densely populated areas in the world with over 70% of the world's inhabitant (Alexander et al., 2003). Coastal zones face many hydrogeological problems due to over exploitation of water resources. One of the most common hydrogeological problems is the seawater intrusion into coastal aquifers. Seawater intrusion occurs naturally in almost coastal aquifers due to hydraulic connection between the aquifer and the seawater. The seriousness of the sea water intrusion problem in coastal aquifers is associated with extension of the fresh/salt groundwater interface in the coastal aquifer. The fresh/salt groundwater interface may either have a thin or a thick dispersion zone, depending upon several factors, including density difference between fresh water and salt water, aquifer geometry, hydraulic properties, discharge rate to the sea, and dispersion parameters of the aquifer (Sakr, 1999). Furthermore, it varies in response to ground water levels change and tidal fluctuations (Li and Jiao 2002, Turner 1993, Nielsen 1990, Li et al., 1997). These factors must be considered in the coastal aquifers management.

Fresh groundwater resources management in coastal aquifers is a sensitive issue for developed and developing countries. In developed countries, coastal zones are subject to concentrate economic and touristic activities that require high water consumption. In developing countries, coastal zones are characterised by high rates of population growth, coupled with uncontrolled water consumption. A comprehensive management program is required for sustainable water resources.

Gaza Strip is a typical developing region that suffers from both water scarcity and quality deterioration. Sustainable water resource management in regions like Gaza Strip requires not only careful use of groundwater but also using of additional water resources, for instance reuse of treated wastewater, desalinisation and use of storm water. People of Gaza Strip depend completely on the coastal aquifer to satisfy all daily needs. This aquifer suffers from over exploitation. The annual pumping rates reached 168 x 10^6 m^3 in 2010, while the annual recharge by rainfall for the period between 2009 and 2010 was 65 x 10^6 m^3, which indicate a severe deficit in the aquifer budget (Mushtaha, 2011), as a result, the groundwater level lowered by several meters regarding Mean Sea Level (MSL). This situation activates the sea water penetration into the aquifer. Presently, more than 70% of the aquifer is brackish or saline water and less than 30% is fresh water (Yaqubi, 2006). A noticeable deterioration in the water quality is evidenced by high concentration of chloride and nitrate in most of Gaza wells with percentage exceeding the maximum contaminant levels announced by World Health Organization (WHO) and Palestinian potable water standards. Many recent studies referred this deterioration to the sea water intrusion (Moe et al., 2001, Qahman and Zhou 2001, Agah and Nakhal 2004, Vengosh et al., 2005, Alnahhal et al., 2010, Rabia Ahmed 2010, Shomar et al., 2010, Mushtaha, 2011). Many technical solutions have been adopted by the Palestinian Water Authority (PWA) to manage the aquifer and to control the seawater intrusion problem, for instance, reuse of treated wastewater, desalinization and harvesting. However, these solutions are applied in limited manner. There are three treatment plants in Gaza Strip producing about 40 x 10^6 m^3/yr, of whole only 7.2 x 10^6 m^3/yr were infiltrated in 2010 into the aquifer by infiltration basin. Three brackish desalination plants already exist and produce about 60,000 m^3/day of desalinated water using reverse osmosis technology (Ismael, 2003). Using these solutions in effective way and for a long time will not only contribute in controlling sea water intrusion but also resolving many other environmental problems caused by the untreated wastewater or partially treated wastewater infiltration and/or discharge to the sea.

1.2 Problem identification

Gaza Strip is the coastal region of Palestinian territories that has 45 Km of shoreline along the Mediterranean Sea. This region is considered as one of the highest population density areas not only in Palestinian territories but in the world. Palestinian people in the Gaza Strip depend completely on the ground water of coastal aquifer for drinking and all other purposes. Nowadays, the aquifer is accessible by more than 4000 wells distributed randomly through the Gaza Strip with more than 168 x 10^6 m^3 of water abstraction in 2010 (Mushtaha, 2011). Due to the presence of this high number of pumping wells in the limited and small area of Gaza Strip (365 Km^2), the Gaza coastal aquifer faces an overexploitation which leads to a noticeable lowering in groundwater level and consequently the occurrence of sea water intrusion in many parts of the aquifer. Only about 10 % of the total aquifer volume meet the WHO drinking water standards. This corresponds to a total volume of about 450 - 600 x 10^6 m^3 (Moe et al., 2001).

The aquifer budget indicates a notable imbalance between the recharge and demand components, which disturbed significantly the flow pattern, the ground water being lowered by several meters under MSL. This situation affects directly the natural equilibrium between fresh and sea water and facilitates the sea water penetration into the aquifer as a lateral penetration or upconing under wells. In view of this, it is very clear that the seawater intrusion represents a great threat to the Gaza coastal aquifer, so it is very important to keep it under control.

1.3 Objectives

The main goal of this research is to investigate optimization management solutions to control seawater intrusion in Gaza coastal aquifer by reducing pumping rates and using additional water resources. A numerical groundwater flow model has been developed in order to study the aquifer behavior and control seawater intrusion process in Gaza coastal aquifer by remediate groundwater table using different management scenarios.

The objectives of this thesis are the following:

1. To deeply understand of Gaza aquifer behavior.
2. To determine the more sensible areas to pumping.
3. To determine the areas of potential saltwater intrusion
4. To identify the favorable zones to artificial recharge.
5. To study the aquifer vulnerability to sea water intrusion
6. To develop a simulation optimization model for the control of saltwater intrusion in coastal aquifers using different management scenarios
7. To apply the developed model to study the impact of variable pumping and recharge on the groundwater level to control the sea water intrusion.

1.4 Research motivations

The problem of seawater intrusion in Gaza aquifer is an outcome of the complex interaction between plural factors, mainly, the pumping wells and population growth. A groundwater flow model will be developed to deeply understand the complex aquifer behavior and to simulate different management scenarios including variable pumping rates and using of additional water resources in order to control saltwater intrusion efficiently in the Gaza aquifer.

1.5 Methodology

The approach followed in this thesis is summarised in figure (1.1).

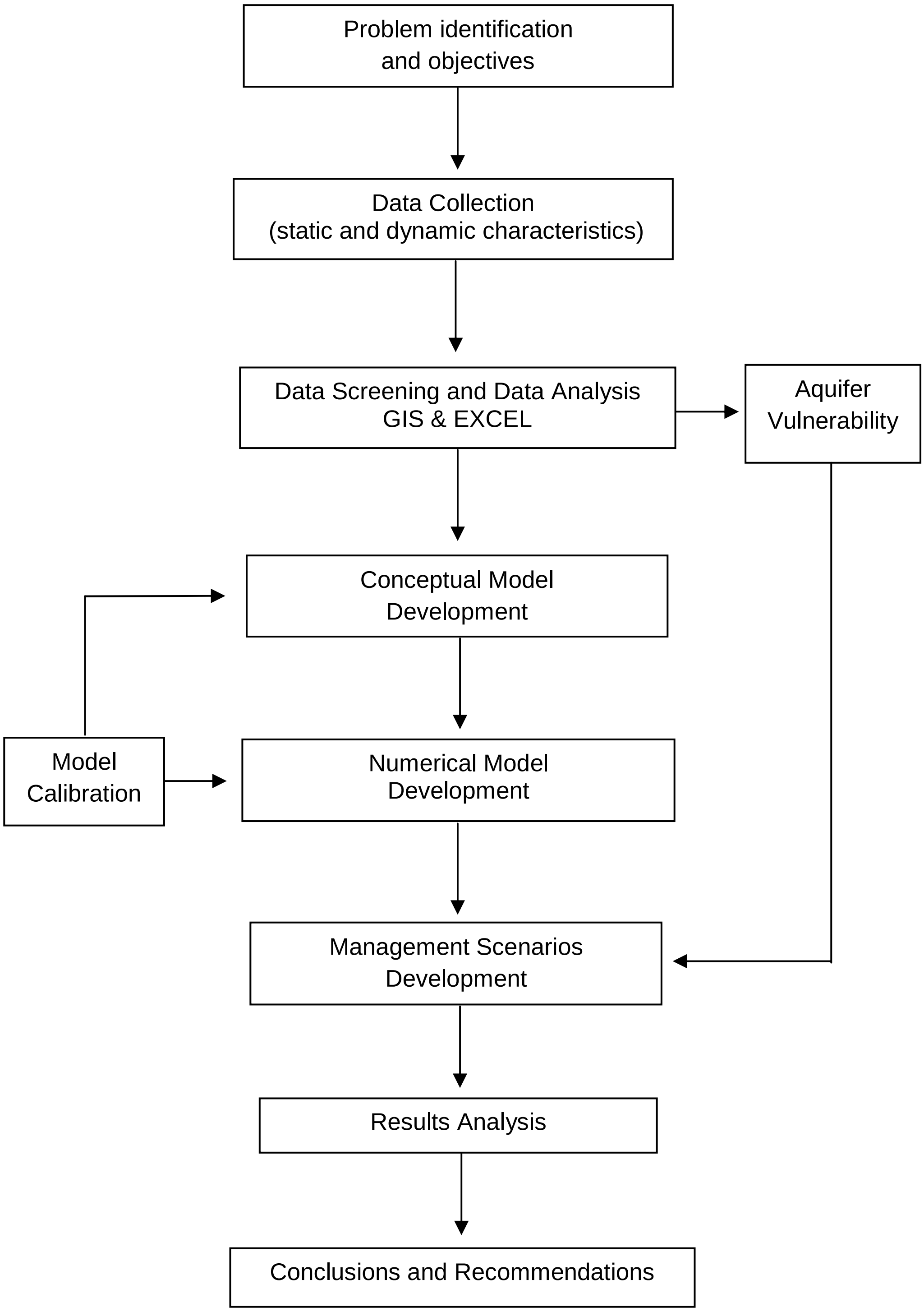


Figure (1.1) The approach followed in this research.

Specifically, the study method can be divided into 5 phases:

1.5.1 Data Collection

The good quality and quantity of the data used in the development of the conceptual model contribute to increase the validity of numerical model results; therefore, it is considered as a critical step during the modulation phases. Data collection process is based on the static (stratigraphic information) and dynamic characteristics (piezometric measurements) of the hydrogeological system, punctual (wells) and spatial (Digital Elevation Model). Collected data are filtered by using Geographic Information Systems and Excel spreadsheets.

Initially, the study started by collecting the available updated and recorded data from different sources and by different personal communication with local specialists. Data include:

- Digital Elevation Model (DEM) with resolution of 30*30 m.
- 20 Geologic cross sections distributed regularly all over the Gaza Strip per perpendicularly to the sea shoreline.
- Drilling completion records of piezometric wells.
- Pumping rate records for 3600 wells.
- Groundwater level and quality parameters measurement from 1990 to 2008.
- Rainfall records and other relevant climate data from 1980 to 2011.

These data were procured from varies government and semi-government organizations in Gaza Strip.

Different reference types of data resources were used, like research papers, MSc thesis, PhD thesis, PWA reports, Palestinian Ministry of Agriculture (PoA) reports and Coastal Municipalities Water Utility (CMWU) reports.

1.5.2 Data screening and analysis

The data have been screened to check errors that might be encountered in the several steps of measurement and data insert. Some of the collected data are used directly and others indirectly for the estimation procedures. After preparation and processing, the data are analyzed using Microsoft Excel and a GIS for the different purposes of the study.

1.5.3 Aquifer vulnerability to sea water intrusion

This part of the present thesis discusses the vulnerability of Gaza aquifer to sea water intrusion by applying the GALDIT index method. The method applied on the Gaza aquifer for the first time. Many thematic maps were prepared for seawater intrusion indicators and overlaid to develop the vulnerability map, which can be used as an additional guide tool to determine the areas of potential saltwater intrusion and to identify the favorable zones to artificial recharge in the management model present in this thesis.

1.5.4 Model construction

For the realization of the 3D numerical flow model, the MODFLOW code (finite difference method) was selected. The used graphical interface is GMS 6.0 (Groundwater Modelling System). By using the mathematical finite difference code, the groundwater flow model was developed in order to understand and simulate the aquifer behaviour and sea water intrusion control. A careful calibration of the model has been computed, in which the simulated piezometric are compared with field measurements to determine the validity and reliability of the model. Model validity can be obtained from budget mass estimation of the system.

1.5.5 Management scenarios

Based on the developed transient flow model, 3 scenarios were applied in order to study the impact of pumping rates vulnerability and using additional water resource on the groundwater level for the next 20 years in order to control the sea water intrusion in view of Coastal Aquifer Management Plan (CAMP) adopted by PWA. The results obtained from the model runs are analyzed and finally, the conclusions and recommendations are announced.

1.6 Thesis structure

This thesis consists mainly of 7 chapters.

Chapter 1 includes a general introduction, presentation and identification of the problem targeted by this research and the research objectives.

Chapter 2 provides the literature review of the problem of saltwater intrusion, modelling, management options.

Chapter 3 contains an overview of the study area (Gaza Strip) and Gaza coastal aquifer. The chapter describes the study area with respect to its geography, geology, hydrology and hydrogeology, and land use.

Chapter 4 represents data analyzed using Microsoft EXCEL and Geographic Information System (GIS) for the different purposes of the study.

Chapter 5 discusses the aquifer vulnerability by applying the GALDIT method using the sea water intrusion indicators of Gaza aquifer, with numerical ranking for product thematic maps and finally produce the Gaza aquifer vulnerability map to sea water intrusion.

Chapter 6 explains the groundwater flow model development.

Chapter 7 illustrates the model scenarios with result analysis and finally, it draws the conclusions and recommendations,

CHAPTER 2

LITERATURE REVIEW

Chapter 2: Literature Review

1.2 Introduction

Coastal aquifers represent a vital component of the freshwater resources for human beings and activities. Rapid population growth and climate change in coastal zones have caused many environmental problems. The most common environmental problem that may occur in coastal aquifers is the seawater intrusion (Freeze and Cherry 1979; Fang 1997; Todd and Mays 2005).

Seawater intrusion is a serious global concern. Many coastal aquifers suffer from this problem like North Africa, the Middle East, the Mediterranean Coasts, China, Mexico, Atlantic and Gulf Coasts of the United States, and Southern California.

Recently, coastal areas received considerable attention due to the great impact of seawater intrusion. Influential research effort has been dedicated to understand better coastal aquifer flow and transport processes, to coastal groundwater protection, and to avoid environmental degradation of coastal systems (Diersch and Kolditz 2002; Post 2005, Goodman 1985, Custodio and Bruggeman 1987, Galeati et al., 1992, Richter and Kreitler 1993, Hallaji and Yazicigil 1996, Bear et al., 1999, Qahman 1999, Das and Datta 1999, Ataie-Ashtiani et al., 1999, Lambrakis and Kallergis 2001, Diersch and Kolditz 2002, Mantoglou 2003, Mogheir 2003, Langevin 2003, Chen et al. 2004, Cheng and Ouazar, 2004, Reichard and Johnson 2005, Kallioras et al., 2006, Narayan et al. 2007, Abd-Elhamid and Javadi 2008).

Seawater intrusion is a natural process that exists in most coastal aquifers due to the density differences between seawater and fresh water (Bear, 1972). Naturally, freshwater and saltwater in coastal aquifers are in dynamic equilibrium due to continue change in ground water level in response to changing in recharge and discharge. Intensive groundwater abstraction and climate change alter this equilibrium and result in inland lateral movement of the sea water. This indicates a reduction in the available freshwater storage volume and contamination of production wells due dispersion of salt water into fresh water.

Saline water generally causes environmental problems because it contains high concentration of dissolved solids so it is unsuitable for human consumption and for irrigation. Drinking water standards established by the WHO require that drinking water contains less than 600 mg/l of Total Dissolved Solids (TDS) (WHO, 2008) as a measure of salinity while the sea water contains 35000 mg/l of TDS, approximately 58 times higher than the WHO drinking water standards.

2.2 Seawater intrusion process and mixing zone

Saltwater intrusion is determined by the density difference between salt and fresh waters and can be intensified by different factors (Bear, 1972). Under undisturbed condition in costal aquifers, a state of dynamic equilibrium between freshwater and seawater is maintained. Flow of ground water in coastal aquifer is regulated by hydraulic gradient, hydraulic conductivity, anisotropy, porosity, boundary conditions, recharge, pumping, and other geological settings (e.g., Bear, 1972, 1979; Freese and Cherry, 1979; Silliman, 1995; Gerke and van Genuchten, 1996; Kim and Parizek, 1997; Whitaker and Smart, 1997; Bakker et al., 1999; Kim et al., 2000; Lambrakis and Kallergis, 2001; Simmons et al., 2001). The flow of fresh ground water is from inland recharge areas, where groundwater level (hydraulic heads) typically is higher, to coastal discharge areas where ground water levels are lowest, see figure (2.1). Fresh ground water comes in contact with saline ground water at the seaward margins of coastal aquifers where fresh ground water (lower density, 1,000 kg/L) float above sea water (heavier density, 1,025 kg/L). Due to hydro-dynamic dispersion, an immediately moveable interface is formed between two fluids; the dynamic equilibrium of any point in the dispersion zone is very delicate, because it is regulated by hydro-dynamic head of fresh groundwater and the quantity of recharged and discharged water. The processes and factors associated with seawater intrusion are described qualitatively by Custodio (1987a, 1987b). Fundamental aspects of sea water intrusion theory and management are covered by Reilly and

Goodman (1985), Custodio and Bruggeman (1987), Bear et al. (1999), Diersch and Kolditz (2002) and Cheng and Ouazar (2004).

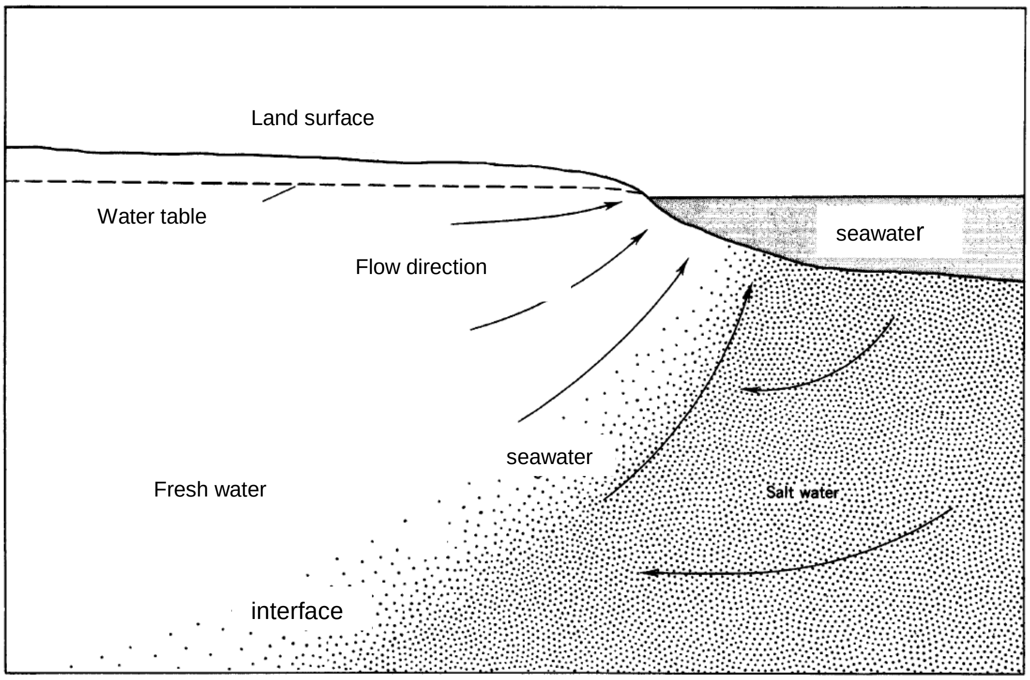


Figure (2.1) Schematic representing of the mechanisms of saltwater intrusion Source (Hilton et al., 1964).

2.3 Factors influencing seawater intrusion

The natural equilibrium between seawater and freshwater in costal aquifer are affected by many factors, some are man-made and could be controlled as pumping induced water table variability. Others are natural and usually can not be controlled, such as geologic structure, the heterogeneous nature of aquifer, hydraulic properties, tidal impacts, climate change, and solute dispersion effects. The time required for saltwater to move through an aquifer can be quite long depending on the location and lateral width of the transition zone.

Many studies have been conducted to understand how are natural and human factors affecting the sea water intrusion in coastal aquifer. Calvache and Pulido-Bosch (1997) developed a mathematical model of saltwater intrusion processes in three aquifers in the southern coast of Spain (Río Verde, Río Vélez and Castell de Ferro) in order to study the effects of geology and human activity on the dynamics of salt-water intrusion. They have undertaken a mathematical simulation of various possible measures to counteract intrusion, according to the specific characteristics of the process in each aquifer. These measures include artificial recharge, use of natural recharge from the river as a hydraulic barrier, and the construction of a low permeability barrier. They confirmed that the human activity has a highly significant influence on salt-water intrusion and that there are cases, such as the aquifers of Río Verde and, most particularly, Río Vélez, where measures based on the correct administration of surface and groundwater resources are essential to avoid a problem with severe consequences in areas already threatened with desertification (Calvache and Pulido-Bosch, 1997).

Ranjan et al., (2006) evaluated the impacts of climate change salinity intrusion in stressed coastal aquifers using the Hadley Centre climate model, HadCM3 with high and low emission scenarios (SRES A2 and B2) for years 2000–2099. In both scenarios, the annual fresh groundwater resources losses indicate an increasing long-term trend in all stressed areas, except in the northern Africa/Sahara region. He found that precipitation and temperature individually did not show good correlations with fresh groundwater loss. However, the relationship between the aridity index and fresh groundwater loss exhibited a strong negative correlation.

Gambastiani et al., (2007) presented a study that aimed at understanding how past and present human activities have affected the saltwater intrusion process in the phreatic aquifer and how the predicted future sea level rise will affect the salinization process in Ravenna (Italy). He developed a numerical model to quantify these effects on the density-dependent groundwater flow, hydraulic head and salinity distribution, seepage and salt load fluxes to the surface water system. The simulations show that over the last century artificial subsidence and heavy drainage started the salinisation process in the study area and a relative sea level rise will accelerate the increase in salt load in the coming decades, affecting the entire aquifer (Gambastiani et al., 2007).

Processes and factors associated with seawater intrusion are described qualitatively by Custodio (1987a, 1987b).

2.4 Mathematical solution

To study the seawater intrusion in coastal aquifers, two approaches are distinguished: the sharp interface and the disperse zone representing the transition between salt and fresh. Sharp interface models generally can be used to model freshwater flow and coupled freshwater and saltwater flow.

Analytical solution with the sharp interface assumption has been used widely and successfully in the 60's, 70's and 80's. It considered as a simple and flexible tool even it has a physical limitation.

Badon Ghyben (1889) - Herzberg (1901) studied the location of the fresh and salt water interface in a coastal homogeneous, isotropic unconfined aquifer based on piezometric heads. They represented a relation describe the position of a sharp interface between seawater and fresh ground water.

$$h_f=\alpha H_s \quad (1)$$

Ghyben and Herzberg established that seawaters penetrate deeply into fresh underground aquifers and that the depth of a diver's border between sea salt and freshwater is ~ 40 times greater than the level of the sallow ground water in unconfined aquifer (Khublaryan, 2007).

They assumed that the boundary between fresh and salt to be sharp. However, in reality a brackish transition zone of finite thickness separates the freshwater and saltwater. This zone develops from dispersion caused by the flow of freshwater and unsteady movement of the interface by external influences (Hiscock, 2005).

The Ghyben-Herzberg theory is only the beginning of many attempts and efforts to understand the seawater intrusion problem. In 1940 Hubbert solved the seawater-freshwater interface problem under a more realistic steadystate flow condition. Keulegan developed the tilting interface solution in 1954. Bear and Dagan studied the moving interface solution. Dupuit worked on transient location of interface due to sudden change of flow rate. Dagan and Bear developed the upconing solution assuming that the upconing of the interface is due to a point sink, and used the perturbation technique to reach the solution. Other more complicated models have been developed to study the miscible transport analytical solutions (e.g. Henry 1964) (Liu, 2004).

2.4.2 Flow of Groundwater with Variable Density

Darcy's law and specific discharge have been developed assuming that the pore water density is constant. There are several situations where this assumption cannot be valid.

When the water density variations are large, they must be taken into account in the analysis of groundwater flow. Instead of using the standard definition of Darcy's law, a more fundamental one is needed where the pore water density ρ w is treated as a variable. Assume that the principal directions of intrinsic permeability align with the x, y, z coordinate system with x and y horizontal and z vertical. Darcy's law for variable density flow is then written as (Bear, 1972):

$qx = -kx/\mu \,.\, \partial P/\partial x$ (1)

$qy = -ky/\mu \,.\, \partial P/\partial y$

(2)

$qz = -kz/\mu \,(\partial P/\partial z + \rho_w g)$ (3)

Where q is specific discharge, k is intrinsic permeability, μ is dynamic viscosity, P is pressure, and g is gravitational acceleration. If we define the fresh-water hydraulic conductivity in terms of the fresh water density ρ f as

$K = k\rho_f g / \mu$ (4)

and the fresh water head as

$h_f = (P/\rho fg) + z$ (5)

Then Eq (3) can be written as

$$qx = -Kx. (\partial hf / \partial x) \quad (6)$$

$$qy = -Ky .(\partial hf / \partial)y \quad (7)$$

$$qz = -Kz ((\partial hf / \partial z) + (\rho w - \rho f)/ \rho f) \quad (8)$$

These equations reduce to the familiar form of Darcy's law when $\rho w = \rho f$ = constant.

Many studies concentrate on the density variation as a fundamental aspect of sea water intrusion in coastal aquifers. Simmons et al. (2001) studied the variable density ground water flow and solute transport in heterogeneous porous media. Langevin and Guo (2006) presented a study about the coupling of MODFLOW and MT3DMS for the simulation of variable density ground water flow.

Koldiz et al., (1998) studied the Henry, Elder, and salt dome (HYDROCOIN level 1 case 5) problems benchmarks using two finite element simulators - ROCKFLOW. Post et al., (2007) presented a methodology which provides a framework for determining quantitatively when variable-density effects on ground water flow need to be taken into account or can be justifiably neglected.

2.5 Saltwater intrusion investigating methods

Understanding the mechanisms of fresh saline water interface movement is an important issue for hydrology studies. Therefore, it has been investigated by several methods including geophysical, geochemical and different analytical and numerical models, these approaches attempted to ascertain the position of freshwater/saltwater interface and predict changes in water levels and salinity. Here is a brief description of these methods.

2.5.1 Geophysical investigations

Recently several geophysical methods were developed to investigate and measure the spatial distribution of physical properties (Bear et al., 1999). Employing drilling, and exploitation boreholes in study the thickness and geometry of depositional systems, is useful but also expensive and time consuming, particularly on a large scale. Geophysical methods can provide a less expensive way to improve the knowledge of a set of boreholes (Maillet et al., 2005). For this reason, geophysical prospecting techniques can provide complementary data that enable geological correlation, even in sectors where there are no data from boreholes (Gurunadha Rao et al., 2011). Geophysical methods can be divided into:

1- Surface geophysical methods

- Electrical methods, such as: DC resistivity, frequency domain electromagnetic methods, airborne EM, loop-loop EM, time-domain electromagnetic sounding, and very low frequency EM
- Seismic methods, such as: seismic refraction, and seismic reflection
- Ground penetrating radar

2- Borehole methods

- Electric logs
- Radiometric logs
- Integrated use of borehole logs

3- Integrated geophysical surveys

Many of these methods were used to investigate saltwater intrusion in different coastal aquifers, for instance:
McDonald et al., (1998) tested how tide and geological structure affect saline intrusion beneath an area of coastal wetland in Hampshire, southern England. He used Resistivity tomography and time-dependent ground conductivity surveys at two closely located survey sites. Resultant maps and sections show clear geophysical anomalies that can be attributed to tidal saline

intrusion and to the position of geological structures (McDonald et al., 1998). Abdul Nassir, et al (2000) evaluated the use of survey technique as a tool employed in electrical imaging to detect the salt-water intrusion boundary in Yan, State of Kedah, northwest Malaysia. He incorporated the technique into surveys. The results proved to be a robust method for accurately mapping of the fresh-water/saline-water boundary (Abdul Nassir et al., 2000).

Wilson et al., (2006) used direct current resistivity traversing to characterise the nature of the saline interface at Te Horo on the Kapiti Coast in New Zealand. The results show that the interface in the vicinity of the settlement, which relies on bores for potable water, has intruded inland 10 m further than in undeveloped areas. Resistivity traversing has been particularly successful in defining subsurface areas of higher salinity by providing a two-dimensional image of the bulk resistivity structure. He supported the results of the resistivity surveys by bore water chemistry, the results show evidence of saltwater mixing (Wilson et al., 2006).

2.5.2 Geochemical investigations

Groundwater salinization in coastal aquifers can result from sea water intrusion process and many others sources either of anthropogenic type (e.g., leakage of industrial and domestic waste water, agriculture return flows, irrigation with sewage effluent) or because of saline water flow from adjacent or underlying aquifers (Maslia and Prowell, 1990).

Therefore, the distinction of different salinization mechanisms is crucial to the evolution of the origin, pathways, rates and future salinization of coastal aquifers. Several geochemical criteria can be used to identify the origin of salinity in coastal aquifers (Bear et al., 1999).

The two most frequently used criteria are TDS and Electrical Conductivity (EC):

TDS is "a measure of all dissolved substances in water, including organic and suspended particles that can pass through a very small filter. TDS is measured in a laboratory and reported as mg/l" (GAMA, 2010).

EC is" the ability of an electric current to pass through water. It is proportional to the amount of dissolved salts in the water – specifically, the amount of charged (ionic) particles. EC is a measure of the concentration of dissolved ions in water, and is reported in µmhos/cm (micromhos per centimeter) or µS/cm (microsiemens per centimeter). A µmho is equivalent to a µS. EC can be measured in laboratory or with an inexpensive field meter. It also called specific conductance or specific conductivity" (GAMA, 2010).

Saline water includes many different ions; however, few of them can be used as tracers to salinity in water like chloride (Cl^-), sodium (Na^+), nitrate (NO_3^-), calcium (Ca^{+2}), magnesium (Mg^{+2}), bicarbonate (HCO_3^-), and sulfate (SO_4^{-2}). The concentrations of boron (B), bromide (Br), iron (Fe), and other trace ions can be locally important. Table (2.1) illustrates the chemical parameters used for identification of salinity sources.

Using geochemical investigation in sea water intrusion studies requires a good definition of the hydrogeologic framework, hydraulic properties, and physical boundaries of the aquifer, the distribution of groundwater levels and locations of groundwater withdrawal in the aquifer (Reilly, 1993).

Salinization source	Chemical parameter
Natural saline water versus other	Cl, Br,I, S- 34, ^{18}O, D, Br/Cl,I/Cl,IMg/Cl, K/Cl, Ca/Cl, (Ca+Mg)/$SO_{4,}$Sr
Halite-solution brine versus other	K/Na, Br/TDS,(Ca+Mg)/(Na+K), Na/Cl, Ca/Cl, Mg/Cl, SO_4/Cl, Br/Cl, K/Cl, (Ca+Mg)/SO_4, ^{18}O/D, I/Cl, SO_4/(Na+K), SO_4/TDS, SO_4 I/Cl,
Seawater intrusion versus other	Cl, Major ions Piper, ^{14}C, ^{3}H, I/Cl, B, Ba, I^{18}O, ^{2}H, ^{13}C, Ca/Mg, Cl/ SO_4, B/Cl, Ba/Cl, Br/Cl
Oil field brines versus other	Cl, Major ions, Na/Cl, Ca/Cl, Mg/Cl, $SO_{4,}$ I/Cl, Br/Cl, I/Cl, Major ions ratios, Cl, Br, (Na+Cl)/TDS, Li/Br, Na/Br, Na/Cl, Br/Cl.
Agricultural reflues versus other	Cl, NO3, Cl/NO3, K, TDS.
Saline seep versus other	SO4, Ca/Cl, Mg/Cl, SO4/Cl, NO3.
Road salt versus other	Cl, Major ion Ratios, Br/Cl, dey

Table (2.1) Geochemical parameters used for identification of salinity sources (Richter and Kreitler, 1992)

Recently, many geochemical studies were carried out to identify salinity sources in coastal aquifers. For instance: Panteleit et al., (2001) investigated the geochemical characteristics of a near shore inland aquifer system between Bremerhaven and Cuxhaven in the Northern Part of Germany. Analyses of groundwater samples were carried out to determine possible zones of salinization, their origin, and associated geochemical processes in the transition-zone between salt and fresh water. The results were modelled, using the computer program PHREEQC (Parkhurst and Appelo, 1999), and compared with the geochemical field data (Panteleit et al., 2001).

Gurunadha Rao et al., (2011) carried out geophysical and geochemical investigations assessment in the Godavari Delta Basin, India to decipher subsurface geologic formation and assessing seawater intrusion. Electrical resistivity tomographic surveys carried out in the watershed-indicated low resistivity formation in the upstream area due to the presence of thick marine clays up to thickness of 20–25 m from the surface. He expected that the lowering of resistivity may be due to the encroachment of seawater in to freshwater zones and infiltration during tidal fluctuation through mainly the Pikaleru drain, and to some extent rarely through Kannvaram and Vasalatippa drains in the downstream area. He analyzed the groundwater quality for major ions revealed brackish nature of groundwater water at shallow depth. He found that the chemical analyses of groundwater samples have indicated the range of salt concentrations and correlation of geophysical and borehole litholog data in the study area predicting seawater-contaminated zones and influence of in situ salinity in the upstream of study area (Gurunadha Rao et al., 2011)

Hiroshiro et al (2006) described a geochemical investigation that was carried out to investigate recent salinity increases in groundwater for the Motooka coastal area in Fukuoka, Japan. He observed a strong increase in electrical conductivity at 15–20 m depth, corresponding to the freshwater and saltwater interface. Oxidation–reduction potentials observed in deeper groundwater were low, indicating long residence time for the groundwater. These results indicated that the deeper groundwater is affected by seawater.

Lee and Song (2007) studied seawater intrusion in a monitoring well field, located in western coastal area of Buan, Korea using groundwater chemistry and ionic ratios. The results show that the groundwater was affected by the seawater intrusion featured high levels of Cl and TDS. They used piper plot to study the correlation between major ions, they founded that the groundwater salinization occurred via mixing and cation exchange reaction between two end members (fresh or less affected groundwater and the seawater (Lee and Song, 2007).

Amadi et al., (2012) carried out a Vertical Electrical Soundings (VES) in the Bonny Island utilizing surface Schlumberger electrode configuration with an ABEM Terrameter (SAS 1000) while soil and groundwater samples were collected and analyzed for relevant for relevant geochemical parameters. He founded freshwater less at depths between (180–300 m). The study has shown that Schlumberger sounding resistivity method is an efficient tool for investigating the saltwater-freshwater interface in coastal areas (Amadi et al., 2012).

Combined application of geophysical techniques can provide wide-ranging and high-quality information that is essential for the realistic mathematical modelling of aquifer contamination.

2.5.3 Numerical modelling

A groundwater model is a simplified representation of an aquifer reality; it is a valuable predictive tool that can be used for groundwater resources management (Wang and Anderson, 1982). Numerical modelling is indispensable in groundwater simulations, mainly for making predictions and deeply process understanding. It is more powerful than analytical analysis for a complex system.

Numerical models have been developed and used to understanding the mechanism of sea water intrusion process in coastal aquifers and to identify suitable methods of control (Abd-Elhamid and Javadi, 2008a).

Extensive research has been carried out by using numerical modelling to investigate saltwater intrusion in coastal aquifers for instance:

Frind (1982) investigated the problem of seawater intrusion in a confined coastal aquifer. He used a linear rectangular finite element, with direct integration and an iterative solution technique. The results, for a 300 m thick aquifer overlain by a 100 m thick aquitard, show that the aquitard has a controlling influence on the salt distribution. He found that the zone of mixing in the aquifer extend for several kilometres in the seaward as well as the landward direction (Frind, 1982)

Paniconi et al., (2001) developed a numerical model treats density-dependent variably saturated flow and miscible salt transport to investigate the occurrence of seawater intrusion in the Korba coastal plain of northeastern Tunisia. He examined the effects of and interplays between pumping, artificial recharge, soil/aquifer properties, and the unsaturated zone. The results indicate that the sea water intrusion is the origin of the salt in the aquifer (Paniconi et al., 2001).

Narayana et al.,(2007) described the use of a variable density flow and solute transport model, SUTRA, to define the current and potential extent of seawater intrusion in the Burdekin Delta under various pumping and recharge conditions. He developed a 2D vertical cross-section model, which accounts for groundwater pumping and recharge. Modelling results show that seawater intrusion is far more sensitive to pumping rates and recharge than to aquifer properties such as hydraulic conductivity. Analysis also shows that the effect of tidal fluctuations on groundwater levels is limited to areas very close to the coast (Narayana et al., 2007).

Xue et al., (1995) developed a three-dimensional miscible transport model for seawater intrusion in a phreatic aquifer with a transition zone. He considered many important factors, such as the effect of variable density on fluid flow, the effect of precipitation infiltration and phreatic surface fluctuation on the process of seawater intrusion, the existence of great discharge pumping wells, etc. He used the model to describe seawater intrusion in Huangheying, Longkou, and People's Republic of China. He found that the simulated values agree very well with the field data

Kopsiaftis et al (2008) examined the encroachment of seawater intrusion in coastal aquifers under drought conditions in the current work. He used two different approaches, 2D and 3D variable density models in order to quantify the dependence of aquifer yield on the recharge rate in dry years. The results indicated a nonlinear relationship between the optimal pumping rate and the relative recharge as well as a significant decrease of available water for pumping in drought years.

Mathematical techniques used to solve governing equations are finite-difference or finite-element methods that are implemented in computer codes. Numerous computer codes have been developed to simulate the movement of ground water and contaminants transport in aquifers. Some codes are mentioned below with a summary

SUTRA: Saturated-Unsaturated TRAnsport is a well-documented two-dimensional finite element code (Voss, 1984). This code has become the widely accepted 2D variable-density groundwater flow model throughout the world (Voss and Souza, 1987; Souza and Voss, 1987). It can simulate density dependent groundwater flow with (thermal) energy transport or chemically reactive (single-species) solute transport. The 3D beta-version is available now.

FEFLOW: is a 3D computer code, which employs the finite element method (Diersch, 1996). The governing partial differential equations describe groundwater flow, where differences in density affect the fluid flow. Fluid density effects are caused by contaminant mass as well as temperature differences simultaneously, inducing thermo haline flow.

SEAWAT: (Guo and Bennett, 1998; Guo and Langevin, 2002) is a combination of MODFLOW and MT3DMS (Zheng and Wang, 1999). It is designed to simulate 3D variable-density ground water flow and solute transport. The program was developed by modifying MODFLOW subroutine to solve a variable-density form of the ground water flow equation and by combining MODFLOW and MT3DMS into a single program (Gualbert H.P. Oude Essink).

Mentioned codes were used by many authors to investigate different sea water intrusion topics. The topics most investigated using numerical modelling are saltwater-freshwater interface or saltwater intrusion (Oude Essink, 2001; Naji et al., 1998), variable density flow and contaminant transport (Kolditz et al., 1998 and Simmons et al., 2001), tidally influenced water table fluctuation or periodic boundary conditions (Volker et al., 2002; Li et al., 1997; Townley, 1995), and sloping beaches and seepage dynamics (Li et al., 1997).

These codes were employed in different analyses with different objectives for instance:

2.6 Practical solution to Control Sea Water Intrusion

Management of coastal groundwater involves balancing the demand and the renewable supply of water. The unique aspect of coastal aquifer management is that pumping schemes must be optimized to prevent or at least minimize upconing or lateral migration of saline groundwater (Post, 2005). Todd (1974) discussed various means of preventing saltwater intrusion including: reduction of the abstraction rates, relocation of abstraction wells, subsurface barriers, natural recharge, artificial recharge, abstraction of saline water, and combination of some of these systems

Presently, artificial recharge appears as an effective method to control sea water intrusion. Artificial recharge is not only applied for restoration but also as an element in the continuous optimal exploitation of aquifers. Artificial recharge of groundwater is applied for many reasons, such as to increase the sustainable yield, to control the groundwater table or the piezometric level in order to restrict or to slow down land subsidence, to increase the volume of fresh groundwater available for emergencies, and/or as a barrier against inflow of saline groundwater. Artificial recharge can be realized by (increased) infiltration at the land surface or by recharge wells with well screens in aquifers at any desired depth. Recharge wells, recharge basins and barrier wells have proven to be very useful in maintaining the proper equilibrium between pumping and groundwater recharge. Therefore, proper groundwater monitoring techniques and groundwater management, combined with groundwater conservation are needed to keep saltwater intrusion under control.

Another method used to control salt water intrusion through the use of injection wells is the use of an injection-extraction system. Such a system may be used to inject fresh water inland, while salt water intruded into the aquifer is being extracted along the coast.

A change in pumping patterns can be achieved by reducing pumping and relocating withdrawal wells to eliminate areas of intense pumping. Due to the difference in density between salt water and fresh water, these two methods will maintain the fresh water at a desirable piezometric head.

Here are a brief description of some studies that has been computed to control saltwater intrusion is geven. Mahesha (1996) developed a numerical model to control of seawater Intrusion through injection-extraction well system. Johnson et al., (2001) discussed alternatives to injection wells for seawater intrusion control, central and west coast groundwater basins, Los Angeles County, California. Kacimov (2009) studied the control of sea-water intrusion by salt-water pumping in coast of Oman. Johnson (2007) demonstrated that injection wells have been successfully used to control seawater intrusion in the over-drafted CWCB aquifers since the early 1950s. Abd Elhamid and Javadi (2008) discussed various alternatives to control saltwater intrusion and different mathematical models that have been developed for this purpose in the Middle East, South Europe, and USA. Abd Elhamid and Javadi (2010) developed simulation-optimization model to study the control of seawater intrusion in coastal aquifers using ADR methodology. They confirmed the utility of this method in controlling seawater intrusion. Jr et al., (2011) performed laboratory-scale experiments and numerical simulations to determine the effects of the location and application of recharge wells, and of the location and penetration depth of flow barriers, on controlling seawater intrusion in unconfined coastal aquifers.

CHAPTER 3

DESCRIPTION OF STUDY AREA

Chapter 3: Description of Study Area

In the preliminary stages of the groundwater model development, background information and data analysis are required. This chapter is intended to provide a general overview of the study area, particularly, of the Gaza coastal aquifer. The chapter also presents the results of the data analysis. The following materials and data were collected, screened, reorganized and analysed in response to the problem explained in chapter two of this thesis:

- Digital Elevation Model (DEM) with resolution of 30*30 m.
- 20 Geologic cross sections distributed regularly all over the Gaza Strip per perpendicularly to the sea shoreline.
- Drilling completion records of piezometric wells.
- Pumping rate records for 3600 wells.
- Groundwater level and groundwater quality parameters measurements from 1990 to 2009.
- Rainfall records and other relevant climate data from 1980 to 2011.

These data were provided by varies government and semi-government organizations in Gaza Strip.

Different sources types were used, like research papers, MSc thesis, PhD thesis, PAW, PoA and CMWU reports.

3.1 Background Information

The Gaza Strip is a narrow coastal territory, located along the south eastern coast of the Mediterranean Sea. It covers 365 Km^2 and it is bordered by the Negev Desert and Egyptian Sinai peninsula to the south and the Mediterranean Sea to the west. The region is largely flat and sandy, with dunes stretching along the coast having a width varying from 1.5 km to 4.3 km (Mogheir, 2003). The coastal dunes ridge are broken in the middle of the Strip by a narrow valley called wadi Gaza, the latter valley has been formed by Wadi Gaza, the main Wadi that passes through the Gaza Strip and reaches the Mediterranean Sea (Mogheir, 2003). The highest point of the Strip has an elevation of about 105 m above sea level.

The current population is estimated to be more than 1.5 million inhabitants, with a natural rate of 3.8 % (PCBS, 2007), distributed in five governorates (figure 3.1). Gaza City, which is the biggest governorate, has about 400,000 inhabitants. The two other main governorates are Khan Younis, with a population of about 200,000 inhabitants, and Rafah with a population of about 150,000 inhabitants (UNEP report, 2009). Table (3.1) shows the revised estimates of the population projection in Gaza Strip as given by Palestinian Central Bureau of Statistics (PCBS) in 2005. Gaza Strip has a particular political situation due to many years of occupation and continuous Israeli siege since 2006. In the Gaza Strip, there is both a serious shortage and pollution of natural resources, coupled with long-term environmental degradation (UNDP, 2012). This caused rapid deterioration in all aspects of the life.

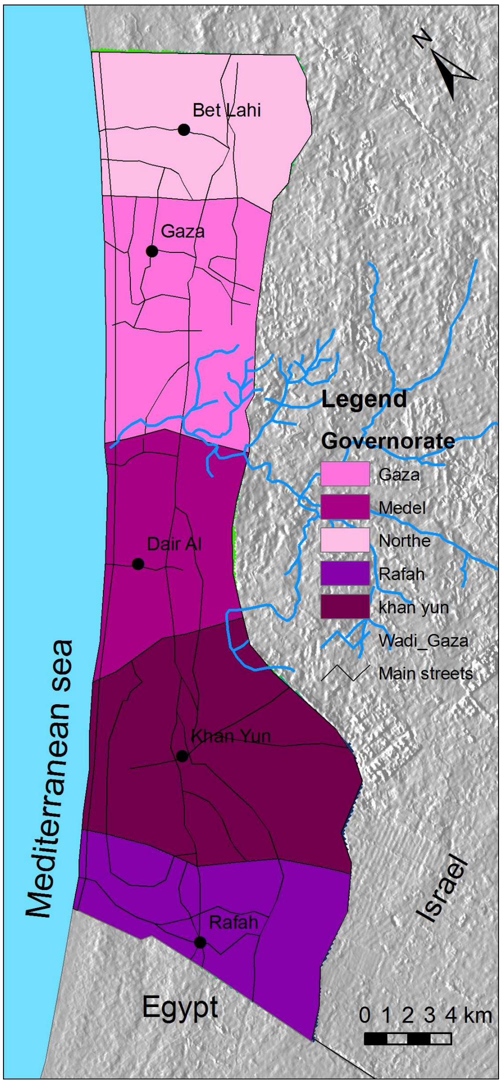


Figure (3.1) The five governorates of Gaza Strip.

Year	Mid Year Population	Growth Rate (%)	Year	Mid Year Population	Growth Rate (%)
1997	995,522	4.3	2007	1,499,369	3.8
1998	1,039,528	4.4	2008	1,556,201	3.7
1999	1,086,970	4.5	2009	1,614,018	3.6
2000	1,137,990	4.6	2010	1,672,785	3.5
2001	1,188,130	4	2011	1,732,438	3.5
2002	1,236,372	4	2012	1,792,895	3.4
2003	1,286,109	3.9	2013	1,854,353	3.3
2004	1,337,236	3.9	2014	1,917,019	3.3
2005	1,389,789	3.8	2015	1,980,825	3.2
2006	1,443,814	3.8			

Table (3.1) The revised estimates of the population projection in Gaza Strip (PCBS, 2005).

3.2 Location

The Gaza Strip is a narrow coastal region located on the Mediterranean Sea between longitudes (34° 2”, 34° 25”) east, and lati tudes (31° 16”, 31° 45”) north. It has a length of about 41 km and a width ranges from 5 to 12 km figure (3.2). It is part of the coastal foreshore plain bordering the El-Khalil Mountains in the West Bank to the northeast, the northern Negev desert to the southeast, and the northern Sinai desert to the south (Ubeid, 2010).

Figure (3.2) Location map of Gaza strip.

3.3 Climate

The Gaza Strip is located in the transitional zone between the arid desert climate of the Sinai Peninsula in Egypt and the temperate and semi-humid Mediterranean climate along the coast. The arid desert climate of Egypt and the Sinai Peninsula along with the Mediterranean Sea, have an imposing influence in the patterns of Gaza weather. Two seasons can be distinguished, the dry season from April till October, and the wet season from November till March (Hallaq et al., 2008).

3.3.1 Temperature

Temperature in Gaza Strip gradually changes throughout the year, with a maximum in August and a minimum in January, the average monthly maximum temperature ranges from about 17.6 C° in January to 29.4 C° in August. Figure (3.3) presents the maximum, minimum and mean monthly air temperatures as observed in the meteorological station of Gaza city for the period from 1970 until 2000 (Aish, 2004).

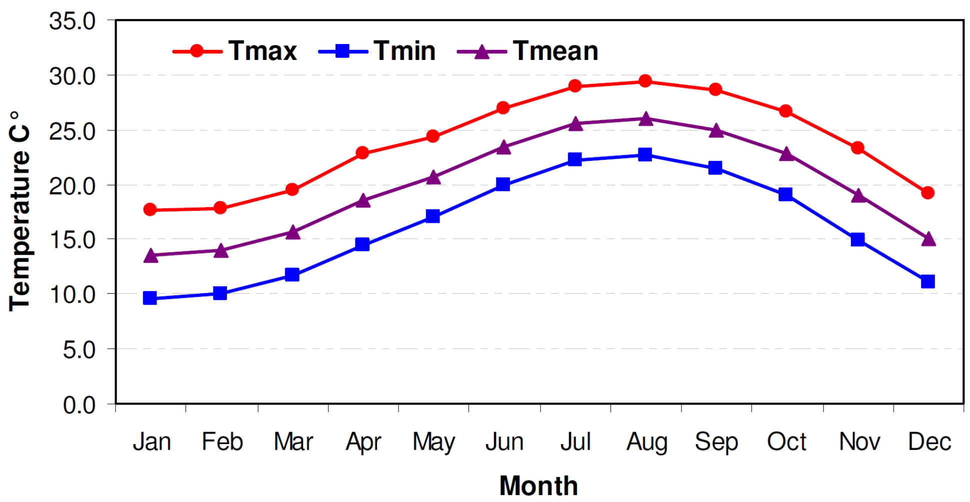


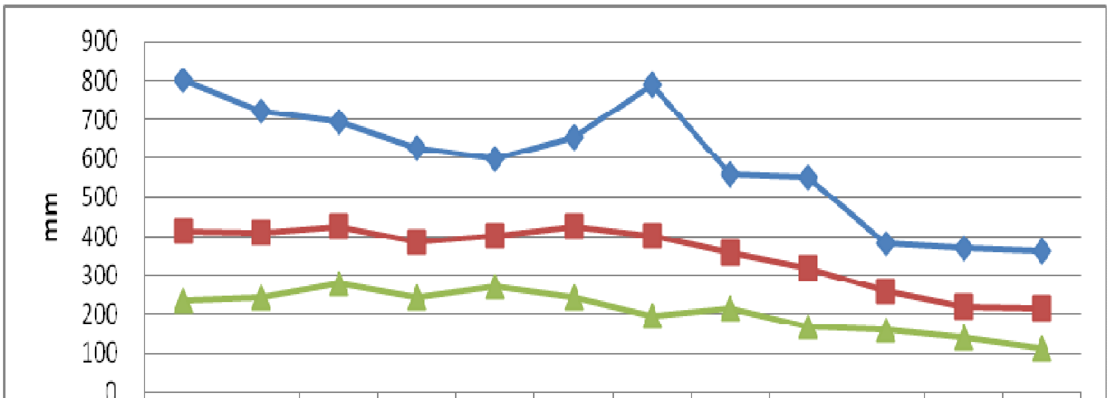
Figure (3.3) Mean monthly maximum, minimum and average temperature (C°) for the Gaza Strip (period 1970 – 2000) (Aish, 2004).

3.3.2 Humidity

In the study area, the humidity rate in summer is about 65% during the daytime and 85% at night time, and it is about 60% during the day and night times in winters. The average annual potential evaporation is about 1200 to 1400 mm/yr (PNIC, 1999).

3.3.3 Rainfall

Rainfall is the main source for the natural recharge of Gaza coastal aquifer, and it is affected by climatic variables such as temperature, speed and direction of winds, insolation, evaporation and evaportranspiration. The rainfall data set of the Gaza Strip is based on the data collected from 12 rain stations owned by PoA (figure, 3.5). Data are collected daily. According to the available historical data, the average rainfall ranges from 400 mm/yr in the north to 200 mm/yr in the south areas (figure 3.4). The maximum rainfall occurs during January. The rainy days range from 45 to 50 (Abu Safia, 1995).



	B Hanon	B Lahia	Jabalia	Shati	Remal	Tuffah	Moghragah	Nussirate	Dr-Elbalah	Khan Younis	Khuzaa	Rafah
Max	801.5	724	692.6	627	599	653.5	790.7	558.3	550.5	381	368	360.2
Ave	412.18	408.27	424.09	386.99	401.94	426.18	401.05	356.21	317.98	257.48	219.32	213.84
Min	234.3	243.9	277	243.95	272.3	242.4	197.05	217	169.5	159.3	142	113.5

Figure 3.4 The average rainfall in 12 rain stations for 2000 to 2011 period.

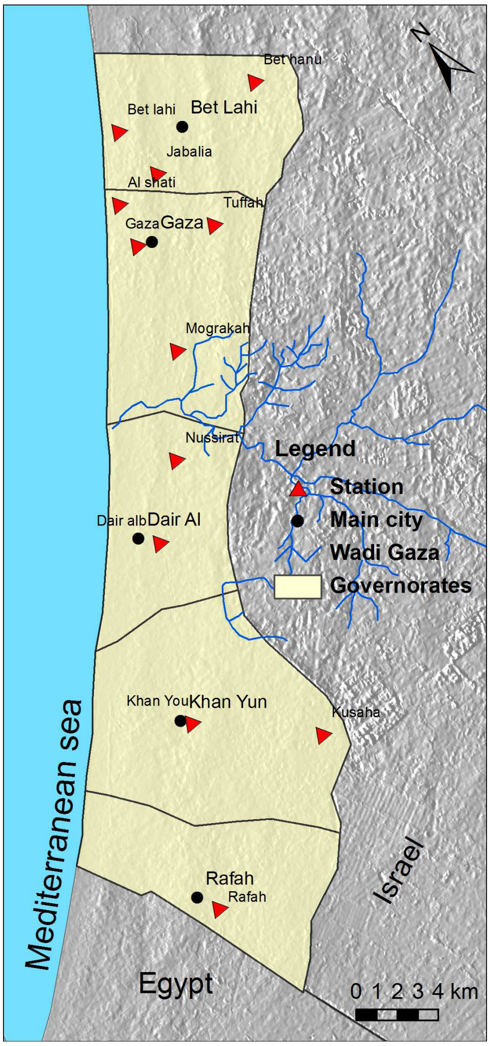


Figure (3.5) Meteorological stations in Gaza strip.

3.3.4 Evaporation

In the Gaza Strip there is a small spatial variation in evaporation than in rainfall. Evaporation measurements 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 evaporation values of around 70 mm/month were measured from December to January. In Gaza Strip the mean evapotranspiration is about 54 x 10^6 m^3 (PWA, 2000).

3.4 Gaza Topography

As shown in figure (3.6) Gaza topography is characterized by elongated ridges and depressions, dry streambeds and shifting sand dunes. The ridges and depressions generally extend in a NE–SW direction, parallel to the coastline. Ridges are narrow and consist primarily of Pleistocene-Holocene sandstone (locally named as Kurkar) alternated with red brown layer (locally named as Hamra). In the south, these features tend to be covered by sand dunes. Land surface elevations range from mean sea level to about 110 m above mean sea level (Al-Khatib, 2010).

3.5 Soil Types

The types of soil which can be found in Gaza Strip are sandy, loessial sandy, loess, sandy loess, dark brown/reddish brown (figure 3.7) (PAA, 1994). The sandy soil can be found along the coastline extending from south to outside the northern border of the Strip. The thickness of sand fluctuates from two meters to about 50 meters due to the hilly shape of the dunes. Clay soil can be found in the north eastern part of the Gaza Strip. Loess soil is located around Wadis, where the approximate thickness reaches about 25 to 30 m (JURY & GARDNER, 1991). Wadi Gaza representing the main surface water drainage toward the Mediterranean has transported finer soils. Silt and clay content generally increases with distance from the coast, improving the soil ability to retain water. The quantity of organic matter also generally increases with distance from the coast, making the soil suitable for a wide variety of crops including citrus, olives, and vegetables. Table (3.2) shows the classification and characteristics of different soil types in Gaza Strip adopted by MOPIC (MOPIC, 1997; Goris and Samain, 2001).

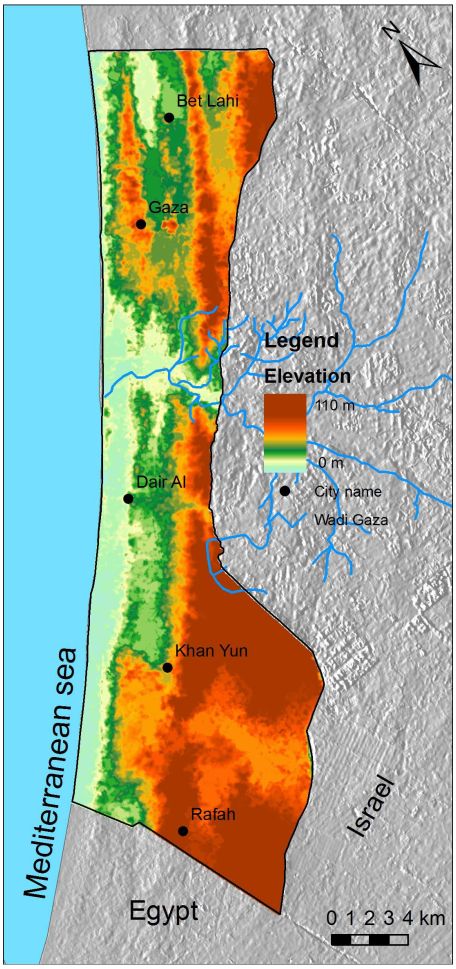


Figure (3.6) DEM of Gaza strip

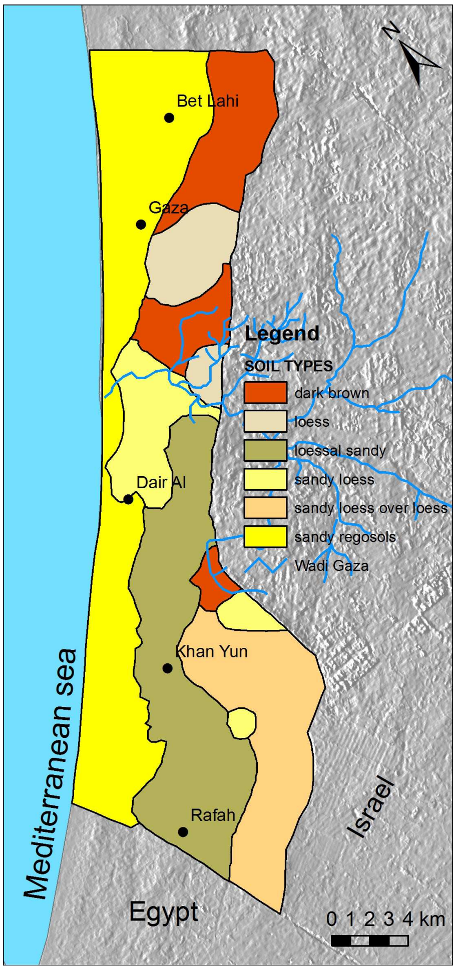


Figure (3.7) Soil types of Gaza strip.

Local Classification	Location	Description	Texture
Loess soil	Between the Gaza city and the Wadi Gaza	Loess soils sedimented in Pleistocene until Holocene Series. The grain size of loess fluctuates from 0.002 to 0.068 mm. Loess has been transported by winds and sedimented in loose form in the upper part, and in hard form in the lower part of the layers. They are brownish yellow-colored often with accumulation of lime concretions in the subsoil and containing 8 – 12 % calcium carbonate.	Sandy loam (6% clay, silt 34% , Sand 58%)
Dark brown /reddish brown	Beit Hanoun and Wadi Gaza	These alluvial soils are usually dark brown to reddish in colour, with a well developed structure. At some depth, lime concretions can be found. The calcium carbonate content can be around 15–20%	Sandy clay loam (25% clay, 13% silt, 62% sand)
Sandy loess soil	Deir el Balah and Abssan	This is a transitional soil, characterized by a rather uniform, lighter texture. Apparently, windblown sands have been mixed with loessial deposits.	Sandy clay loam (23% clay, 21% silt, 56% sand)
Loessial sandy soil	It is found in the central and southern part of the strip	Forms a transitional zone between the Sandy soil and the loess soil, usually with a calcareous loamy sandy texture and a deep uniform pale brown soil profile.	The top layer is sandy loam (14% clay, 20% silt, 66% sand). The lower profile is loam (21% clay, 30% silt, 49% sand)
Sandy loess soil over loess	It is found east of Rafah and Khan Younis	Loess or loessial soils which have been covered by a 20 to 50 cm thick layer of sand dune	Sandy loam (17.5% clay, 16.5% silt, 66% sand)
Sandy regosol	It is found a long the coast of Gaza Strip	Soil without a marked profile. Texture in the top meters is usually uniform and consists of medium to coarse quartz sand with a very low water holding capacity. The soils are moderately calcareous, very low matter and chemically poor, but physically suitable for intensive horticulture in greenhouses. In the deeper subsurface occasionally loam or clay loam layers of alluvial origin can be found	Top layer is loamy sand (9% clay, 4% silt, 87% sand). Deeper profile is sand (7.5% clay, 0% silt, 92.5% sand)

Table (3.2) Classification & characteristics of different soil types in Gaza Strip. (MOPIC, 1997; Goris and Samain, 2001)

3.6 Land use

Land is one of the scarcest natural resources in the Gaza Strip. The major part of the Gaza Strip land is owned by privates. Therefore, it is important to consider the ownership in any development plan. Figure (3.8) shows the spatial distribution of land use in the Gaza Strip. Table (3.3) Show the percentages of the different land uses in the Strip; about 40% of the land is used for agriculture, most of which is in the eastern half of Gaza where population density is low. The land use data were obtained from the analysis of aerial photographs taken in 2008 (Abu Fakher & Yahya, 2010).

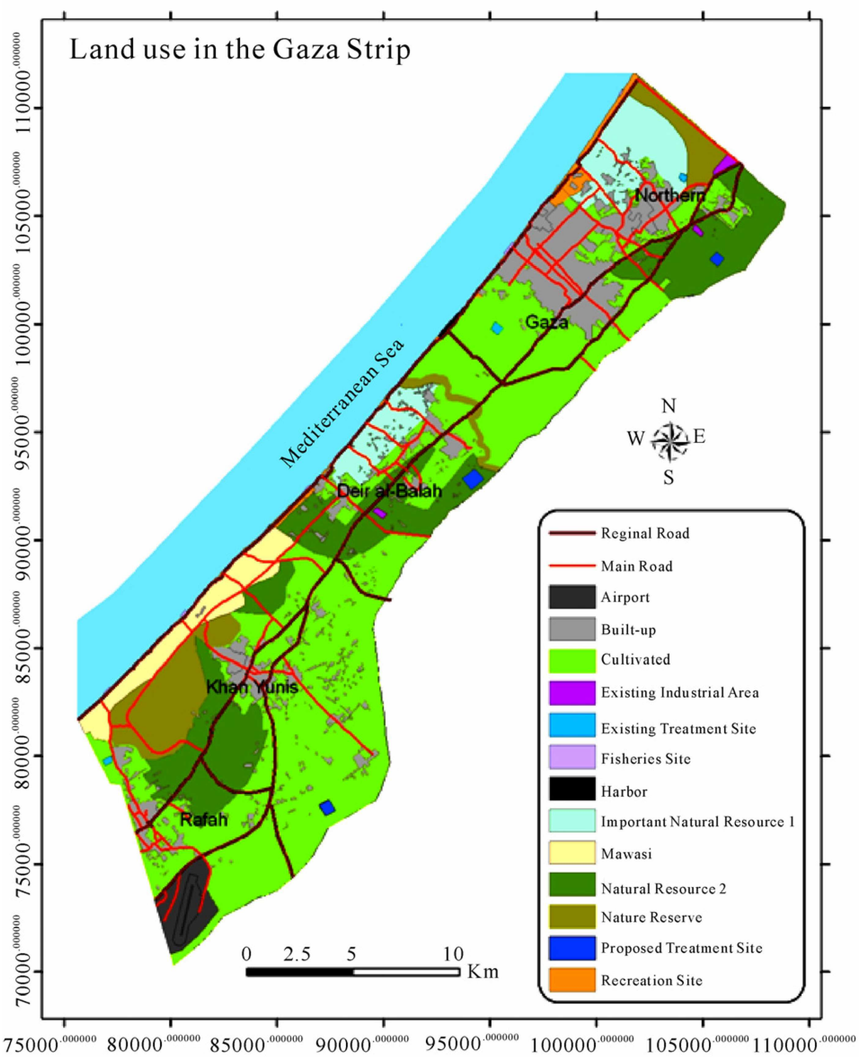


Figure (3.8) Land use map of Gaza strip (Abu Fakher & Yahya, 2010).

ID	Land use type	Area Km2	Percent (%)
0	Airport	7.5	2.05%
1	Built-up	54	14.79%
2	Cultivated	157.5	43.15%
3	Existing Industrial Area	0.9	0.25%
4	Wastewater Treatment Site	0.45	0.12%
5	Fisheries Site	0.3	0.08%
6	Harbor	0.35	0.10%
7	Important Natural Resource	24	6.58%
8	Mawasi	14.5	3.97%
9	Natural Resource	62	16.99%
10	Nature Reserve	26.5	7.26%
11	Proposed Treatment Site	1.1	0.30%
12	Recreation	6.1	1.67%
13	Roads	9.8	2.68%
Total Area		365	100%

Table (3.3) Land use distribution in the Gaza Strip (Abu Fakher & Yahya, 2010).

3.7 Geology of Gaza coastal aquifer

Geology construction of the Gaza strip was based on the oil and gas exploitation logs up to a depth of about 2000 m drilled by Israelis and on wells drilled during the Costal Aquifer Management Project (CAMP) (Al-Ramlawi, 2010). "The coastal aquifer of the Gaza Strip consists of the Pleistocene Kurkar and recent (Holocene age) sand dunes. The Kurkar Group consists of marine and Aeolian calcareous sandstone (“kurkar”), reddish silty sandstone, silts, clays, unconsolidated sands, and conglomerates. The Kurkar Group is distributed in a belt parallel to the coastline, from north to south of the Gaza Strip. It is extends about 15-20 km inland, where it un-conformably overlies Eocene age chalks and limestone, or the Miocene-Pliocene age Saqiye Group, a 400-1000 m thick sequence of marls, marine shales, and claystones. The Kurkar Group consists of a complex sequence of coastal, near-shore and marine sediments. Marine calcareous sandstone forms the base of each transgressive sequence, and marine clays form the end of regressions. the thickness of the Kurkar Group increases from east to west, and ranges from about 70 m near the Gaza border to approximately 200 m near the coast. Israeli literature suggests that the Kurkar Group becomes more clastic towards the east. The distinct ‘layering’ of sedimentary cycles becomes less obvious, and the presence of red silty-clayey sandstone becoming more dominant. In addition, alluvial clays and soils become more evident along the courses of major drainage features such as Wadi Gaza. Clay formations are of two types: marine and fluvial. Marine clays are present along the coast, at various depths within the formation. They pinch out about 5 km from present coastline, and based on existing data, appear to become more important towards the base of the Kurkar Group" (Jamal and Yaqubi, 2001) .Figure (3.9) represents a typical hydrogeological cross section of Gaza Strip.

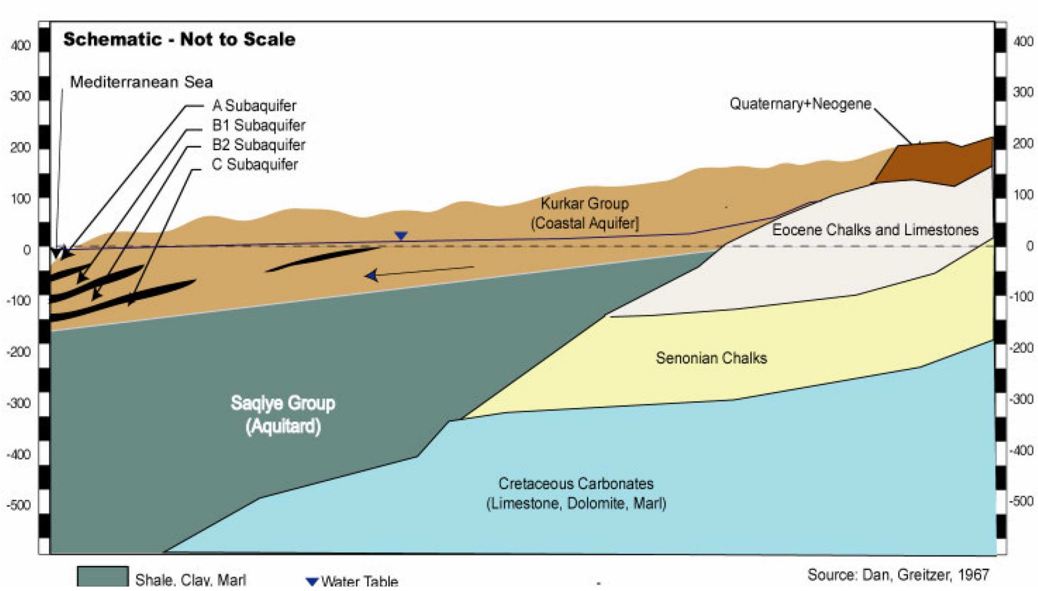


Figure (3.9) Geological cross section of Gaza coastal aquifer (PWA, 2000).

3.8 Aquifer hydraulic properties

The results of aquifer tests carried out at different places in the Gaza Strip, show that transmissivity values range between 700 and 5000 square meters per day (m2/d). The corresponding values of hydraulic conductivity K are mostly within a range of 20-80 meters per day (m/d). Most of the tested wells are municipal wells screened across more than one sub-aquifer. Hence, little is known about any difference in hydraulic properties between sub-aquifers (PWA, 2000b). The estimated effective porosity is 25%, where is the Specific yield values are estimated to be about 15-30 percent and specific storativity is about 10 - 4 (PWA, 2000b).

3.9 Water resources availability

3.9.1 Surface water

There are no permanent surface water bodies in Gaza Strip. The surface water system in the Gaza Strip consists mainly of valleys (locally named Wadis), which only flood during very short periods during winter. Wadi Gaza is the major wadi crossing the Gaza Strip in its central part. The geographical basin of the wadi has a large catchment area where extends far beyond Bear Esaba as shown in figure (3.10). Since several decades, it rarely flows due to numerous water diversion and storage projects created upstream in Israel. The second wadi is wadi Halib which drains the depression of Beit Hanon. The third valley is Wadi Silka near Khan Younes, now a dry wash only flowing after torrential rains and no longer reaching the sea (Ubeid, 2010).

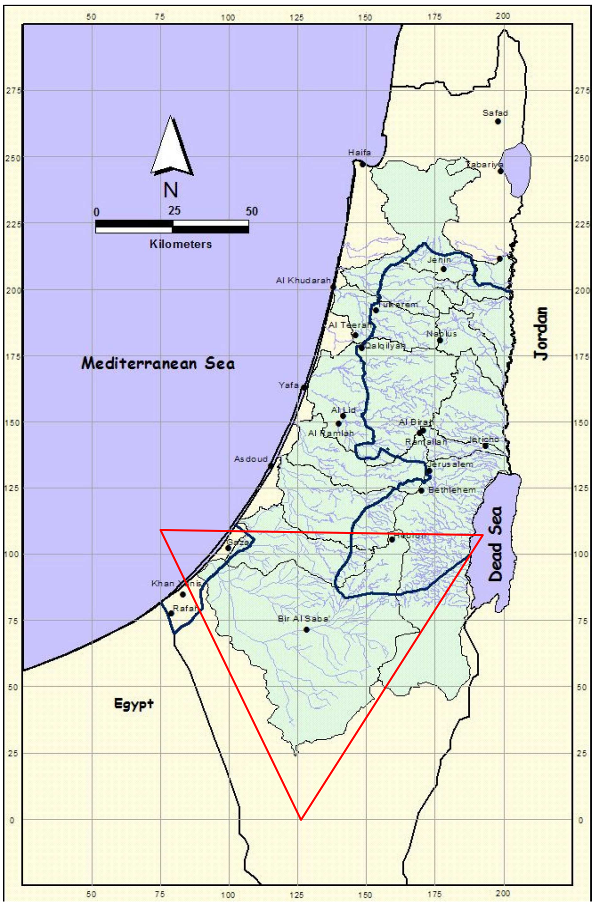


Figure (3.10) Wadi Gaza catchment area and sites boundaries (Aliewi, 2009).

3.9.2 Groundwater and Aquifer status

Gaza coastal aquifer has a great strategic importance for Palestinian people being the only fresh water source able to satisfy the daily consumption needs. The aquifer occupies the extreme western edge of the shallow coastal aquifer presents in figure (3.11).

The layered stratigraphy of the Kurkar Group within the Gaza Strip subdivides the coastal aquifer into 4 separate subaquifers near the coast previously shown in figure (3.9). Further east, the marine clays pinch out and the coastal aquifer can be regarded as a single hydrogeological unit. The upper subaquifer “A” is unconfined, whereas subaquifers “B1, B2, and C” become increasingly confined towards the sea (Jamal and Yaqubi, 2001). The aquifer thickness varies from 200 m along the coastline to a few meters at the eastern margins (Vengosh et al, 1999). In the eastern part, the depth of the saturated zone varies between 30 and 80 m, whereas in the western part, the depth various from 120 to 150 m (Mercado 1968; Fink 1992; Livshitz 1999; Guttman 2002).

The aquifer is recharged by different components: rainfall, agricultural return flow, water and waste water network losses, and recharge basins in different places all over the Gaza Strip.

The total water abstraction from the aquifer in 2009 was estimated between 160 and 165 x 10^6 m^3 while the average of replenishment was estimated between 100 – 110 x 10^6 m^3 (HWE report, 2010), this indicates a deficit in the aquifer balance ranging from 55 to 60 x 10^6 m^3/yr.

The coastal aquifer holds approximately 5000 x 10^6 m^3 of groundwater of different quality. However, only 1400 x 10^6 m^3 of this is fresh water, with a chloride content lower than 500 mg/l. This fresh groundwater typically occurs in the form of lenses that float on the top of the brackish and/or saline groundwater. Approximately 70% of the aquifer is brackish or saline water and only 30% is fresh water (Yaqubi et al, 2007).

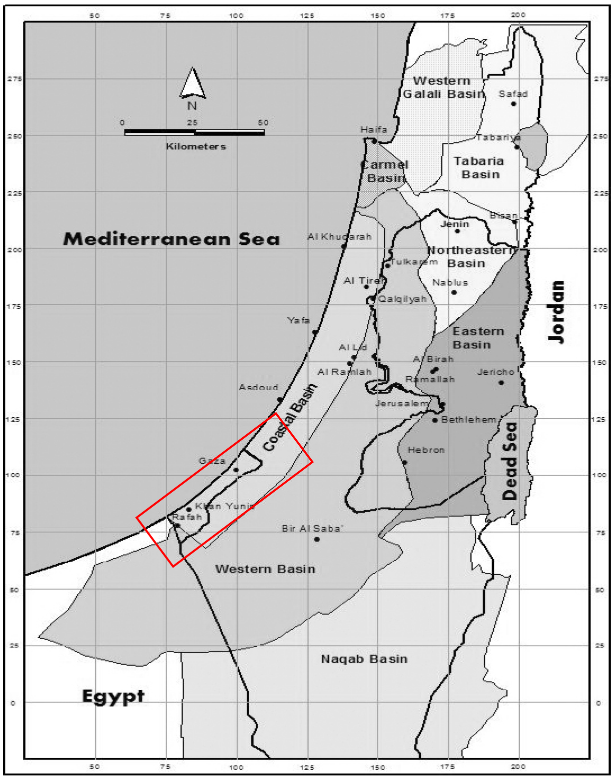


Figure (3.11) Groundwater basins in Palestine (Yaqubi et al, 2007).

3.10 Wells

There are an estimated 4,000 wells within the Gaza Strip, almost all privately owned and used for agricultural purposes. Approximately 110 wells are owned and operated by individual municipalities and are used for domestic supply. The average density of wells is about 5 km^2, but some areas north of Gaza City, the density is greater than 20 per km^2 (figure 3.12). There is significant uncertainty around historical pumping in Gaza, but it is believed that large scale abstraction started in the early 1960s, when agricultural development of the Gaza Strip began (Jamal and Yaqubi, 2001).

Agricultural wells are mostly drilled and installed as large diameter boreholes (<2.5 m) to the water table (using regular excavation techniques and placing caissons in the subsurface), and as drilled holes (<10-inch). Most agricultural wells in Gaza are shallow and extend only to a few meters (5-15) below the groundwater table, tapping almost exclusively Subaquifer “A”. Municipal wells are deeper, and may tap Subaquifers A, B1, and B2 depending on location and distance from the coast. Municipal wells are typically screened throughout their length below the water table, and are not selectively screened across individual subaquifers. Hence, subaquifers are hydraulically connected in places (including near the coast). Detailed abstraction records have not been obtained for years prior to 1996 (Jamal and Yaqubi, 2001).

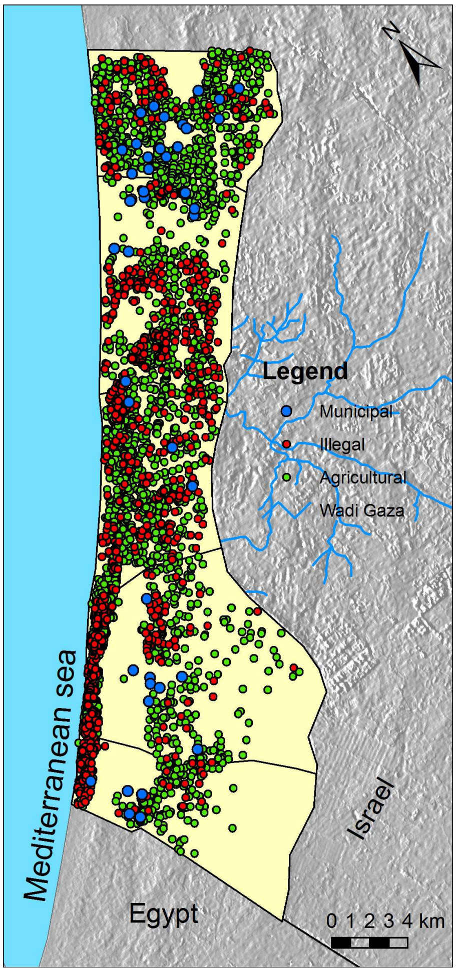


Figure (3.12) Wells distribution in Gaza Strip (2000).

3.11 Ground water flow

Under natural conditions, groundwater flow in the Gaza Strip is towards the Mediterranean Sea. However, overpumping disturbed natural flow patterns over the past 40 years. A slow lowering in groundwater levels has been verified in 1970 and it continues until now with an average of about 1, 6 m/y (CAMP, 2000). This continued lowering in ground water levels led to formation of two deep cones of depression in the northern and the southern. Generally, water levels are presently below mean sea level in many parts of the aquifer increasing the risk of sea water intrusion (PEPA, 1994).

3.12 Alternative water resources

Alternative water resources like wastewater reuse, desalinization, and rain-storm water harvesting are applied in many developing and developed countries to face water scarcity. Due to the continue population increase and limited water resources in Gaza Strip, search for other alternative resources is essential to face the future demand and keep the aquifer in sustainable use. Reuse of treated wastewater appears as a suitable solution to solve different problems caused by overpumping and uncontrolled sewage infiltration. Recently, PWA has adopted the reuse of treated wastewater as an important renewable resource for artificial recharge, trees irrigation and aquaculture production. Using treated wastewater for agriculture production could help to reduce the gap between supply and demand, consequently minimizing the dependency on the aquifer (PWA, 2010).

3.13 Wastewater treatment planets

Recent reports indicate that 60 % of the Gaza Strip population is connected with sewage networks, while the other 40 % uses septic tanks and cesspits (Ashour et al., 2009). Daily, about 110,000 m^3 of waste water produced in the Strip, only 70 % us collected and with a treatment capacity of 45- 49’000 m^3/day only 60 % of the sewage is partially treated by the existing Waste Water Treatment Plants (WWTPs) (Giorge, 2009). In 2010 the treated waste water was estimated about 40 x 10^6 m^3, and only 7.2 x 10^6 m^3 are infiltrated to the aquifer. Table (3.4) shows the total production of treated wastewater in different governorate of Gaza Strip (CMWU, 2010).

Figure (3.13) shows the positions of existing WWTP and the proposed positions for new WWTPs. In the north Governorate Beit Lahia Wastewater Treatment Plant serve about 290.000 inhabitants. Current inflows to the plant are greater than 20.000 m^3/day, beyond plant capacity.

Gaza wastewater treatment was established in 1977 over a sand dune area south west of Gaza city at Esheikh Ejlene area. In Gaza city there is only one wastewater treatment plant for sewage, designed with a capacity of 40,000 m^3/d (Lubbad, 2005). The partially treated wastewater that is generated in Gaza is currently discharged into the sea (60,000 m3/day). The beaches in front of Gaza city, Beach Camp, and Deir El-Balah are polluted by sewage discharges, and individual sewage drains ending either on the beach or a short distance from the seashore (Afifi et al., 2000).

The wastewaters of the municipalities of the Middle Governorate are not treated at all and are partially infiltrated but mainly discharged directly into the Wadi Gaza and directly to the sea. The waste waters of the Khan Younis town and of some municipalities are collected to a WWTP of limited treatment capacity and were disposed to an infiltration lagoon (Giorge, 2009).

Rafah wastewater treatment plant serve about 90 % of the city population with capacity of 20.000 m3/d. Currently, the treatment plan treat partially about 10,000 m^3/d. The treated waste water is discharged into the sea (Ashour and Abu Obaid, 2010).

Govern	Pop-capita	Connect to sewage network %	Sewage production m^3/d	Treatment availability	Final destination
North	290.000	80%	20.000	Available partially treatment	infiltration
Gaza	550.000	90%	60.000	Available partially treatment	To sea
Middle	220.000	55%	10.000	Available partially treatment	To wadi gaza and to sea
Khan youns	185.000	40%	9000	Available partially treatment	To sea
Rafah	180.000	65%	10.000	-	To sea
total			109.000 m^3/d 40 $x10^6$ m^3/yr		32 $x10^6$ m^3/yr to sea

Table (3.4) Treated quantity of waste water for every governorate in Gaza strip. source, Coastal Municipality's Water Utility (CMWU), (2010).

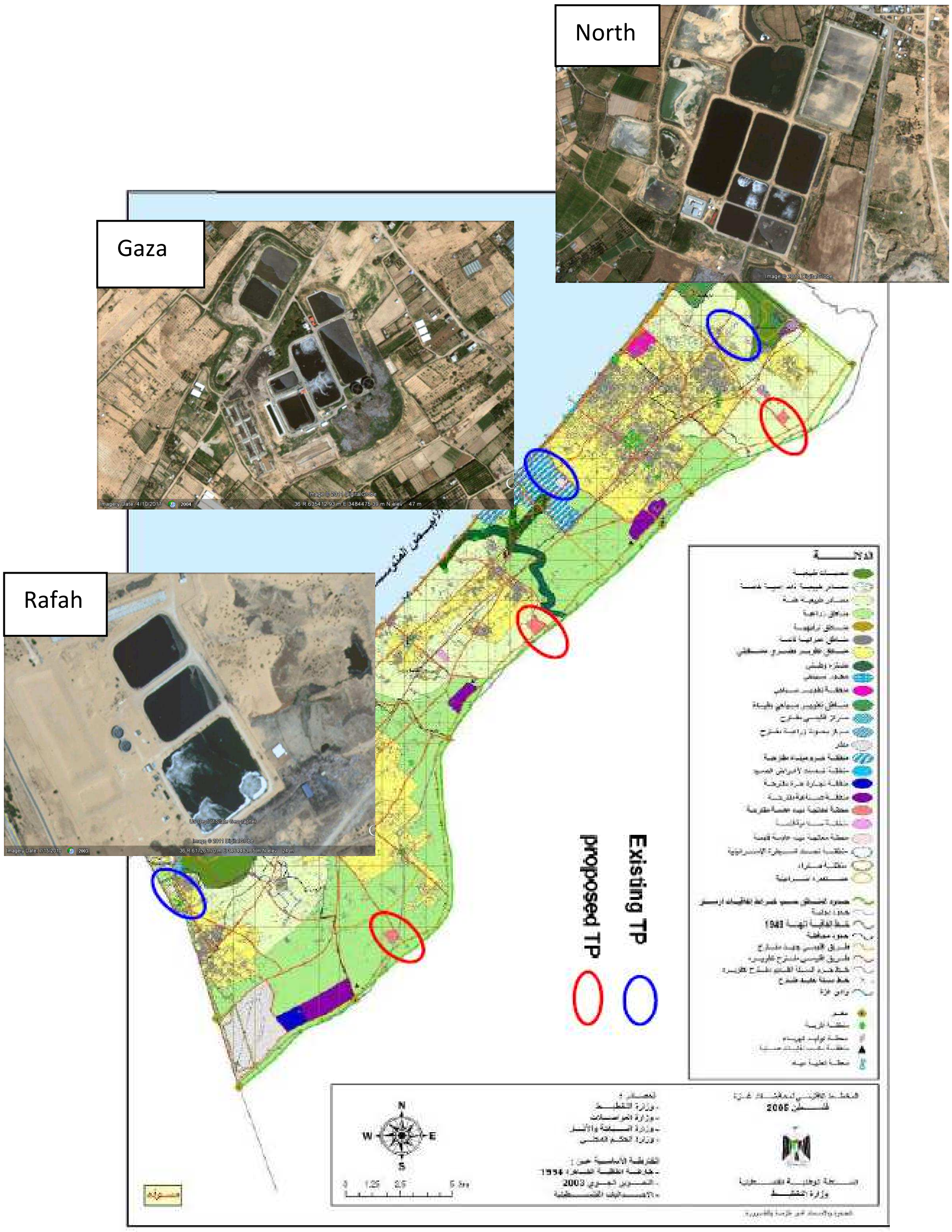


Figure (3.13) Position of treated waste water planets.

3.14 The Palestinian National Water Plan

"To address the water quality related issues and problems, the Palestinian Water Authority (PWA) in collaboration with the Palestinian Environmental Quality Authority (EQA) has developed the first National Water Plan and the National Environmental Action Plan in part to better manage and preserve the water resources including groundwater by promoting protective policies. Such policies demand that the agricultural and industrial development to be in full compliance with the available water resources based on sustainable development and that pollution control measures ought to be introduced and ensured through enforcement if needed" (Almasri, 2008)

"The National Water Plan outlines the direction in which the Palestinian water sector is proposed to develop to the year 2020 and proposes the actions to be taken to achieve these goals. The strategic planning element of the Plan has confirmed the logic for this direction and identified the alternatives, which may have to be considered if assumptions do not materialize as anticipated. As a strategic plan for the water sector, the plan will be implemented under the direction of the Palestinian Water Authority (PWA) but in close collaboration and co-ordination with other Palestinian stakeholders. It is intended as a dynamic tool to identify, define, and describe an implementation process for the integrated management and development of Palestinian water resources.

The planning approach has been based on estimates of demand for planning horizons up to 2020. These demands have been estimated utilizing internationally recognized standards appropriate to the location and to the development objectives. In accordance with the scarcity of resources in the region, demand management measures and utilization of alternative sources to fresh water have been incorporated wherever appropriate.

The implementation plan has identified projects, which are programmed to achieve the following:

- As a first priority, infrastructure will be expanded to progressively provide quality water service to all domestic consumers reaching an average of 150 L/c/d by the year 2020. Standards of water quality related to WHO criteria and provision within municipal and industrial supplies to meet industrial demand will be met.

- Water exploration and aquifer modelling will be carried out to determine additional quantities of water and sustainable yields.
- Sewer and wastewater treatment facilities will be expanded to safeguard public health, avoid pollution and to utilize water for beneficial purposes.
- Conservation measures such as metering, leakage reduction, and improved agriculture technologies will be implemented to save water.
- Storm water will be channelled to collection facilities for beneficial purposes including agriculture and groundwater recharge and to reduce flooding.
- Reclaimed wastewater, as well as brackish water, will be treated to standards appropriate for the relevant irrigation and for aquifer recharge" (PWA, 2000).

Chapter 4

Data Analysis

Chapter 4: Data analysis

4.1 Annual average rainfall

The annual rainfall records at 12 meteorological stations were used in the calculation of average rainfall for the period between years 2000 and 2010. Thiessen method was used to represent the spatial distribution of regional average rainfall. In Thiessen method the rainfall is calculated as the nearest neighbor value (Viessman and Gary, 2002, Wilson, 1998). The area is subdivided into Thiessen polygons based on the rainfall station. The average regional rainfall in Gaza Strip is calculated as:

$$p_{avg} = \frac{\sum P_i * A_i}{\sum A_i} \qquad (1)$$

Where,

Pavg : is the average amount of rainfall in mm/year

Ai : is the area of the i^{th} polygon determined by Thiessen method in Km^2

Pi : is the rainfall of the i^{th} polygon.

Figure (4.1) shows that the average rainfall ranges from 213 to 425 mm/yr. The average annual rainfall in Gaza strip for the past 12 years is 290 mm/yr.

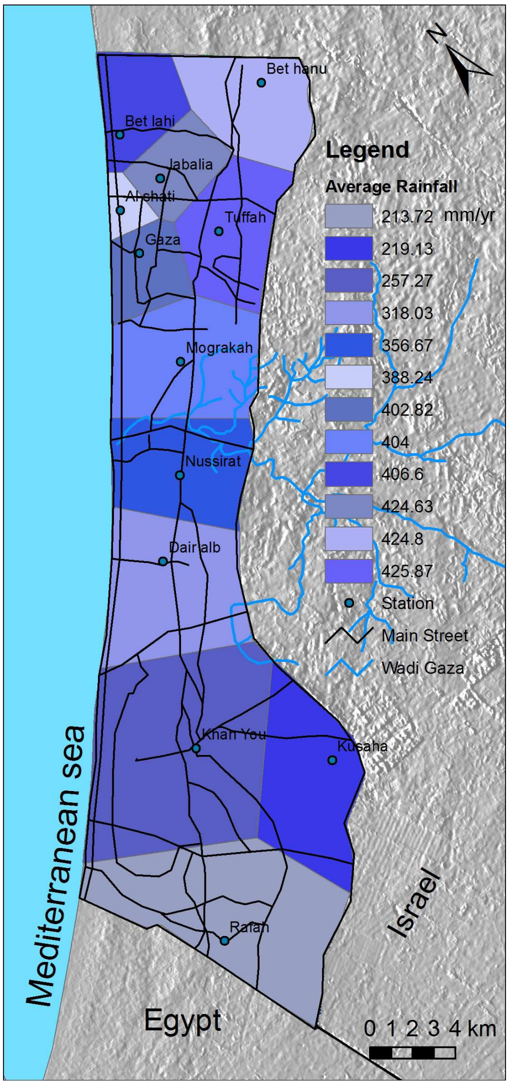


Figure (4.1) Regional average rainfall in Gaza Strip for the past 12 years.

Date Year	B. Hanon	B. Lahia	Jabalia	Shati	Remal	Tuffah	Moghragah	Nussirate	Dr-Elbalah	Khan Younis	Khuzaa	Rafah
1999/2000	406.4	390.5	388.5	425.1	334.8	357.2	368.3	278.5	256.7	191.8	142.2	198.5
2000/2001	497.5	490.4	540	478.9	511.9	533.4	563.6	558.3	550.5	381	284.3	308
2001/2002	548.4	542	565.5	522.1	544.4	604.3	660.5	545.5	390.6	311.7	258.5	241.7
2002/2003	801.5	724	692.6	627	599	653.5	790.7	446.2	372.6	298	261.2	220.8
2003/2004	349.4	393.1	366.4	324.5	378.2	429.6	466.1	316.5	316.4	207	186	173.5
2004/2005	358.7	320.6	345.5	296.6	310.7	350.7	323.6	405.0	345.5	373.0	368.0	360.2
2005/2006	368.90	363.80	345.40	317.20	322.40	363.50	274.40	295.00	257.00	270.50	214.00	203.00
2006/2007	509.90	530.30	536.70	469.00	501.20	545.50	388.20	403.00	418.00	252.00	255.80	225.00
2007/2008	253.20	322.10	295.40	286.50	336.50	370.00	243.75	249.50	235.50	159.30	151.00	205.30
2008/2009	347.00	332.50	437.20	398.80	414.60	378.60	262.50	305.00	269.50	271.80	207.80	174.90
2009/2010	270.9	246	298.9	243.95	272.3	242.4	197.05	217	169.5	186.1	161	141.7
2010/2011	234.3	243.9	277	254.25	297.3	285.5	274	255	234	187.6	142	113.5
Total for 12 years (mm)	4946.10	4899.20	5089.10	4643.90	4823.30	5114.20	4812.65	4274.50	3815.80	3089.80	2631.80	2566.10
Annual Average (mm/y)	412.2	408.3	424.1	387.0	401.9	426.2	401.1	356.2	318.0	257.5	219.3	213.8
Area of each station (Km2)	27.36	15.35	14.11	2.98	12.50	25.50	34.40	28.93	38.40	86.70	43.40	35.00
Rainfall * Area	10250.9	5696.6	5439.4	1048.3	4567.1	9878.7	12540.8	9367.3	11099.4	20292.3	8652.2	6803.4
Rainfall average (mm/year)	289.71											

Table (4.1) Annual average rainfall in Gaza strip

4.2 Groundwater table

4.2.1Ground Water level history

The Gaza coastal aquifer is a sandy shallow unconfined aquifer where water table is free to fluctuate in response to infiltration and pumping. Over-pumping with insufficient recharging is the principal cause of ground water level decline in the Gaza aquifer. Figure (4.2) shows the ground water level of Gaze strip in 1935, when the aquifer was not yet overexploited (Qahaman and Zhou, 2001). The ground water level ranged between 10 m to 2 m above mean sea level and the ground water flow was directed toward the sea. Figure (4.3) represents the ground water level in 1969, when the aquifer began to be overexploited. Groundwater level dropped in all the aquifers by several meters and the water level gradient was steeper.

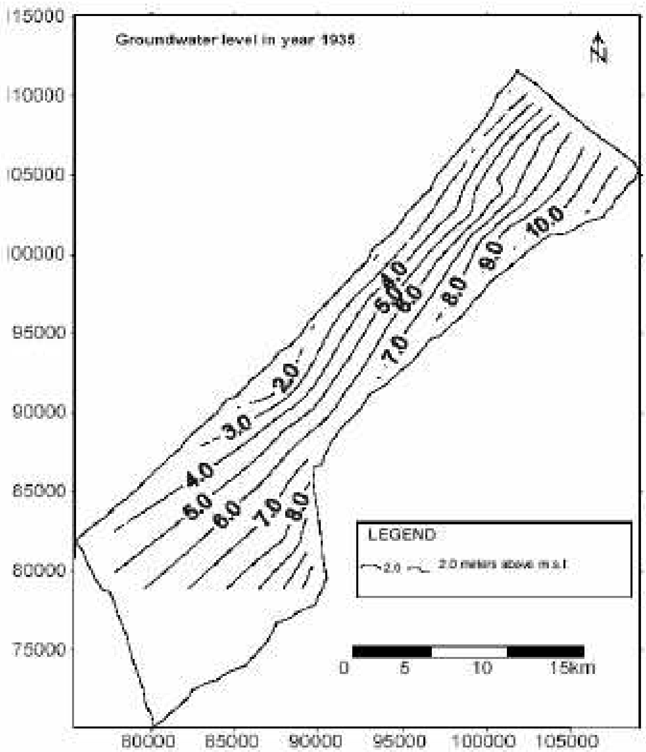


Figure (4.2) Ground water levels in1935 (Qahman and Zhou, 2001).

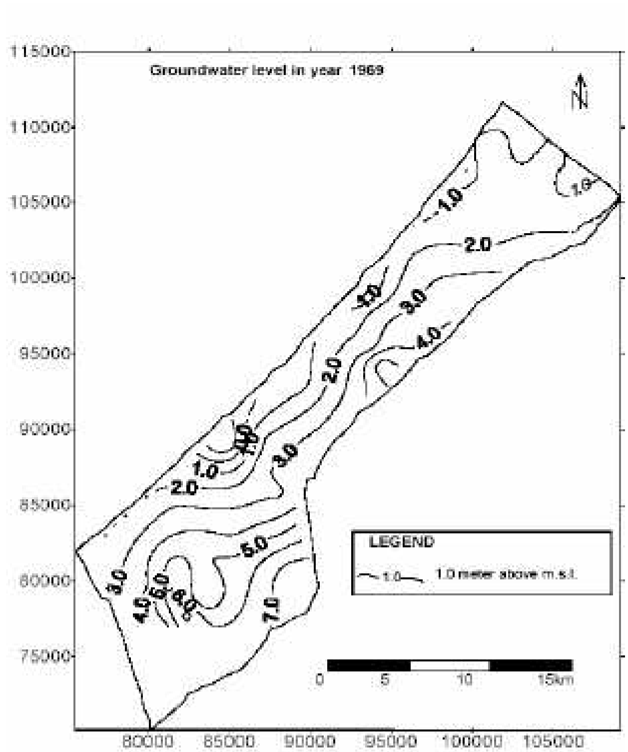


Figure (4.3) Ground water level in 1969 (Qahman and Zhou, 2001).

Since 1975, groundwater level continued to decline in most areas of Gaza aquifer (Qahman and Zhou, 2001). Lowering of regional water level means loss in storage and reduction in the fresh groundwater availability. Reduction in Gaza aquifer storage is documented in many areas of the Gaza Strip by recording of water levels on a regional scale and through the time. Records indicate decreasing in groundwater level by 1.6 m/yr on average between 1970 and 1993. This is equivalent to an average 5 x 10^6 m^3/yr decline in overall aquifer storage (assuming a specific yield of 0.2) (Moe et al, 2001).

In view of this, studying the spatio-temporal variation of groundwater level distribution in Gaza aquifer over the years is an essential step to understand the historical aquifer behavior and determine areas of depression. Several piezometric maps were computed using kriging technique in GIS. Interpolation process of groundwater table was performed using 95 water level measurements from agricultural, agri-domestic and monitoring wells, shown in figure (4.4).

Figure (4.4) Distribution of wells used in the groundwater level interpolation.

4.2.2 Methodology

The spatio-temporal analysis of the groundwater level was carried out using kriging technique in GIS environment. Kriging is a quick local interpolation method which takes in consideration the spatial structure of the interpolated parameter and also provides a variance value at every point as an accuracy indicator of the estimated value. This make the kriging method preferable than deterministic methods like distance weighted method, nearest neighbour method, arithmetic mean method and polynomial interpolation (Kumar and Remadevi, 2006).

The general formula for interpolator is a weighted mean of the data (Isaaks and Srivastava, 1989):

$$Z(s_o) = \sum_{i=1}^{n} \lambda_i Z(s_i)$$

Where:

Z (si) = the measured value at the i^{th} location.

λi = an unknown weight for the measured value at the i^{th} location.

so = the prediction location.

n = the number of measured values used for local interpolation.

Interpolation method is based on the regionalized variable theory, which assumes that the spatial variation in the study parameter is distributed homogeneously throughout the surface. In other words, the same pattern of variation can be found at all locations on the surface. This hypothesis of spatial homogeneity is fundamental to the regionalized variable theory (Salha et al., 2010). In case of data sets with notable changes, the data can be pre-stratified into regions of uniform surface behavior other wises the data set is not appropriate for the Kriging technique (Oliver, 1990).

Kriging methods include Ordinary kriging, Universal kriging, Indicator Kriging, co-kriging and others. The choice of which kriging type to use depends on the characteristics of the data and the type of spatial model desired (Lefohn et al., 2005).

4.2.3 Results

Initially, groundwater data was explored using Exploratory Spatial Data Analysis (ESDA) tool in ArcGIS software to study the data distribution, global and local outliers and to discover data trends. This tool allows to examine the data in different ways, and gives a deep understanding of the investigated phenomena. Data explorations shown no trend, so, the Ordinary kriging was selected for this analysis as a suitable method to interpolate the data set and create the continues surface of groundwater level. Figure (4.5) displays an example of the application of the EDSA tool on the groundwater level data of 2009.

An example of the experimental semivariogram and covariance for the best-fitting model for the 2009 dataset are shown in figures (4.6) and (4.7). For all year groundwater level data, spherical model resulted in the minimum standard error and was considered the best-fitting model.

Before producing the final interpolated surface the semivariograms of best fitted theoretical models was validated using the cross validation plot as shown in figure (4.8) for the same example year (2009).

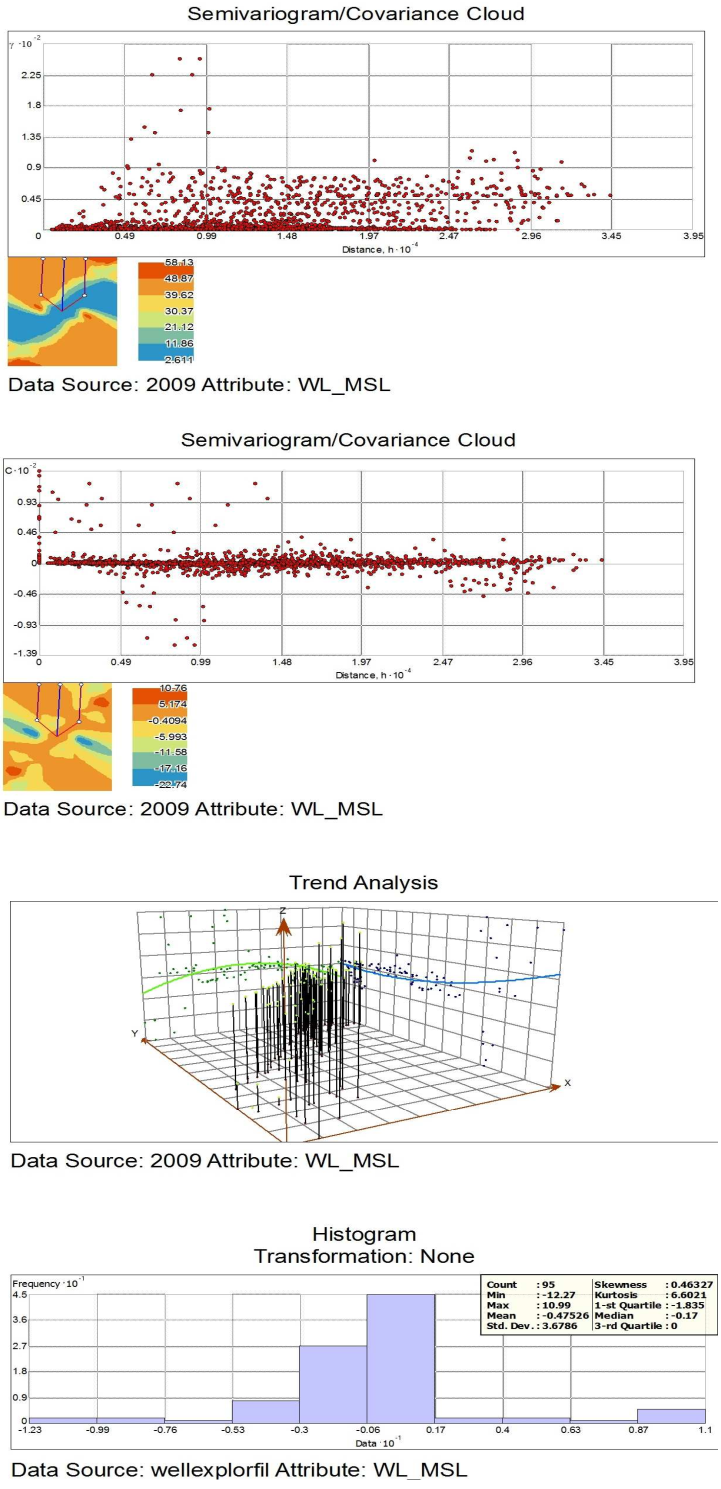


Figure (4.5) An example of the EDSA used to explore the measurements data of groundwater level.

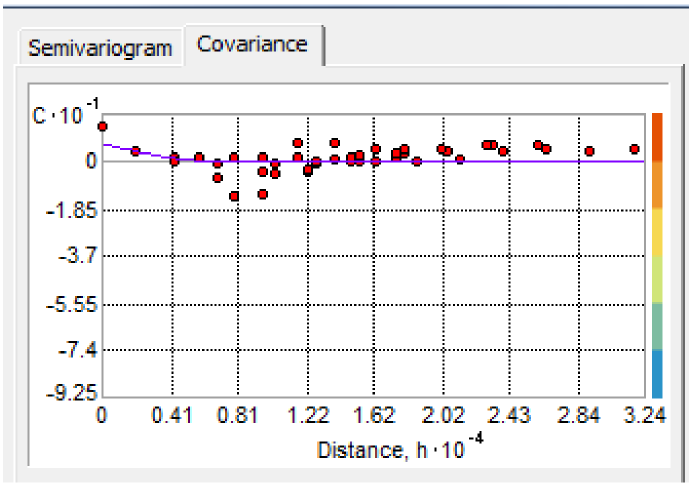


Figure (4.6) The experimental semivariogram for the best-fitted theoretical model for 2009.

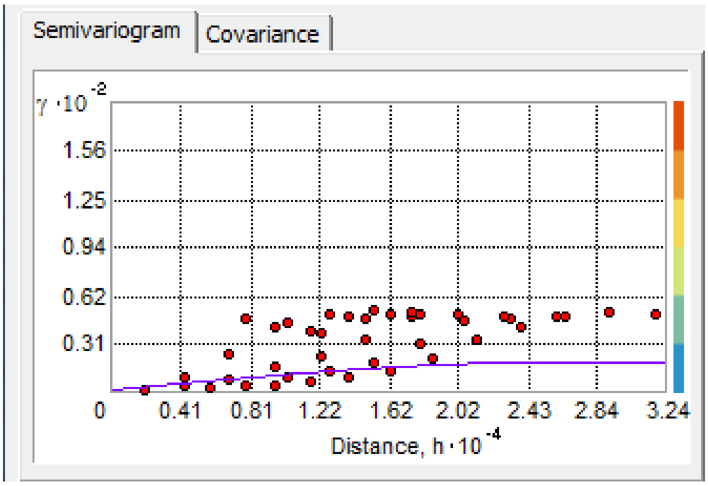


Figure (4.7) The experimental covariance for the best-fitted theoretical model for 2009.

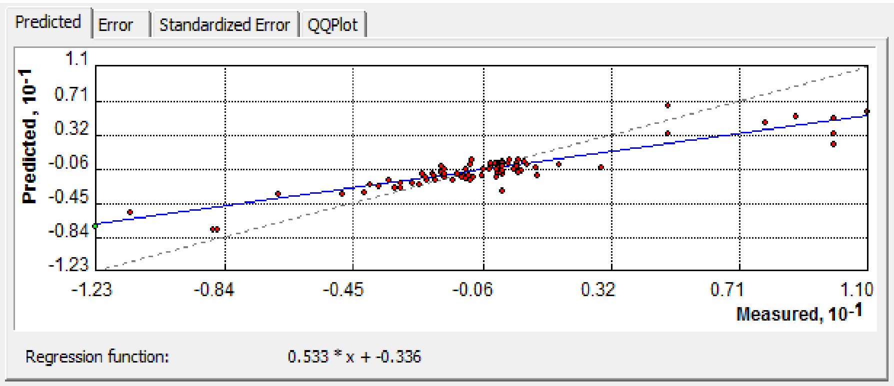


Figure (4.8) Validation plot error of the modelled semivariogram and covariance.

The interpolated surfaces of ground water level are shown in Figure (4.9) for year 2000 (a), 2001 (b), 2002 (c), 2003 (d), 2004 (e), 2005 (f), 2007 (j), 2008 (h) and 2009 (g) with a resolution of 110x110 m. The interpolated maps show a lowering trend in groundwater level over the measurement time period between years 2000 and 2009. The trend is especially evident in two sensitive zones, to the north and to the south. Here, the groundwater level has been lowered below sea level by 5 m in the north and 12 m in the south, respectively. The interpolated maps indicate a lowering by 4m in the north and by 8 m in the south from 2000 to 2009, while the central zone, corresponding to wadi Gaza basin, decreased only by 1 m for the same period. The interpolated maps allow to delineates the ground water flow direction, which is in undisturbed condition towards the sea, However, due to the deep depression zones to the north and the south, the groundwater direction has been converted from the sea toward the inland.

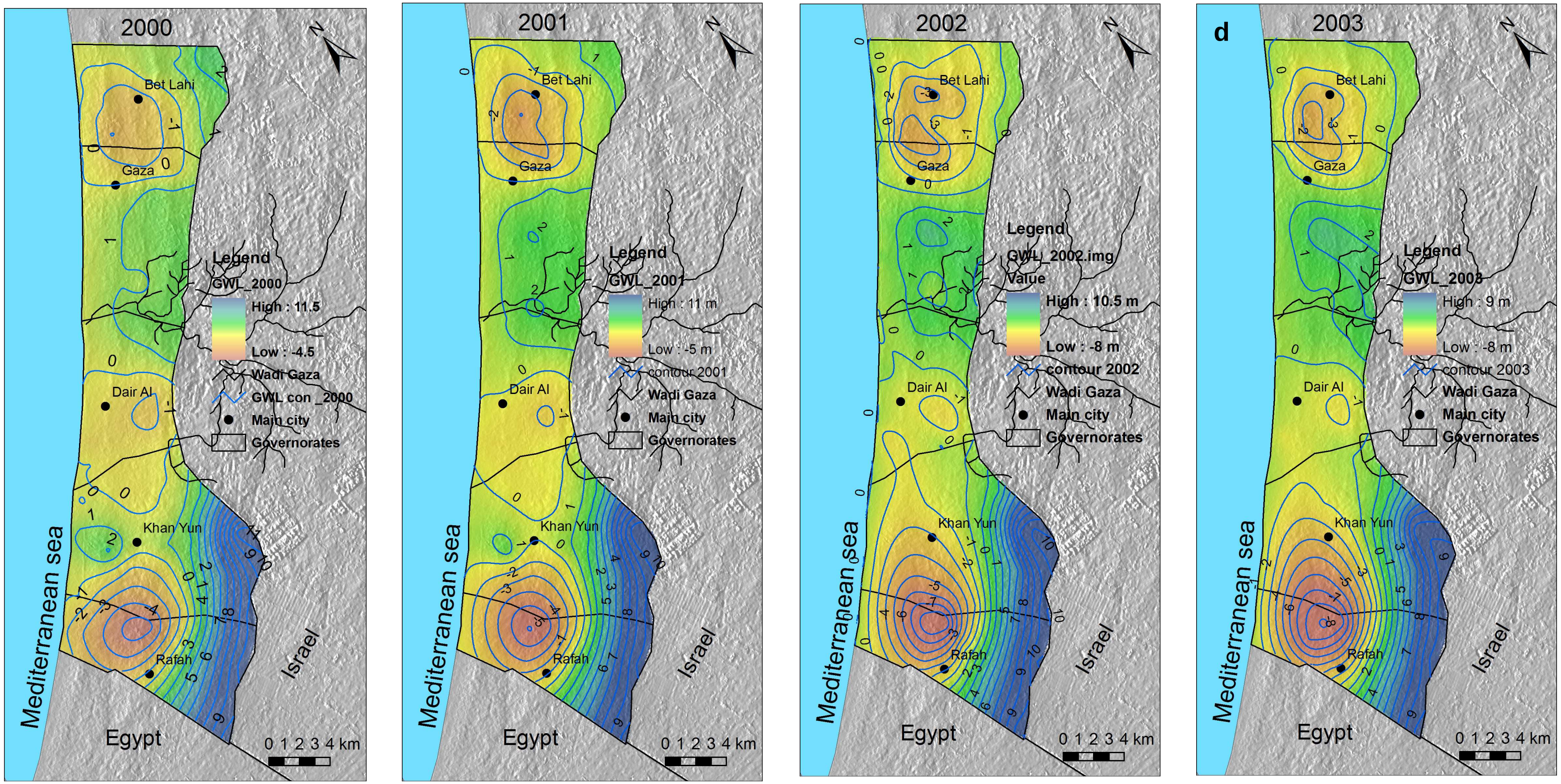


Figure (4.9) Interpolated Groundwater levels for years 2000 (a), 2001 (b), 2002(c), 2003 (d), 2004 (e), 2005(f), 2007(j), 2008 (h) and 2009(g).

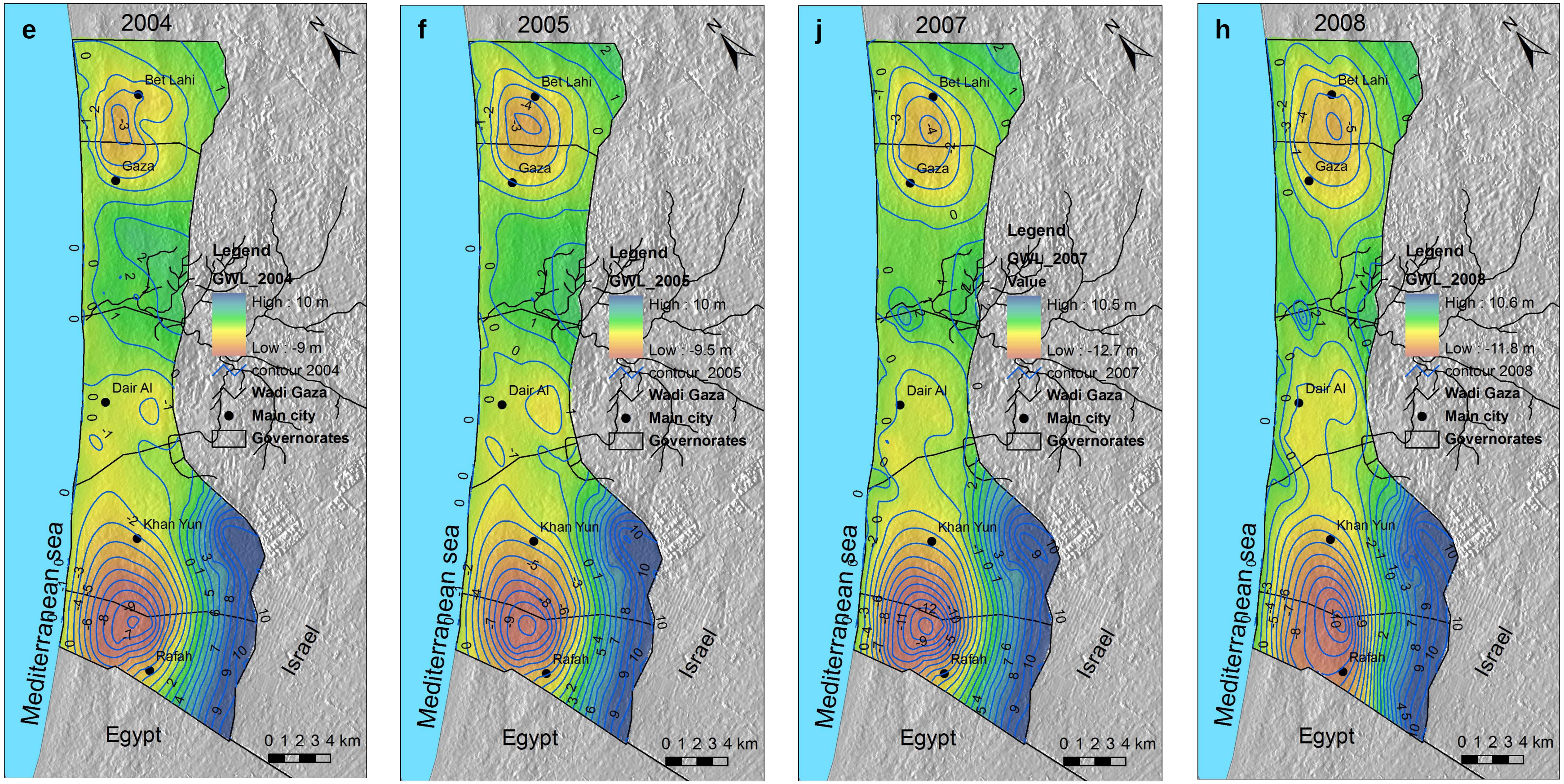


Figure (4.9) Interpolated Groundwater levels for years 2000 (a), 2001 (b), 2002(c), 2003 (d), 2004 (e), 2005(f), 2007(j), 2008 (h) and 2009(g).

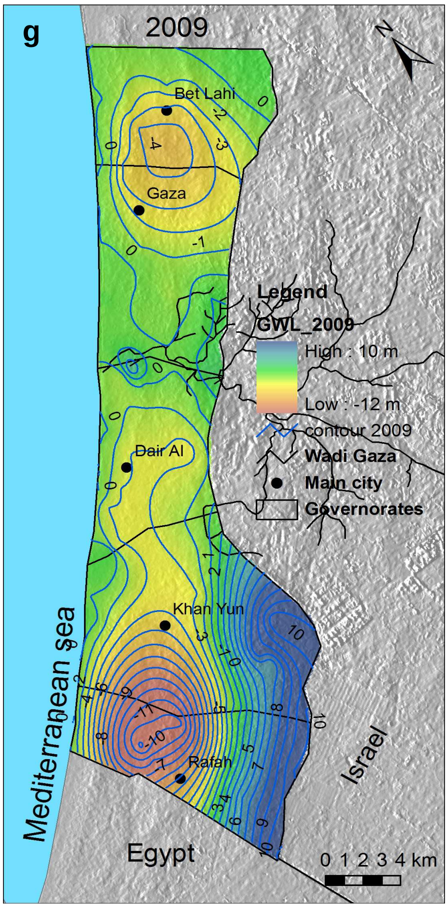


Figure (4.9) Interpolated Groundwater levels for years 2000 (a), 2001 (b), 2002(c), 2003 (d), 2004 (e), 2005(f), 2007(j), 2008 (h) and 2009(g).

4.2.4 Seasonal variation

Well monthly records reflect seasonal and annual water level fluctuations. Figure (4.10) depicts the seasonal average variation of ground water table in Gaza coastal aquifer for January and August during five years between 2000 to 2005, Water level was within 0.14 m above sea level for January 2000 and tend to decline under sea level until January 2005 while the average of levels remain under the sea level in August for all the period. Figure (4.11) shows the monthly ground water levels fluctuation for some wells at different locations from January to December for the year 2000. Water level was low during the summer and autumn months, but return to rise during the winter in response to rainfall events. After the initial winter rises, water level fluctuates but remained high until at least mid-May. Levels decrease in all wells from Jun to late September or early October before come back to rise again by July.

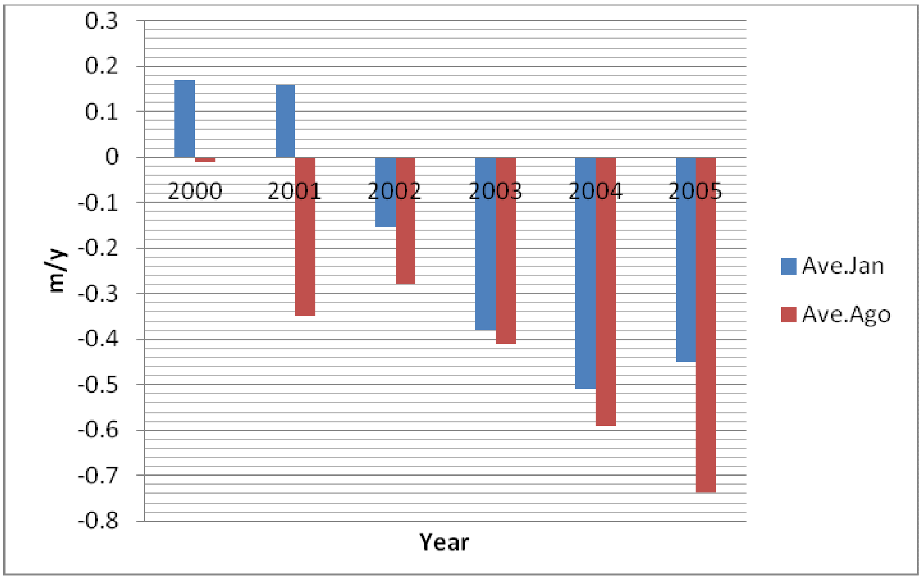
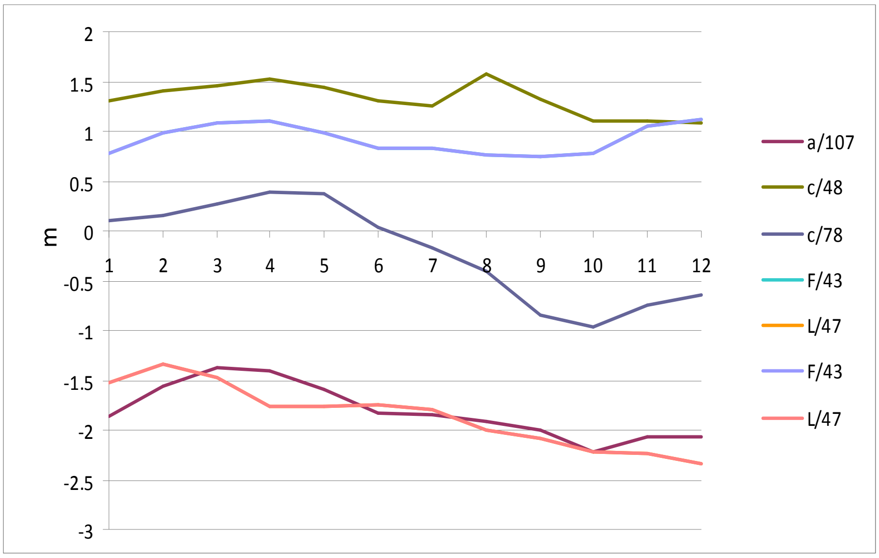


Figure (4.10) Average seasonal variation in January and August for the period between 2000 to 2005.



Figure(4.11) Seasonal fluctuation for many wells during 2000 months.

4.3 Groundwater quality

Ground water quality is well documented in many parts of Gaza Strip by PWA, PoA and CMWU. Most recent published reports about Gaza ground water quality indicate a noticeable chemical and biological deterioration. Several contaminants are present in the groundwater, and many chemical elements like chloride, nitrate, sulfate, and fluoride show concentrations exceeding the maximum contaminant levels adopted by the PWA and WHO for drinking water standards. In most of the wells in the Gaza Strip the major water quality problem is presented by high levels of chloride and nitrate concentration (Qahman and Zhou, 2001), (e.g. Abu Maila, El-Nahal and Al-Agha 2004, Shomar 2006, Issam Al-Khatib , Arafat 2009, Shomar, Al-khatib . Abu-dia 2009, Mogheir and Seyam 2009, Abu Fakher, Yahya 2010, annual PWA reports). The chloride Cl and nitrate NO3 concentration is extremely high than the Palestinian drinking water standard and world health organization drinking standards which are 250 mg/l as a maximum concentration for the chloride and 50 mg /l as a maximum concentration for the nitrate.

Figure (4.12) shows the annual average of Nitrate concentration in municipal wells in the period from 1990 to 2008. The average concentration nitrate range from 110 to 200 mg/l and it exceeds the 50 mg/l in all years. Figure (4.13) shows the interpolated map of nitrate concentration for the year 2008. The zones affected by the high concentrations of nitrate are the North, Khan yuonis and the South. These zones are subjected to concentrate agricultural activities and partially are connected with sewage network.

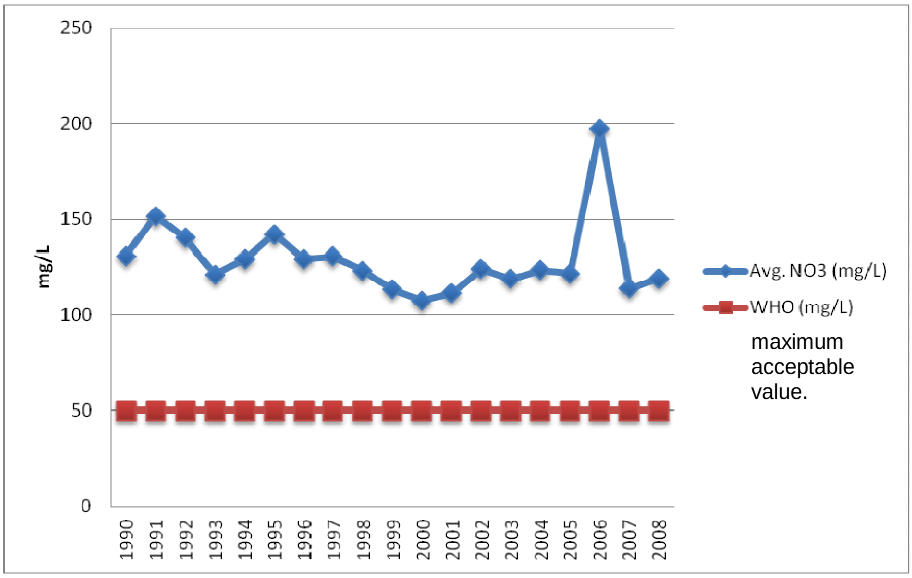


Figure (4.12) Average nitrate concentration in municipal wells in the 1990- 2008 period.

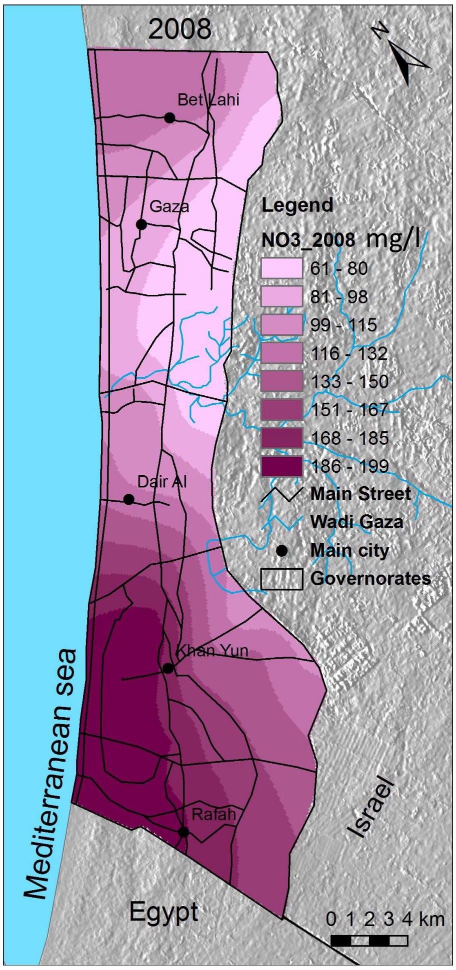


Figure (4.13) Interpolated map of NO3 concentration for the year 2008.

The annual average of Cl in municipal wells for the 1970 - 2008 period are shown in figure (4.14). The average chloride ion concentration ranges from less than 200 mg/l to more than 600 mg/l all over the period. Figure (4.15) presents the interpolated map of the chloride concentration records for the year 2008. In the north the chloride concentration is within the Palestinian drinking water standard (300 mg/l), while the other regions suffer from a high chloride concentration. In particular, the chloride concentration is high because of the sea water intrusion in the western part of the Strip and lateral inflow of brackish water from the east.

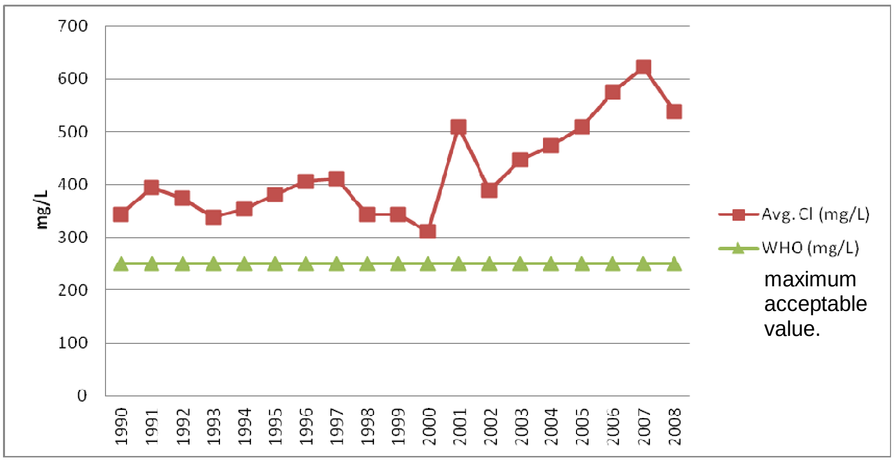


Figure (4.14) Average chloride concentration in municipal wells for the 1990 - 2008 period .

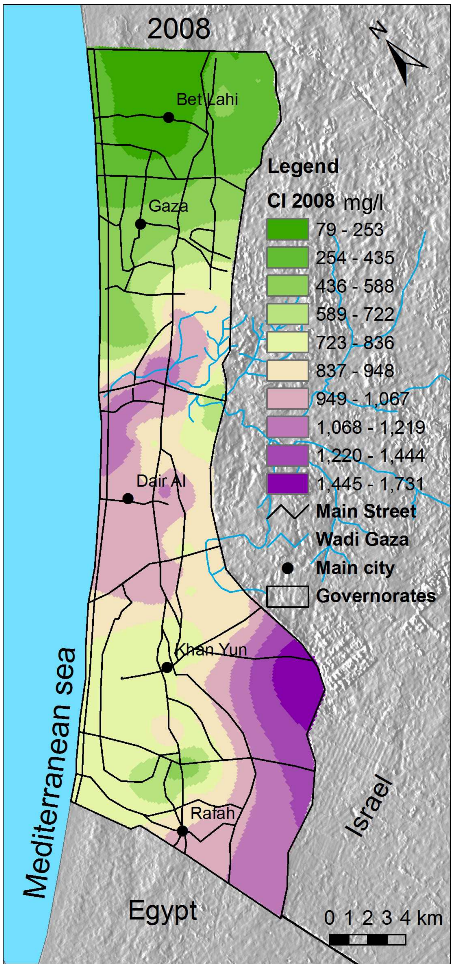


Figure (4.15) Spatial distribution of chloride concentration in 2008.

4.4 Geochemical analysis

The extensive use of ground water from the Gaza coastal aquifer during the past decades resulted in widespread seawater intrusion and deterioration of water quality along most of the aquifer. Extensive use of ground water leads to activates the sea water intrusion processes and existing point and non point source of contamination inside and outside the Gaza strip. The two main sources of salinity in Gaza strip are the sea water intrusion and the brackish water from the east due to the hydraulic connection with the underlying Eocene chalk and marl of Hashepela Group that has a relatively high TDS

(Rosenthal et al., 1992; Vengosh & Rosenthal, 1994). High values of TDS, Cl and electric conductivity (EC) were found in many municipal and agricultural wells at different places in the Gaza Strip. Figures (4.16) (4.17) (4.18) show the trend of the TDS, Cl, EC in different wells from 1987 to 2008. Figures show a progressive increase in concentrations in all wells with a notable oscillations from year to year. Plotted data can be distinguished clearly in two groups, the northern group (North and Gaza) and the southern group (Khan younis and Rafah) with two different types of water quality. Wells in the northern region demonstrate a good water quality with respect to the southern region for all years. This is mainly because the rainfall are 50% larger in the north than in the south.

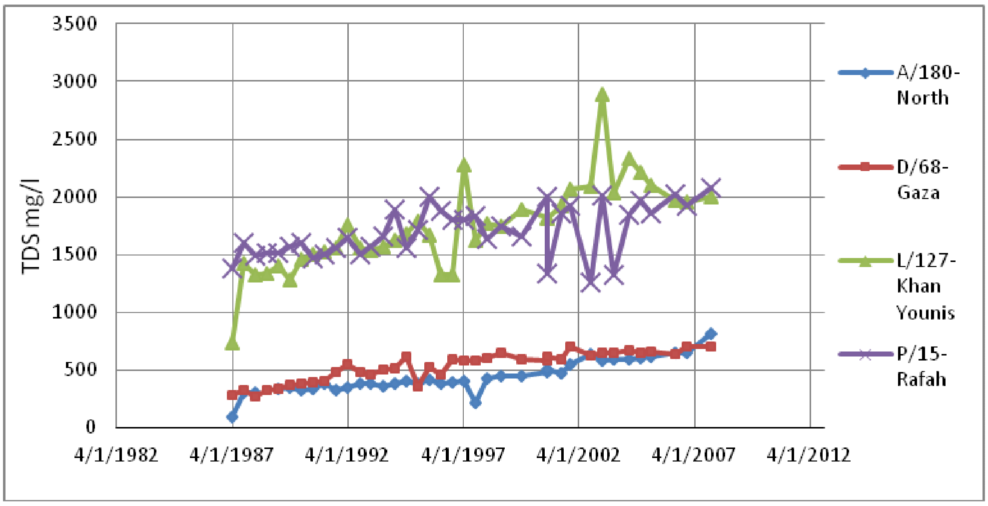


Figure (4.16) Trends of TDS in different Wells from 1987 to 2008.

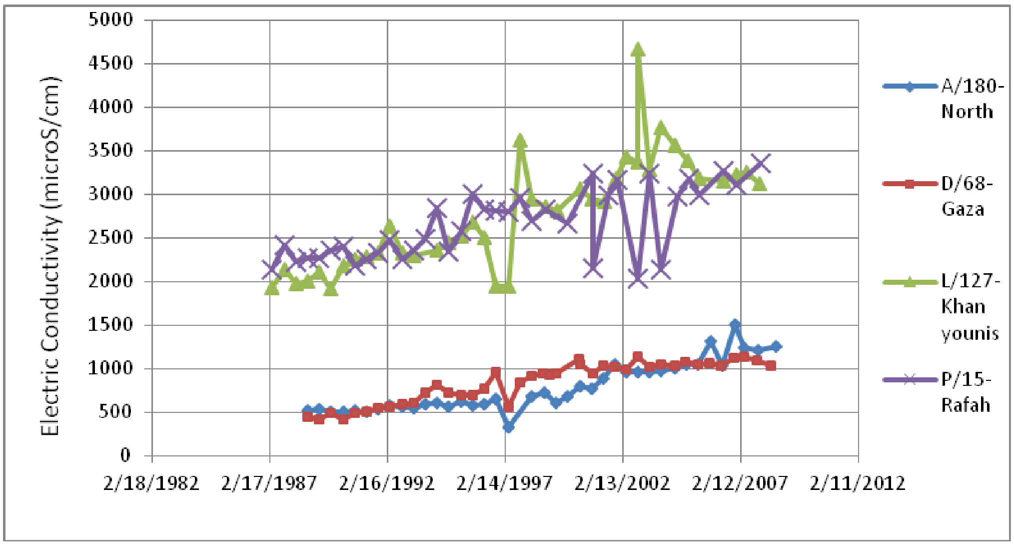


Figure (4.17) Trends of EC in different Wells from 1987 to 2008.

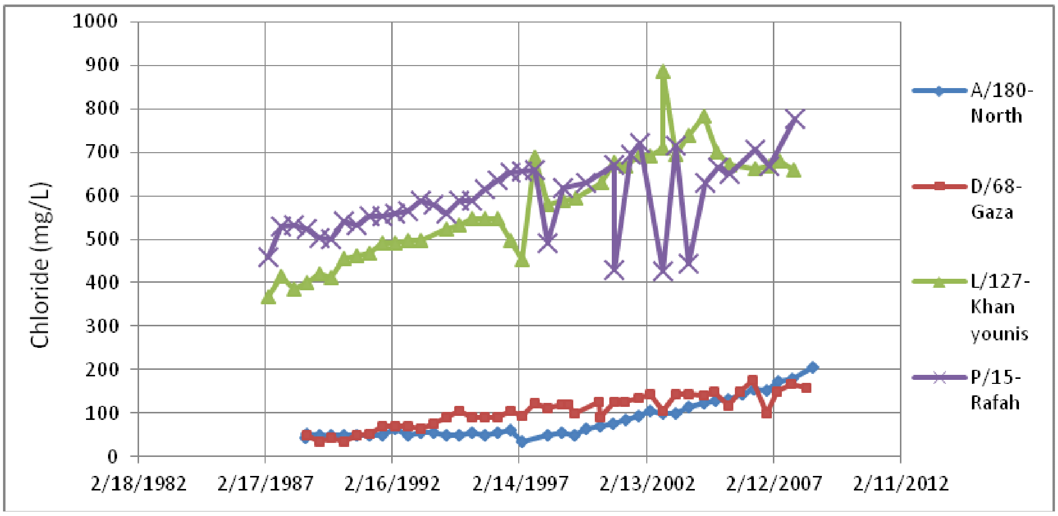


Figure (4.18) Trends of Cl in different Wells from 1987 to 2008.

Generally, increasing Cl and TDS concentrations in groundwater, are used as indicator of seawater intrusion in coastal aquifers. However, there are other potential sources of high-chloride water in coastal areas (Piper, 1953; Martin, 1984, Izbicki, 1991; Rosenthal, 1992; Hanson et al, 2002). Other major ions, and cations, often give a clear chemical index that can be used to identify and distinguish between different sources of high-chloride concentration and to evaluate the geochemical processes affecting water quality within the aquifer systems (Land et al., 2004).

4.4.1 Sources of salinity and Chemical Faces

In order to identify the salinization sources and to classify the chemical facies in Gaza aquifer, the diagnostic chemical properties of groundwater are presented by Piper (1944) diagrams. This diagram allows to screen and sort large numbers of chemical data making interpretation easier. The diagram classifies the groundwater facies in an aquifer based on the major-ion percentages as shown in figure (4.19). Furthermore, Piper diagram can be used to study the patterns of spatiotemporal changes in the Groundwater chemistry among geological units, along a line of geological section or along a path line (Raji & Alagbe, 1997; Domenico & Schwartz, 1998).

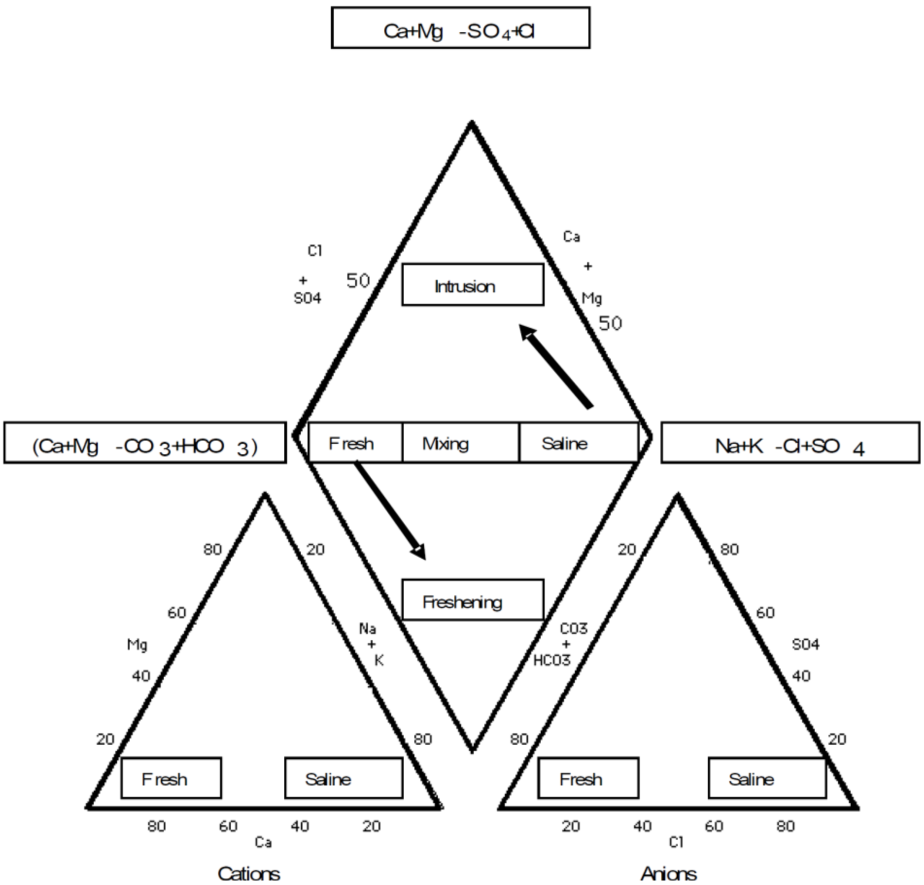


Figure (4.19) Piper plots showing the location of the identified hydrochemical facies in relation to freshwater and seawater (after Appelo & Postma, 1993); source (Agha and Nakhal, 2004).

The data of 168 wells were plotted using Piper diagram for the year 2010 in order to identify and classify the geochemical of ground water facies. The investigated wells were selected to represent the whole Gaza Strip in view of their geographical location. Table (4.2) shows the number of investigated wells in each governorate. The Piper diagrams, are presented in figure (4.20). This diagram shows that most of the ground water is classified as (Na^{+} K^{+} - Cl^{-} So_4) faices, a dominant water type that prevails in sea water, and Ca-Mg-HCO3 facies that range from fresh to mixed water.

Governorate	Well Number
North	37
Gaza	31
Middle	37
Khan Younis	42
Rafah	21

Table (4.2) Number of investigated wells in each governorate.

The investigated wells were classified on the basis of the governorates as shown in the diagram. All most investigated wells in the northern governorate are found in the fresh to mixed water zone of the diagram, characterized by Ca-Mg-HCO3 facies (alkaline water). Generally, it is known that the northern region has a better quality than the other regions in the strip (Agha and Nakhal, 2004). The geologic and climatic factors have a positive effect on the water quality in the north. This is due to the higher rainfall with respect to the south and the presence of sand dunes that increase the infiltration of rainwater to the aquifer during the rainfall periods.

The Gaza region wells dominate the right hand of the diagram that indicates Na-Cl-SO4 faices (saline water). In the Gaza region, the sand dunes become narrower going towards the wadi Gaza. The large built up area in the region, causes decrease of infiltration to the aquifer. Furthermore, the pumping rates are higher than in other regions due to population density. These regional characteristics, contribute to the salinity increase in the aquifer.

In the middle and Khan younis regions the ground water is characterized by Na-Cl-SO_4 and Ca-Mg-HCO3 facies. In these regions the water quality is controlled by decreasing rainfall and the proximity of the seawater to the west. These factors contributed to characterize the saline water in these regions while the other facies of water seems related to the presence of sand dunes in these regions.

Rafah region is dominated by Na-Cl-SO_4 facies as wells in this region have the highest percent of anions and cations. Pumping from these wells exceeds the aquifer replenishment from the rainfall. This resulted in saline water to be observed from different sources, seawater from the west and brackish water from the east.

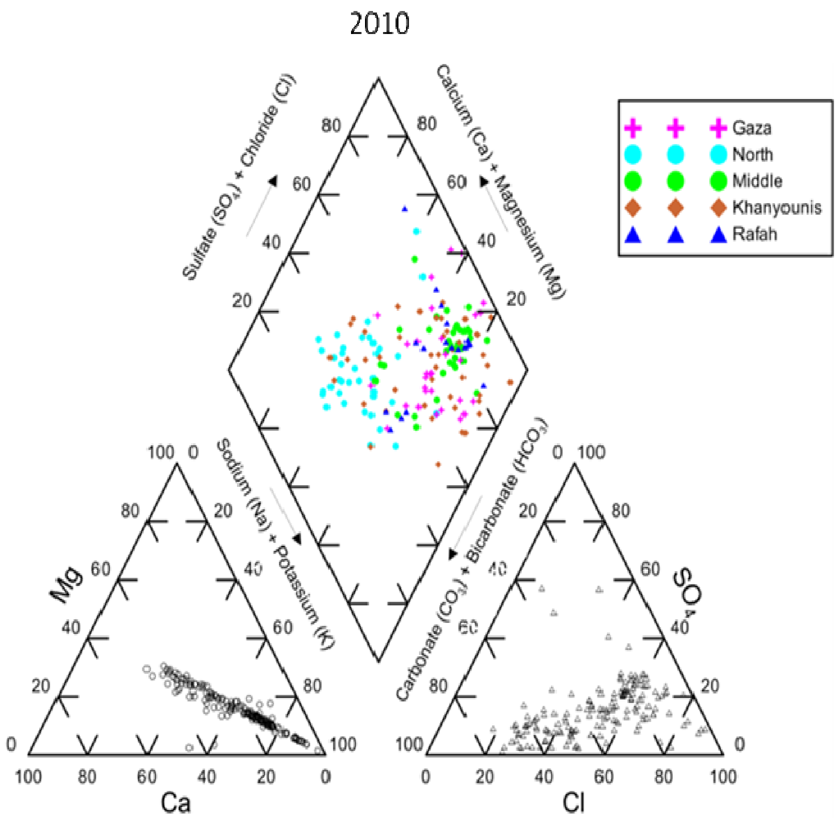


Figure (4.20) Piper diagram for the investigated wells of the Gaza Strip.

4.4.2 Salinizatin Process

In order to understand the process of salinization in the Gaza aquifer during the past years, a group of old wells was selected from all governorates. Selected wells are presented in figure (4.21). Hydrochemical data of wells related to the year 1987 and 2010 are given in table (4.3).The hydrochemical data plotted as piper diagram for both years separately as shown in figures (4.22) and (4.23).

1987									
Name	ID	Na + K	Ca	Mg	HCO3+CO3	Cl	SO4	SO4 + Cl	K
E/154	A	28.94	40.84	30.23	66.64	25.51	7.84	33.36	12.26
R/162B	B	49.67	46.47	3.86	59.92	31.82	8.26	40.08	29.63
R/162C	C	37.28	38.29	24.43	61.22	31.29	7.48	38.78	17.90
R/162L	D	51.62	29.10	19.28	47.02	43.26	9.72	52.98	25.13
R/25B	E	65.81	17.77	16.42	40.67	44.84	14.49	59.33	36.15
R/25D	F	86.09	6.38	7.53	33.01	53.52	13.47	66.99	52.60
J/32	G	81.39	9.09	9.52	11.37	63.15	25.47	88.63	37.08
L/41	H	86.51	7.44	6.05	22.46	56.15	21.38	77.54	47.74
L/43	I	63.17	22.58	14.25	25.06	58.31	16.63	74.94	25.70
P/124	J	68.03	16.27	15.70	29.04	57.89	13.07	70.96	32.56
P/15	K	77.41	15.06	7.53	19.79	62.49	17.72	80.21	37.31
2010									
Name	ID	Na + K	Ca	Mg	HCO3+CO3	Cl	SO4	SO4 + Cl	K
E/154	A	58.33	28.29	13.39	1.64	89.31	9.05	98.36	9.15
R/162 B	B	52.05	32.78	15.17	16.20	80.91	2.90	83.80	10.15
R/162 C	C	70.07	16.36	13.57	24.63	66.82	8.55	75.37	32.38
R/162L	D	66.10	18.75	15.15	23.23	66.59	10.18	76.77	27.71
R/25 B	E	67.18	17.85	14.97	35.42	45.85	18.72	64.58	34.90
R/25 D	F	86.34	7.54	6.12	30.50	53.94	15.56	69.50	51.59
J/32	G	74.26	14.26	11.48	17.90	57.90	24.19	82.10	33.21
L/41	H	87.17	7.06	5.77	20.87	56.14	22.99	79.13	47.60
L/43	I	65.21	20.67	14.12	29.64	54.80	15.56	70.36	30.03
P/124	J	61.47	22.87	15.66	30.95	56.92	12.13	69.05	26.94
P/15	K	71.05	16.49	12.47	21.21	56.95	21.83	78.79	31.65

Table (4.3) Hydrochemical data wells used for the year 1987 and 2010,data are in %.

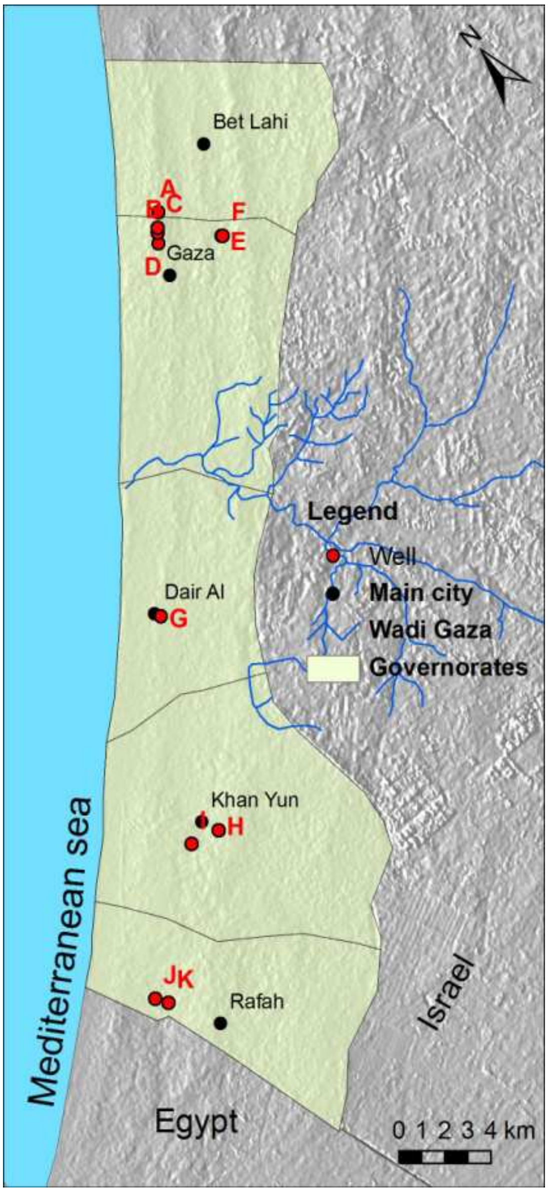


Figure (4.21) Location of selected wells plotted as Piper diagram.

Figure (4.22) shows the wells data for the year 1987 indicating a fresh to salted ground water quality characterized by Na-Cl-SO4 and Ca-Mg-HCO3 facies. Figure (4.23) shows the plot of the same wells for the year 2010, the figure indicates ongoing salinization process in the aquifer. Wells are characterized by Na-Cl-SO4 facies moving toward Ca+ Mg-SO4+Cl facies. Comparing the tow figures (4.22, 4.23) wells can be divided into two categories, one with a drastic change in the water quality from 1987 to 2010 and another with no significant changes. The groundwater in wells A,B,C and

D located in the Gaza region are extremely enriched in Cl and Na from 1987 to 2010. This indicates a high probability of sea water upconing occurrence as these wells were active before 1987 and placed near the shoreline. The other wells (E, F, G, H, I, J, K) plot on the Piper diagram in the same position with only slight changes. The groundwater in these wells is classified as Na-Cl-SO4 facies both investigated years. This indicates that the water quality in these wells is originally poor and the salinization process occurred already before 1987. Salinity in these wells is close to brackish water. The probable source of salinity in these wells is the brackish water flowing from the eastern sectors since the plotted wells have a quasi constant concentration.

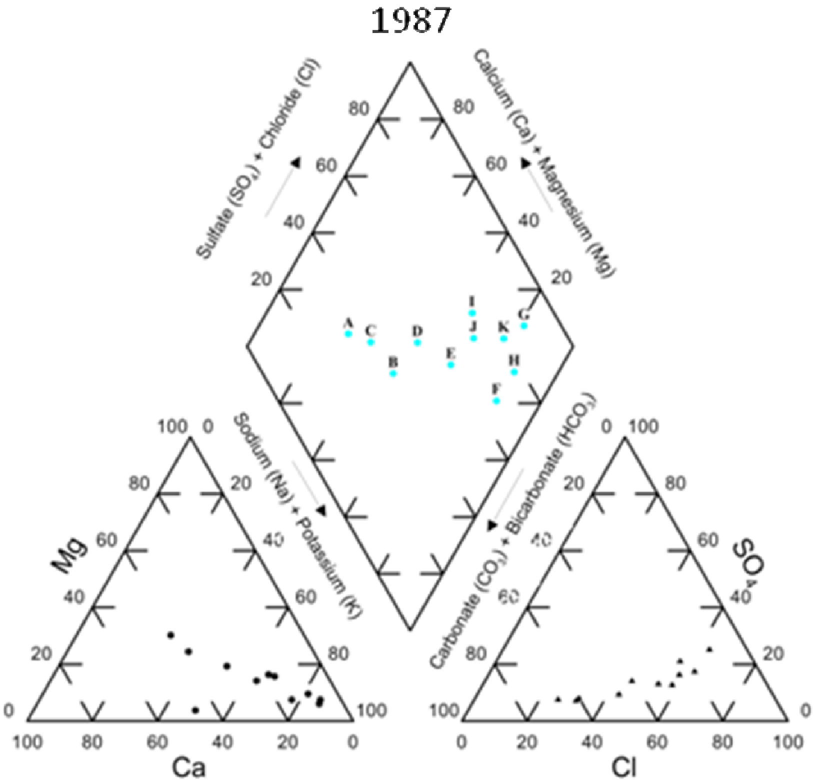


Figure (4.22) Piper diagram for the investigated wells in the year 1987.

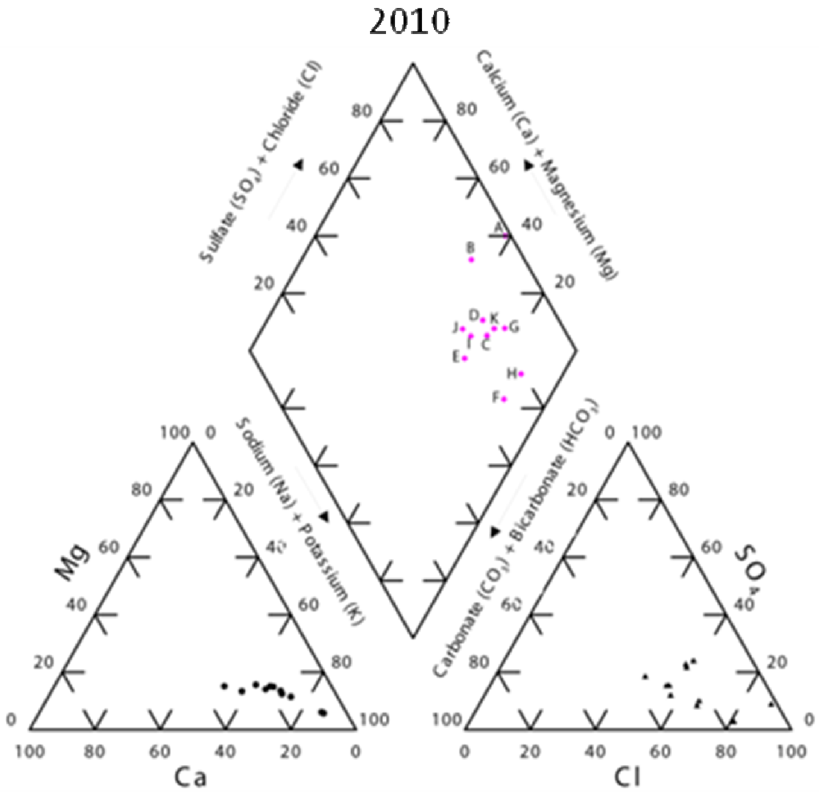


Figure (4.23) Piper diagram for the investigated wells in the year 2010.

4.4.3 Discussion

Generally, the ground water in Gaza aquifer is poor due to the high concentration of anions and cations from north to south. The occurrence of salinization process at different places in the aquifer is related to the presence of the seawater in the west side and the hydraulic connection with brackish aquifer in the eastern margin. The climate and the geology play an important role in the salinization process of the aquifer. Although the aquifer is hydraulically connected with the eastern brackish aquifer along the eastern boundary from north to south, the most saline water is found in the south, where the annual rainfall is lower by 50 % than that in the north (200 and 400 mm, respectively). In addition the aquifer in the north has an open system that allows good mixing between brackish groundwater flowing from the east and the infiltrating rainwater, this makes the brackish water more dilute resulting in relatively good quality (Agha and Nakhal, 2004). The other parts of the aquifer

(Middle and Khan youns and South) are semi confined and confined which makes the natural recharge more controlled by the geological stratigraphy.

Piper diagram in figure (4.20), shows a clear trend for cations where is the wells are with data aligned from salt water to fresh water. Furthermore, most of the plotted wells are concentrated in the saline water zone in the diagram of the anions, this distribution making the aquifer characterized by sodium chloride facies, except for the northern part where water mixing results by calcium carbonate facies and low chloride content.

4.5 Water Budget Components of Gaza aquifer

Water budget represents the accounting balance between incoming and going water in a well defined area. Identification of the net groundwater recharge and discharge is essential for groundwater resources management. this is an helpful tool for groundwater modeling as it represents the quantitative status of water resources even if sometimes only an approximately estimate is possible. In arid and semiarid regions like Gaza Strip, estimation of water balance components is essential for an efficient water resources management and territorial planning.

The groundwater system in the Gaza Strip area is represented by a coastal sandy shallow aquifer which divided into three subaquifers by impervious and semi pervious clayey layers. There is no simple method that can be applied to estimate the water budget components in the Gaza Strip. This is primarily a function of the extreme variability observed between numerous influencing factors such as distributed land-use, soil texture, slope, groundwater level and rainfall. The main balance components of the Gaza aquifer are rainfall, lateral groundwater inflow, lateral groundwater outflow, pumping wells, and leakage of pipes infrastructure as shown in figure (4.25).

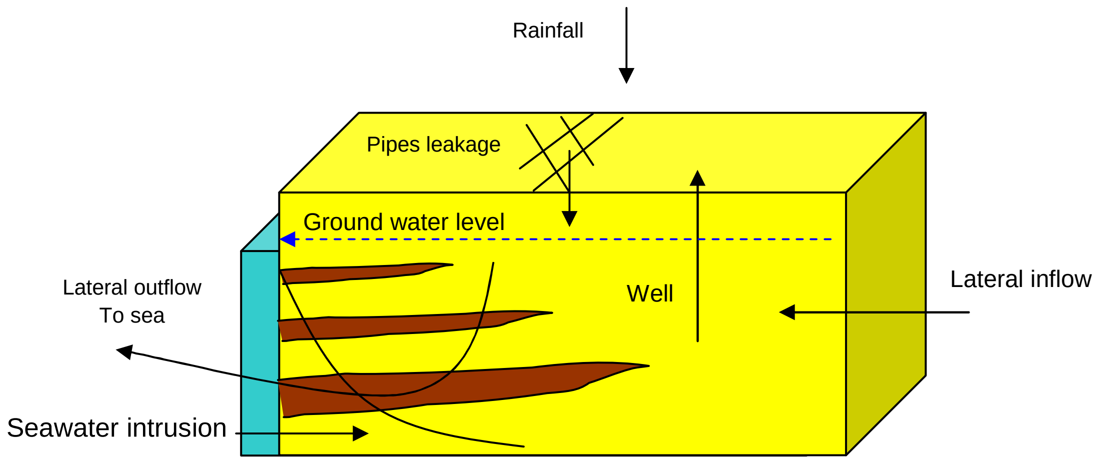


Figure (4.25) Budget components of the Gaza aquifer.

Regarding the Gaza Strip area, many studies have been carried out to estimate the balance components, and these were concentrated on the more critical components of the aquifer balance. For instance, Melloul and Bachmat (1975) estimated the groundwater recharge for the Gaza Strip using recharge coefficients. They subdivided the area into three subzones and computed the coefficients for each sub-zone based on the soil type, and the average rainfall. According to their study, the annual groundwater recharge in the area equaled to 41 x 10^6 m^3 (Baalousha, 2005).

Another study was carried out in the area by Baalousha (2005) used the Cumulative Rainfall Departure method (CRD) to estimate the net groundwater recharge from rainfall in the Gaza Strip. He used the optimisation approach to minimise the root mean square error between the measured and the simulated groundwater head. The results show that the annual amount of groundwater recharge from rainfall in the Gaza Strip is about 43 x 10^6 m^3. (Baalousha, 2005).

Recently, Aish et al, (2009) used the WetSpass model to estimate the distributed regional recharge in the Gaza Strip. The results show that the recharge values range from 0 to 320 mm/year. Values reclassified into eight classes are shown in figure (4.26). He estimated the spatial average recharge as 108 mm/year that corresponds to a volumetric average annual recharge of 39 – 40 x 10^6 m^3/yr (Aish et al., 2009).

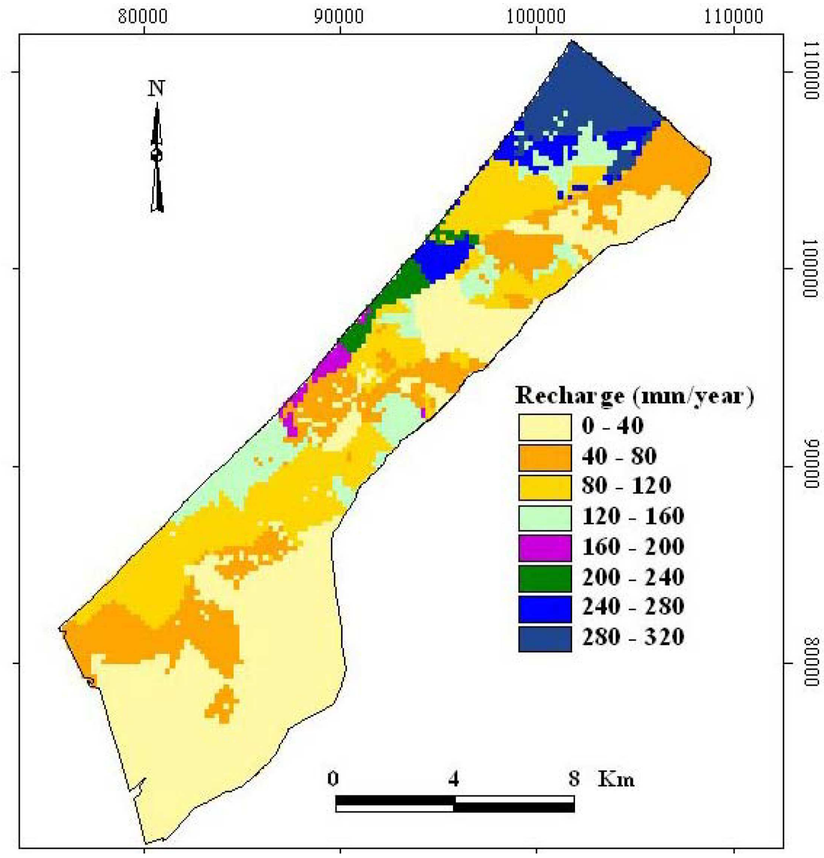


Figure (4.26) Net annual groundwater recharge, simulated with the WetSpass model. (Aish et al., 2009).

4.6 Budget components estimation

A water budget of the Gaza coastal aquifer has been developed in this thesis based on the estimation of substantial water inputs and outputs to and from the regional aquifer system. The two main components of the water balance are the rainfall infiltration and pumping wells (municipal and agricultural well).

The components of the current water budget of the Gaza Strip are:

- Recharge components (Inflows):

Effective recharge + Lateral inflow + Total return flows.

- Demand components (Outflows):

Total abstraction + Lateral outflow (discharge to the sea)

4.6.1 Recharge components

The quantitative estimation of recharge to unconfined aquifers is an important step in determining the sustainable pumping rates from the aquifer. This is particularly substantial in areas where recharge is mainly from rainfall coupled with a high demand for ground water. These are typical conditions of Gaza aquifer where rainfall is the only natural renewable recharge resource and the abstraction quantity exceeds the effective recharge quantity.

4.6.1.1 Effective recharge

Effective recharge in a specific area can be defined as the quantity of precipitation that reaches the water table (Ashooh et al., 2003).

The effective recharge of rainfall for the Gaza aquifer was computed using the following equation:

$$\text{Effective recharge (Infiltration)} = P \times A \times C \qquad (2)$$

Where

P : Net rainfall for each station in (mm)

A : Area of each type of soil for each station (Km^2)

C : Recharge coefficient of each type of soil.

Since the rainfall in Gaza Strip decrease by 50 % from north to south and the soil types vary from east to west, the effective recharge was computed using the Thiessen map of rainfall stations and the soil types map. In other words, the effective recharge for each rainfall station was computed for different classes of soil founded using equation (2). Table (4.4) shows the applied methodology using the data for year 2000. The net rainfall is obtained subtracting the average evapotranspiration (ET) from the annual rainfall quantity of each station. The average ET used in the applied methodology is 141.7 mm/yr, computed using the ET data from 2000 to 2005 as shown in figure (4.26). The ET was computed for these years using Penman method. The infiltration coefficient was estimated according to soil type, land use and ET rate. Appling these parameters in equitation (2), the computed effective regional recharge of rainfall for each station from 2000 to 2009 is computed as shown in Table (4.5).

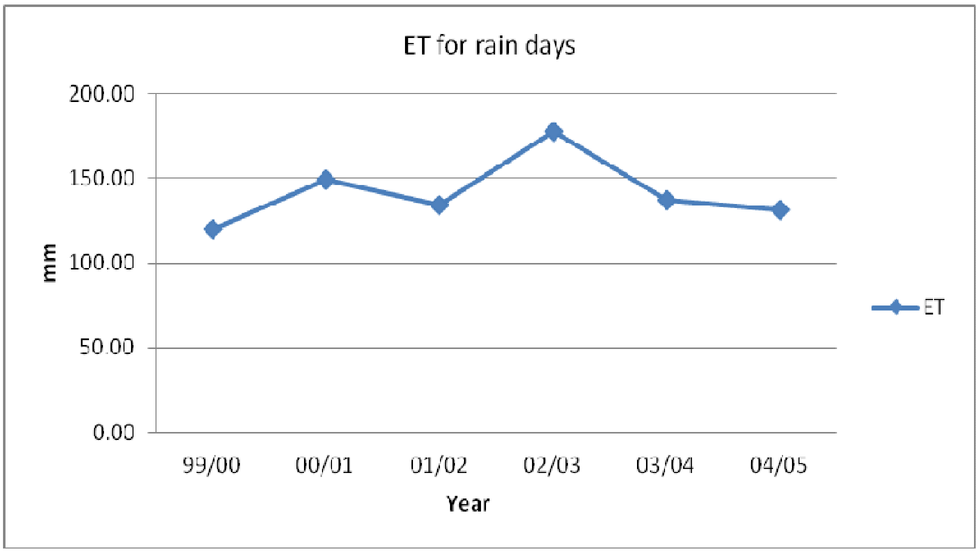


Figure (4.26) ET for the period from 2000 to 2005.

Station	Soil types	Area (m2)	Rainfall (mm/year)	Ave.ET mm/y	Net rain (m/year)	R.coefficient	Infiltration x $10^6 m^3$/yr
Beit hanun	Dark brown / reddish brown	18500000.00	497.50	141.70	0.356	0.03	0.16
	Sandy regosols	10580000.00	497.50	141.70	0.356	0.70	2.64
Beit lahia	Sandy regosols	15550000.00	490.40	141.70	0.349	0.70	3.80
Jabalia	Dark brown / reddish brown	198000.00	540.00	141.70	0.398	0.03	0.00
	Sandy regosols	14790000.00	540.00	141.70	0.398	0.70	4.12
Shati	Sandy regosols	3000000.00	478.90	141.70	0.337	0.70	0.71
Gaza	Dark brown / reddish brown	130000.00	511.90	141.70	0.370	0.03	0.00
	Loess soils	1950000.00	511.90	141.70	0.370	0.15	0.11
	Sandy regosols	10100000.00	511.90	141.70	0.370	0.70	2.62
Tuffah	Dark brown / reddish brown	11870000.00	533.40	141.70	0.392	0.03	0.12
	Loess soils	11630000.00	533.40	141.70	0.392	0.15	0.68
	Sandy regosols	1230000.00	533.40	141.70	0.392	0.70	0.34
Mogragah	Dark brown / reddish brown	15380000.00	563.60	141.70	0.422	0.03	0.16
	Loess soils	8090000.00	563.60	141.70	0.422	0.15	0.51
	Sandy loess soil	3610000.00	563.60	141.70	0.422	0.30	0.46
Nossirate	Dark brown / reddish brown	2050.00	558.30	141.70	0.417	0.03	0.00
	Loess soils	2230000.00	558.30	141.70	0.417	0.15	0.14
	Loessal sandy soil	6980000.00	558.30	141.70	0.417	0.25	0.73
	Sandy loess soil	15430000.00	558.30	141.70	0.417	0.30	1.93
	Sandy regosols	3780000.00	558.30	141.70	0.417	0.70	1.10
Dr Elbalah	Dark brown / reddish brown	1320000.00	550.50	141.70	0.409	0.03	0.01
	Loessal sandy soil	18380000.00	550.50	141.70	0.409	0.25	1.88
	Sandy loess soil	6990000.00	550.50	141.70	0.409	0.30	0.86
	Sandy regosols	12370000.00	550.50	141.70	0.409	0.70	3.54
Khan Younis	Dark brown / reddish brown	3210000.00	381.00	141.70	0.239	0.03	0.02
	Loessal sandy soil	25800000.00	381.00	141.70	0.239	0.25	1.54
	Sandy loess soil	4590000.00	381.00	141.70	0.239	0.30	0.33
	Sandy loess soil over loess	21470000.00	381.00	141.70	0.239	0.35	1.80
	Sandy regosols	27350000.00	381.00	141.70	0.239	0.70	4.58
Khuzaa	Loessal sandy soil	13350000.00	284.30	141.70	0.143	0.25	0.48
	Sandy loess soil	3470000.00	284.30	141.70	0.143	0.30	0.15
	Sandy loess soil over loess	35590000.00	284.30	141.70	0.143	0.35	1.78
Rafah	Loessal sandy soil	17950000.00	308.00	141.70	0.166	0.25	0.75
	Sandy loess soil over loess	7620000.00	308.00	141.70	0.166	0.30	0.38
	Sandy regosols	9770000.00	308.00	141.70	0.166	0.70	1.14
Total							39.55
Total amount of effective recharge to the ground water = 39.6 x $10^6 m^3$/yr							

Table (4.4) The effective recharge of rainfall by different type of soil in Gaza Strip for the year 2000.

Station	2001	2002	2003	2004	2005	2006	2007	2008	2009	Ave
B. Hanon	2.8	3.2	5.2	1.6	1.7	2.9	2.9	0.9	1.0	2.5
B. Lahia	3.8	4.4	6.3	2.7	1.9	4.2	4.2	2.0	1.1	3.4
Jabalia	4.1	4.4	5.7	2.3	2.1	4.1	4.1	1.6	1.6	3.3
Shati	0.7	0.8	1.0	0.4	0.3	0.7	0.7	0.3	0.2	0.6
Gaza	2.7	3.0	3.4	1.7	1.2	2.6	2.6	1.4	1.0	2.2
Tuffah	1.1	1.3	1.5	0.8	0.6	1.2	1.2	0.7	0.3	1.0
Moghragah	1.1	1.4	1.7	0.9	0.5	0.7	0.7	0.3	0.1	0.8
Nussirate	3.9	3.8	2.8	1.6	2.5	2.4	2.4	1.0	0.7	2.4
Dr-Elbalah	6.3	3.8	3.6	2.7	3.1	4.3	4.3	1.4	0.4	3.3
Khan Younis	3.8	5.9	5.4	2.3	8.0	3.8	3.8	0.6	1.5	3.9
Khuzaa	4.0	2.0	2.0	0.7	3.8	1.9	1.9	0.2	0.3	1.9
Rafah	2.3	1.4	1.1	0.4	3.0	1.6	1.1	0.9	0.0	1.3
sum	36.7	35.3	39.7	18.3	28.8	30.4	29.9	11.2	8.4	26.5

Table (4.5) The effective recharge for each rainfall station for the period between 2000 and 2009 (All data are x 10^6 m^3/yr).

4.6.1.2 Subsurface lateral Inflow

Lateral inflow is an important element of water balance in the Gaza Strip; however, it is not a quantity of water that can be relied on as a water resource for the Gaza Strip because it is affected by pumping from the coastal aquifer in Israel and/or irrigation return flows.

The groundwater lateral inflow can be estimated using different approaches. Darcy's Law was used to estimate the groundwater lateral inflow.

$$Q = Kia \quad (3)$$

Where,

K = the permeability of the soil,

i = groundwater gradient,

a = cross-sectional area perpendicular to direction of flow

The area (a) for this calculation is the width along a boundary where water enters the district boundary multiplied by the aquifer thickness (saturated zone) where flow is occurring. This typically needs to be divided into several subsections due to the different aquifer thickness, consequently, the width of the sections. The aquifer thickness can be slightly more difficult to determine. It can be estimated from several sources. The elevation of the aquifer base can be estimated from the available geological cross sections, and the groundwater elevation can be determined from the contour maps. By subtracting the base elevation of the layer at a specific point from the ground water elevation in the same point (Styles and Burt, 1999).

The hydraulic gradient (i) in unconfined aquifer indicates the potential for and the direction of groundwater movement. Groundwater elevation contour maps can be used to calculate the groundwater gradient (DWR, 1993). Taking the elevation of groundwater on each side of the subsection boundary and subtracting the one from the other gives the different in elevation. Then, obtained value is divided by the horizontal distance between the two points to calculate the local gradient.

The hydraulic conductivity (K) in an aquifer could range significantly throughout the aquifer depending on soil types present in the aquifer. In the Gaza coastal aquifer K is considered as 30 m/d on average.

The following calculation is the estimate of subsurface lateral Inflow for Gaza aquifer. For this calculation, the width of the boundary where water is entering the strip was divided into two cross section with different data set for each cross section, section A and section B is shown in figure (4.27). The figure shows the data set used to calculate the lateral inflow through each section as:

Section A

$Q = 30\ m/d \times 0.0003 \times 80\ m \times 22000m = 17600\ m^3/d$

Section B

$Q = 30\ m/d \times 0.001 \times 60\ m \times 10000\ m = 18000\ m^3/d$

Total lateral inflow = 17600 + 18000 = 35600 m^3/d

The following calculation assumes that this condition occurs for 365 days for year, so it can be computed for one year as:

35600 m^3/d x 365 d = 12,994,000 m^3/yr

The computed lateral inflow from the eastern part to the Gaza coastal aquifer is about 13 x 10^6 m^3/yr. The accuracy of the calculated lateral inflow is about (+/- 30 %). This is because of the potential variability of the soils and other parameters that may be neglected locally. The result is close to the values computed by PWA (10 x 10^6 m^3/yr - 15 x 10^6 m^3/yr).

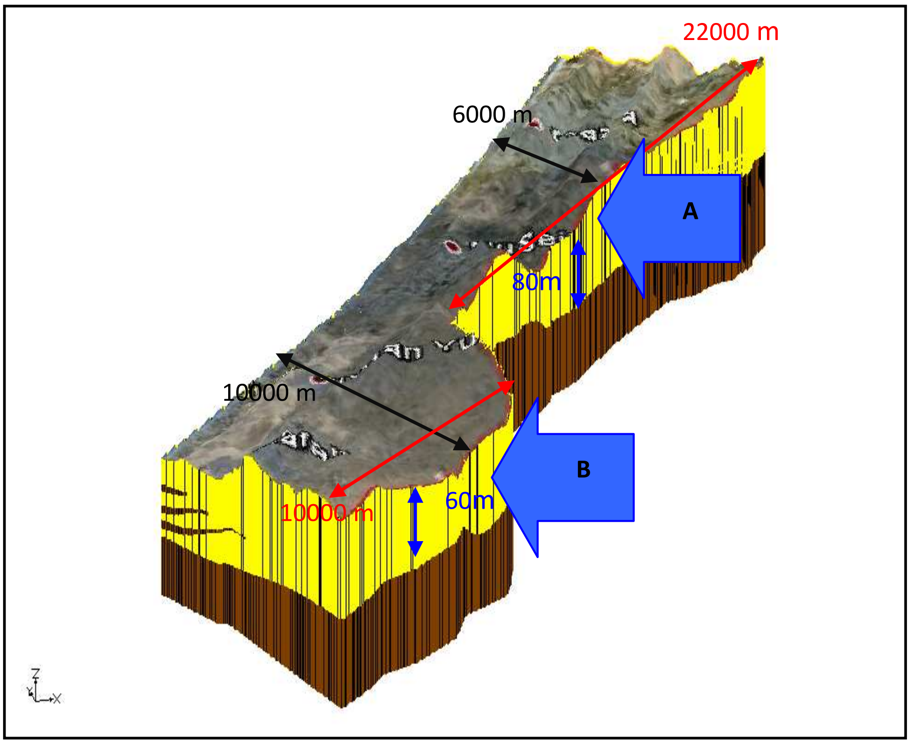


Figure (4.27) Cross section A and B used in the calculation of the lateral inflow to Gaza aquifer.

4.6.2 Other available recharge

Additional recharge is available from other resources of return flow in Gaza Strip: leakage from municipal water distribution system, wastewater return flows and irrigation return flow (Aish, 2004). According to the Palestinian Water Authority, the return flow from agriculture and municipal water distribution system is estimated between 25 % and 29 % respectively, of the total consumption. Table (4.6) shows the quantity of return flow from agricultural and municipal water distribution system for several years with an average of 19.4 x 10^6 m^3/yr and 22.6 x 10^6 m^3/yr respectively.

Year	Agriculture	25%	Municipal	29%
2003	79.5	19.9	68.1	19.7
2004	77.5	19.4	69.7	20.2
2005	73.5	18.4	74.6	21.6
2006	80.0	20.0	76.8	22.3
2007	85.5	21.4	80.7	23.4
2008	74.0	18.5	87.0	25.2
2009	73.0	18.3	89.3	25.9

Table (4.6) Estimation of return flow from agricultural and municipal water distribution system for years from 2003 to 2009 (All data are x 10^6 m^3/yr).

4.6.3 Demand components and water Consumption

Approximately 98% of population in Gaza Strip is connected with piped water supply systems (PNGO IV, 2010). Water demand in Gaza strip is increasing due to population growth. Figure (4.24) shows the total municipal and agricultural water production in Gaza strip from 2003 to 2009. The figure shows that the agricultural sector consumes between 80 to 73 x 10^6 m^3/yr, while the municipal water supply increased yearly in average of 3.5 x 10^6 m^3/yr. In 2003 the total water supply was estimated to about 68 x 10^6 m^3 and in 2009 was about 89 x 10^6 m^3 (PWA, 2010).

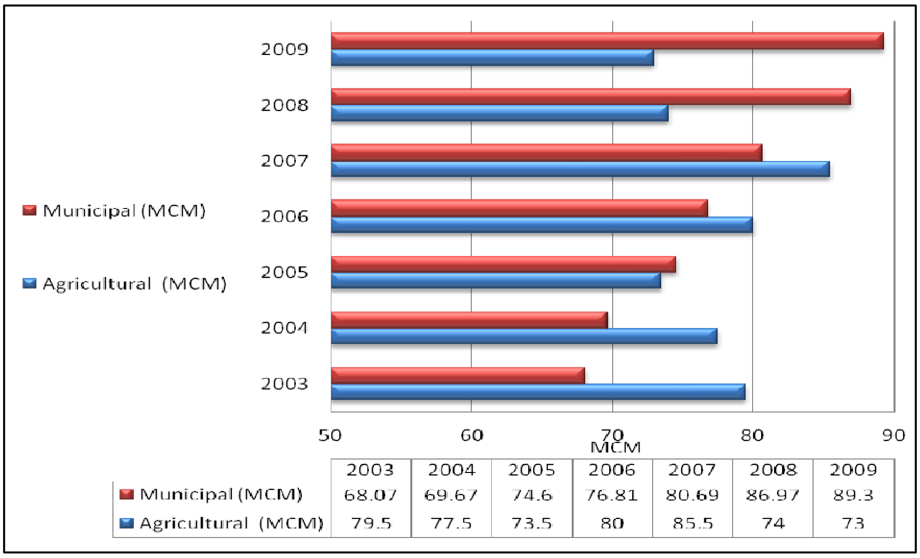


Figure (4.28) Gaza Strip municipal and agricultural water consumption from 2003 to 2009.

4.7 Net aquifer balance estimation

The net aquifer balance was developed based on the previous calculated recharge and demand components for the period between 2003 and 2009. The results, given in table (4.7), reflect the dynamic status of the aquifer, with continuously changing inflows and outflows from the aquifer. The deficit aquifer increase from year to year due to the continuous increasing of Pumping rates and climate variation. For all investigated years the net balance was negative. The results indicate a severe deficit that increases yearly by 6.9 x 10^6 m^3/yr on average.

Year	Effective. R	Ave.Lateral Inflow	Agr.Return	Muni.Return	Total. R	Total abstraction	Recharge - Pumping
2003	39.74	13.00	19.90	19.70	92.34	147.57	-55.23
2004	18.29	13.00	19.40	20.20	70.89	147.17	-76.28
2005	28.81	13.00	18.40	21.60	81.81	148.10	-66.29
2006	30.37	13.00	20.00	22.30	85.67	156.81	-71.14
2007	29.95	13.00	21.40	23.40	87.75	166.19	-78.44
2008	11.19	13.00	18.50	25.20	67.89	160.97	-93.08
2009	8.39	13.00	18.30	25.90	65.59	162.30	-96.71

Table (4.7) The estimated the net aquifer balance for the period between 2003 and 3009.
*All data are x $10^6 m^3$/yr.

Chapter 5

Assessing Gaza Coastal aquifer vulnerability to seawater intrusion using GALDIT method

Chapter 5: Assessing Gaza Coastal aquifer vulnerability to seawater intrusion using GALDIT method

Assessing the coastal aquifer vulnerability to seawater intrusion is a very important step for the future management of any coastal aquifer. GALDIT index method (Chachadi and Lobo Ferreira, 2001) makes use of many indicators to assess the vulnerability of coastal aquifers to seawater intrusion. The assessment of groundwater vulnerability to pollution aims at highlighting areas at a high risk of being polluted form contaminants. This chapter describes the application of GALDIT method on the Gaza coastal aquifer to assess the aquifer vulnerability to seawater intrusion in the actual status. In this area, the aquifer vulnerability is expected to increase in the future. The method is based on the following indicators:

1. Groundwater occurrence (aquifer type)
2. Aquifer hydraulic conductivity.
3. Level of Groundwater.
4. Distance from the shore (distance inland perpendicular to shoreline).
5. Impact of existing status of sea water intrusion in the area.
6. Thickness of the aquifer.

The acronym GALDIT is formed from the initial letters of the indicators for ease of reference. For each GALDIT indicator a thematic map was computed using geographical information systems (GIS). The resulted maps were overlaid using raster calculation to present the different vulnerability areas in one single map which has been reclassified successively using the vulnerability magnitude adopted in this study.

GALDIT index method (Chachadi and Ferreira, 2001) has been successfully used to assess the Gaza coastal aquifer vulnerability to seawater intrusion. The obtained vulnerability map shows the different vulnerability levels for different part of Gaza aquifer regarding seawater intrusion. The distribution of low, moderate and high vulnerability class are 26.9 %, 48.1 %, 25 % of the total study area, respectively. The resulting vulnerability map is a useful management tool that can be used to control and manage the sea water intrusion in different types of coastal aquifers.

5.1 Objective

The main objective of this chapter is to use an indicator-based model to assess and quantify the vulnerability magnitude of the Gaza coastal aquifer to SWI caused by excessive groundwater withdrawals. The vulnerability map can be used as an additional guide tool to identify the area of potential sea water intrusion and favorable areas to artificial recharge to be considered in the management model present in this thesis.

5.2 Introduction

Groundwater is one of the most important natural resources for water supply in coastal zones, it belong to the critical infrastructure and need a special protection, therefore, protection of coastal groundwater against pollution is a critical issue (Zektser et al., 2004). It is known that, in groundwater reservoirs, the water is well protected, better than surface water, but even this does not exclude the water to be at risk due to human activity and climate change. In order to protect this fundamental resource, a groundwater vulnerability assessment is required. Generally, assessment of the coastal aquifer vulnerability represents a challenging task, as it requires many information to indicate areas with different scale risk. The concept of groundwater vulnerability can be classified in two basic parameters: intrinsic vulnerability and specific vulnerability (Gogu and Dassargues 2000).

Vrba and Zaporozec (1994) defined the intrinsic vulnerability of an aquifer as" the ease with which a contaminant reach and diffuse in groundwater" (Vrba and Zaporozec, 1994). Vulnerability assessments prioritize areas for further protection, and monitoring. Groundwater vulnerability assessment commonly gives a map divided in several areas indicating the different potential magnitude of these areas to be contaminated.

Since vulnerability itself cannot be directly measured, information such as geologic structure, soil types, groundwater level, hydraulic properties, and climate measurements are used to assess the relative ease with which contaminants can reach and move through the groundwater system. Many methods integrate such information to determine the vulnerability of groundwater resources to contamination. The methods vary from simple, indexing assessments to complex, costly, numerical modeling assessments (Focazio et al., 2002). However, simple indexing assessment techniques are preferable over more sophisticated ones especially when considering that the output of the vulnerability assessment will be utilized to set up preliminary management options.

Recently, a variety of vulnerability assessment methods have been developed and applied to assess the aquifer vulnerability. The most common ones are: the German method (Von Hoyer and Sofner 1998), EPIK (Doerfliger et al., 1999), DRASTIC system (Aller et al. 1987), the GOD system (Foster 1987), the AVI rating system (Van Stempvoort et al. 1993), the SINTACS method (Civita 1994), the ISIS method (Civita and De Regibus 1995), the Irish perspective (Daly et al., 2002), and GALDIT index method (Chachadi and Ferreira, 2001). However, only a few of these methods were used to assess the sea water intrusion in coastal aquifers. GALDIT index method has been developed specially to assess the sea water intrusion in coastal aquifers based on the sharp-interface and steady state approximation (originally developed by Strack in 1976) (Werner, 2010). The method provides a helpful tool to characterizing seawater intrusion, considering the importance of different indicators. The method can be considered the only example of an assessment vulnerability method that uses a large-scale indexing approach to assess the coastal aquifer vulnerability to seawater intrusion (Werner et al, 2012).

The shallow sandy Gaza coastal aquifer is influenced by many factors that affect the quality and the quantity of the coastal ground water like over pumping and climate change. Recent studies indicate a continue degradation in the aquifer by the years in terms of quantity and quality, (Almasri et al., 2005, Vengosh et al., 2005, Elmanama, 2005, Yaqubi, 2006, Al-Khatib and Arafat, 2009, Shomaret al., 2009, Al-Khatib and Al Najjar, 2010).

Sea water intrusion appears as a serious concern that causes a difficult and irreversible problem for Palestinian people. The sea water intrusion problem in Gaza aquifer is strongly related to continuous over pumping that believed to increase in the future, therefore, the vulnerability of Gaza aquifer is expects to increase, and the aquifer management become more complicated.

In this Chapter the vulnerability of Gaza aquifer is assessed using GALDIT index method (Chachadi and Ferreira, 2001). Groundwater vulnerability map is obtained by superposing a series of indicator thematic maps in GIS environment.

5.3 GALDIT Method

The original development of the GALDIT index was done in the framework of the EU-India INCO-DEV COASTIN project (international and multidisciplinary project, funded by the European Commission, Directorate-General Research, in the frame of the programme “Confirming the International Role of Community Research, (INCO-DEV)").

In the basic concepts for the definition of groundwater vulnerability to pollution presented in Lobo-Ferreira and Cabral (1991), they defined the vulnerability of ground water to sea water intrusion as “the sensitivity of groundwater quality to an imposed groundwater pumping or sea level rise or both in the coastal belt, which is determined by the intrinsic characteristics of the aquifer” (Chachadi and Ferreira, 2005).

The method has been developed by Chachadi and Ferreira (2001). They suggest that the most important factors controlling seawater intrusion were to: aquifer type; aquifer hydraulic conductivity; high of groundwater level above the sea; distance from the shoreline; impact of existing status of seawater intrusion in the area; and thickness of the aquifer. They evaluated each GALDIT index with respect to the others to determine the importance of each indicator to evaluate the seawater intrusion by giving different weighting values for these indicators. GALDIT indices represent measurable parameters for which data are generally available from a variety of sources without detailed examination (Chadi and Ferreira, 2005). The method has been applied successfully on the Bardez aquifer in India and Monte Gordo in Portugal to assess the extent of aquifer contamination due to sea water intrusion (Chadi and Ferreira, 2005).

The GALDIT Index is calculated as

$$GALDITindex = \sum_{j=1}^{6} \{(W_i)R_i\} / \sum_{i=1}^{6} W_i \quad (1)$$

Where,

W1 to W6 are the relative weights assigned to the six indicators.

R is the Importance ratings used for the vulnerability mapping

5.4 Methodology

In this chapter an attempt is made to estimate the Gaza aquifer vulnerability and preparing a vulnerability map by means of the GALDIT index method (Chachadi and Ferreira, 2001).

Primarily and in view of the Gaza aquifer situation, the GALDIT indices were evaluated to determine the weights and importance ratings of each index in the same way as explained previously. The weights and importance ratings used in the computation are given in table (5.1). Weights range between 1 to 4 and importance ratings range between 2 to 10. Using these weights and importance ratings, the maximum GALDIT Index is computed as:

Max = {(1)*10 + (3)*10 + (4)*10 + (4)*10 + (1)*10 + (2)*10}/15 = 10

The maximum GALDIT-Index is obtained by considering the maximum importance ratings (10) for each indicator using equation (1).

The minimum GALDIT-Index is computed as:

Min = {(1)*2 + (3)* 2 + (4)* 2 + (4)* 2 + (1)* 2 + (2)* 2} /15 = 2

The minimum GALDIT index is obtained by considering the minimum importance ratings of the indicators.

Indicator	Weight	Indicator Variables		Importance Rating
Groundwater Occurrence	1	Confined Aquifer		10
		Un Confined Aquifer		8
		Leaky confined Aquifer		5
		Bounded Aquifer		2
Aquifer Hydraulic Conductivity	3	Class	Range	
		High	>40	10
		Medium	30-40	8
		Low	20-30	5
		V. low	20	2
Height of Groundwater Level	4	High	<0	10
		Medium	1 - 0	8
		Low	1 - 2	5
		V. low	>2	2
Distance from shoreline	4	V. small	<1	10
		small	2	8
		Medium	3	5
		Far	>3	2
Impact status of existing seawater intrusion	1	Class	Range of Cl (mg/l)	
		High	>400	10
		Medium	300-400	8
		Low	200-300	5
		V. low	<200	2
Aquifer thickness (saturated) in Meters	2	Large	>40	10
		Medium	30-40	8
		Small	20-30	5
		V. small	<20	2

Table (5.1) Weight, indicator classification and importance ranges used in the vulnerability assessment.

A numerical ranking system was developed to produce the vulnerability map using GIS environment. For each GALDIT index, a thematic map was generated using related weight and importance rating present in table (5.1) by applying equation (1). The attributed weight for each indicator represents the importance of this indicator respect to the other indicators to assess the seawater intrusion. The Indicator variables, shown in the table, demonstrate the ranges used to classify each indicator. Using the raster reclassify tool in GIS, thematic maps were reclassified based on the importance ratings shown in table (5.1).

The vulnerability of the study area to seawater intrusion is assessed based on the magnitude of the GALDIT Index presented in table (5.2). In a general way, lower the GALDIT index less is the vulnerability of the aquifer to seawater intrusion and vice versa.

GALDIT-Index Classes	Range Vulnerability
> 8	Highly vulnerability
5 to 8	Moderately vulnerability
< 5	Low Vulnerability

Table (5.2) Classification of the GALDIT Vulnerability index

The GALDIT index of aquifer and the vulnerability map was obtained as by the procedure shown in figure (5.1):

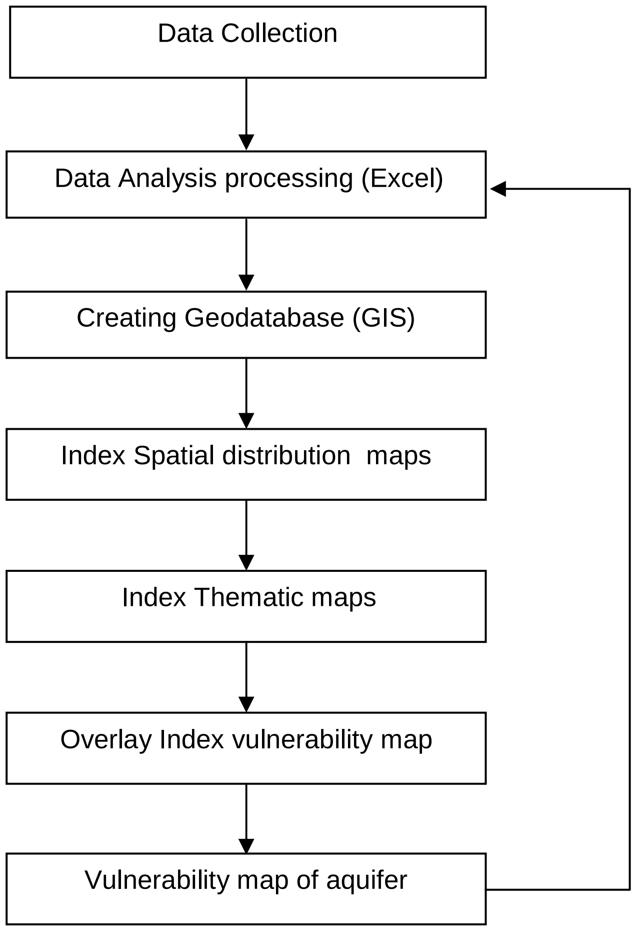


Figure (5.1) The procedure flowed to obtained GALDIT index vulnerability map.

5.5 Description and Estimate of GALDIT index for Gaza aquifer

5.5.1 Groundwater Occurrence (Aquifer Type)

Geological structure is an essential element to characterize and study any hydrogeological system. In case of sea water intrusion, the degree in which the ground water is affected by sea water intrusion depends on the nature of occurrence of ground water and on physical factors that control sources of water and water movement. Although Gaza aquifer is divided into sub-aquifers in the western part for a few kilometers, it is considered as a phreatic aquifer by many authors (Qahman and Zhou, 2001).The importance rating assigned to this index is 8 on the whole study area, as shown in figure (5.2.f).

5.5.2 Aquifer Hydraulic Conductivity

Gaza aquifer is a sandy shallow coastal aquifer, consisting mainly of unconsolidated materials of sand, sandstone and conglomerate. This material has a relatively high hydraulic conductivity that ranges from 20 m/day to 80 m/day (PWA, 2000). The map of hydraulic conductivity used for computing of this GALDIT index was obtained from PWA. The computed map is presented in figure (5.2.g)

5.5.3 Height of Groundwater Level above Sea Level

The level of groundwater with respect to mean sea elevation is the most important factor in the evaluating seawater intrusion in any coastal area, because it determines the hydraulic pressure eventually able to push back the seawater front. The water level for the year 2009 was used in the computation of the GALDIT indexing map for this indicator. Figure (5.2.c) shows the computed GALDIT indexing map.

5.5.4 Distance from the Shoreline

The magnitude of the impact of seawater intrusion generally increases moving towards the shoreline and vice versa. The distance from the shore was classified into three distances (1000, 2000, 3000 m) from the shoreline in the western part of the aquifer. The value of importance rating for this factor is assumed to change linearly with distance. Figure (5.2.a) shows the computed GALDIT indexing map for this indicator.

5.5.5 Impact of existing status of Seawater Intrusion

This GALDIT index takes into account the actual situation of sea water intrusion in the aquifer. It is required in order to develop a complete ground-water-vulnerability assessment. Parameters that are commonly used for seawater intrusion quality analysis are Ca/Mg, TDS, EC and Cl ratios. In this study, the Cl concentration was used to compute GALDIT indexing map, because its value is higher in sea water than in the groundwater. The Cl measurements in 95 wells for the year 2009 were used to prepare a spatial distribution map. The resulting map was reclassified using the importance rating presented in table (5.2.d).

5.5.6 Aquifer Thickness

Aquifer thickness represents the saturated thickness for an unconfined aquifer. Aquifer thickness is an important index to study and determining the extent and magnitude of seawater intrusion in coastal aquifers. Gaza aquifer has a variable thickness. The minimum thickness is in the eastern part and the maximum is near the shoreline. Figure (5.2.f) shows the thematic computed map for this indicator.

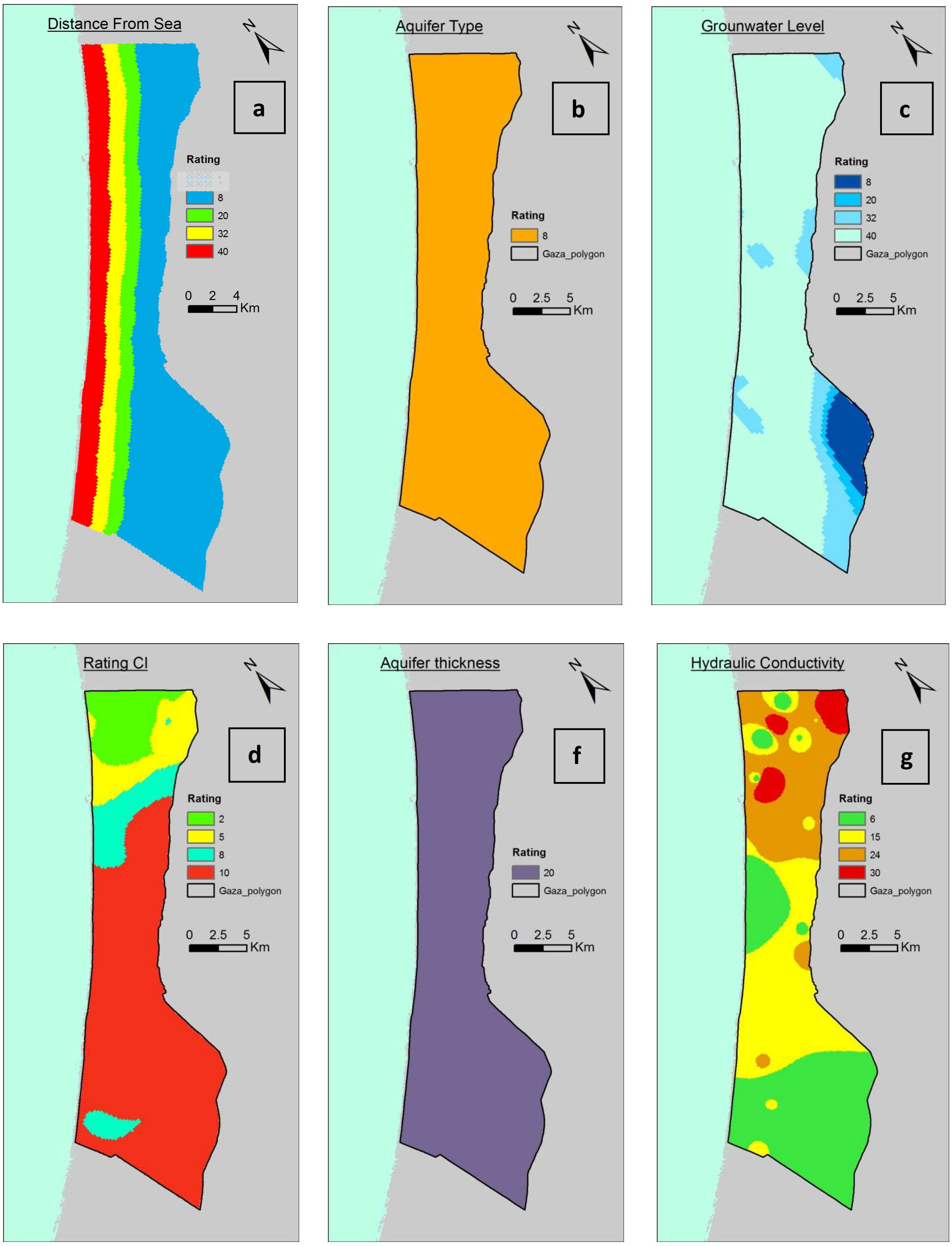


Figure (5.2) Thematic maps used in the computing of the GALDIT indexes vulnerability map.

5.5.6 CONCLUSIONS

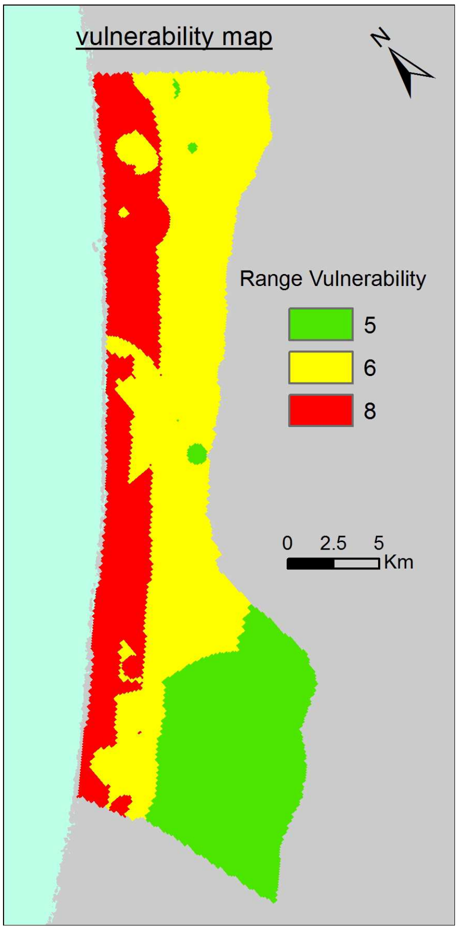


Figure (5.3) Vulnerability map of Gaza aquifer.

The GALDIT index method, developed by Chachadi and Ferreira (2001), for the assessment of coastal aquifer vulnerability to sea water intrusion, has been successfully performed in the Gaza strip. The six indicators influencing seawater intrusion described previously were analyzed individually, and using the weight and the importance rating of each indicator to compute the index vulnerability map, the thematic GALDIT index maps were carried out. Based on these Index maps, the aquifer vulnerability index mapping was computed. GALDIT index was estimated and found to have a minimum value of 65 and maximum value of 140. Reclassification of the final map using the GALDIT index magnitude shown in table (5.2), gives a final vulnerability map presented in figure (5.3). The GALDIT vulnerability map depicts the different degrees of the aquifer sensitivity to sea water intrusion along the Gaza coastal aquifer. The map divides the Gaza strip into three vulnerability zones. The red zone represents a high vulnerability level in the western part of the aquifer, corresponding to the 25 % of the total area. Yellow colour indicates the distribution of moderately vulnerable zones, which cover 48.1 % of the total area. This is due to the lower groundwater levels and the high hydraulic conductivity in these zones. The green coloured zones indicate a lower vulnerability, corresponding to the 26.9 % of the total area..

The GALDIT index vulnerability map shows the impact of seawater intrusion along the Gaza coastal aquifer. The vulnerability map can be used as a management tool for the actual and future situation of the Gaza coastal aquifer and in priority settings for areas where the aquifer is more vulnerable and should be monitored more frequently. Furthermore, the vulnerability map delineates areas favorable for artificial recharge in order to increase the ground water potential which that will be helpful to minimize and prevent the sea water intrusion. The vulnerability map can be used also in ascertaining the wellhead protection areas near the shoreline to prevent seawater intrusion.

Chapter 6

Groundwater Flow Model development

Chapter 6: Model development

6.1 Introduction

Effective management of ground water resources is essential to meet present and future needs for sustainable use (Yaqubi, 2006). Such management is required particularly, in systems where considerable changes continuously occur. As mentioned previously in chapter 1, the Gaza Strip is one of the most densely populated areas in the world with an estimated annual growth rate of 3.8 %. Therefore, it is very important to plan the use of groundwater resources in view of future population growth.

This chapter describes development of a three-dimensional numerical flow model for the Gaza aquifer. The developed model intends to address the control of seawater intrusion in view of the hydrological situation of Gaza aquifer. The developed model represents the previous hydrological conditions of the aquifer for the past ten years and forecasts the groundwater level variation in response of pumping and recharging variation for the next twenty years based on the future increasing in groundwater demands. The developed model aims to study the impact of continuous pumping and use of additional water resources on the ground water level, under different management scenarios, to control sea water intrusion in the Gaza aquifer.

Model development was done in two phases; phase 1 was the design, implementation, calibration and verification of the steady state numerical groundwater flow model based on the 2000 data, phase 2 included conversion of the steady state numerical model to a transient model to be used for future management scenarios. The period between 2001 and 2009 was selected for developing the transient flow model. Accurate calibration was performed to simulate the variation in groundwater level for the target simulation period. Based on the calibrated transient model, the groundwater level forecasting for the next twenty years was simulated based on the PWA pumping prediction and population growth projections from the year 2010 until 2030 by using different management scenarios. The following figure presents the basic modeling protocol followed in this study.

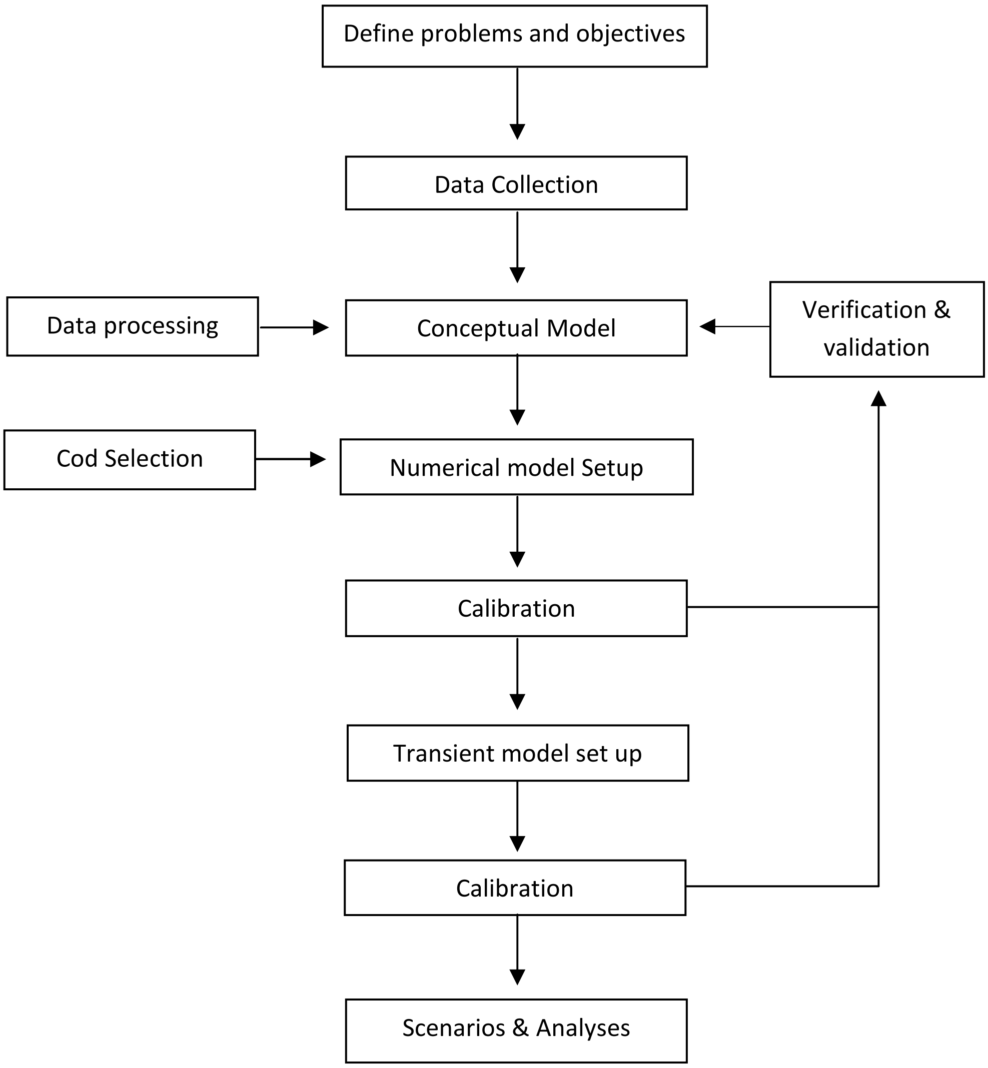


Figure (6.1) Modeling protocol followed in this study.

6.2 Previous studies

Previous studies estimated that a large-scale abstraction from the Gaza aquifer started in the early 1960's, when agricultural sector development began (Jamal and Yaqubi, 2001). Continuous uncontrolled pumping from the aquifer resulted in ground water level lowering by several meters. Between 1970 and 2000, groundwater levels dropped by almost 3 m on average. This drop is most apparent in the south where there is the minimum rainfall recharge rate (Qahman and Larabi, 2006). On the other hand a slow sea water intrusion started in Gaza coastal aquifer in the beginning of the1970 (Qahman and Zhou, 2001) and continued to develop until now due to continuous uncontrolled pumping and ground water lowering in the Gaza coastal aquifer.

Recently, various studies have been carried out to study this phenomenon by using different barouches at different places in the Gaza Strip. Numerical approach has been adopted by many authors to simulate and study the seawater intrusion problem in Gaza aquifer with different scopes.

Qahman and Zhou (2001) selected SUTRA-ANE to simulate the seawater intrusion along a cross-section in the northern part of the Gaza Strip. The model aimed to design a seawater intrusion monitoring network. They used the result of the model to identify the location and the number of monitoring sites.

Qahman and Larabi (2004) investigated saltwater intrusion extent in Gaza aquifer using SEWAT code. They considered different scenarios to predict the extension of saltwater intrusion interface with different pumping rate over the time. They simulated the extent of the saltwater intrusion for 3000, 2000 and 2500 m in the lower sub-aquifer in the northern, the middle, and the southern parts of the Gaza Strip in the year 2003, respectively. Their management scenarios were based on the prediction of the extent of seawater intrusion in the aquifer and also the groundwater level. The first scenario was the worst, which assume that pumping from the aquifer will reach 200 $x10^6$ m^3 by the year 2020, and the second scenario assume that the abstraction will be decreased to keep a considerable discharge to the sea in the order of

11 $x10^6$ m^3/yr. The result of the simulation shows that the second scenario can improve the aquifer situation and recover groundwater levels in the aquifer (Qahman and Larabi, 2004).

Saleh (2007) developed a groundwater flow model for the Gaza coastal aquifer using MODFLOW-2000 to simulate the effects of pumping on the hydraulic head at the coastline of Gaza Strip. Two potential solutions were simulated; reduction in pumping and the injection of water through wells. These two options eliminated the problem of saltwater intrusion (Saleh, 2007).

Qahman et al., (2009) developed multi-objective management models on a local area selected from the regional Gaza coastal aquifer using CODESA-3D code. The objectives and constraints of these management models include maximizing the total volume of water pumped, minimizing the salt concentration of the pumped water, and controlling the drawdown limits. The results of the optimization show that the optimization/simulation approach can support better decision if there is enough information to feed to the model. The study confirmed that the use of the concept of safe yield alone is not enough for sustainable use of the coastal aquifer. Their models show that the optimum pumping rate is in the range of 26% – 34% of the total natural replenishment (Qahman et al., 2009).

Alnahal et al., (2010) developed a decision support system based on a simulation/optimization approach applied on the Gaza coastal aquifer to sustainable management under the effective recharge operations and water quality constraints (Alnahal et al., 2010).

Sarsak and Almasri (2011) studied the seawater intrusion in north Gaza coastal aquifer in response to climate change impacts. Using SEAWAT, they developed a 3D density dependent model to simulate various scenarios to study the impacts of climate change on seawater intrusion due to sea level rise, recharge and pumping rates variability. The results show that the critical in-land movement of salinity, found in the 4 scenarios minimizing the recharge by 30% causes an inland intrusion movement of about 4,500 m with a rate of 80 m/yr. The best results for the inland intrusion were found in Scenario 6, the inland intrusion movement for this scenario was about 2,900 m with a rate of

35 m/yr. This scenario was considered as a management scenario since it is dealing with the proposed strategic plans of PWA.

6.3 Conceptual Model Development

Effective groundwater models are mostly developed in a logical sequence (Kumar, 2012). Prior to simulate the groundwater system, a conceptualization of the system is essential because it forms the basis for model development. Steps in development of a conceptual model include:

1) Geological reconstruction and definition of aquifers and confining units

2) Identification of existing sources and sinks in the aquifer

3) Identification and delineation existing hydrologic boundary conditions surrounding the interested area.

The first two above mentioned steps were accomplished by review and interpretation of existing geological and hydrogeological data. The third step was accomplished by using a screening model.

The hydrogeological reconstruction of the Gaza aquifer conceptual model has 8 layers. Two material types were considered in the geology construction of these layers, unconsolidated materials and clay. The hydrogeological attributes of each layer were assigned based on the material types. The horizontal hydraulic conductivity considered for the Clay was 0.3 m/d and for the unconsolidated materials was 25 m/d. The vertical hydraulic conductivity was considered as 10 % of the horizontal hydraulic conductivity for both clay and unconsolidated materials. The conceptual model is based on the data for the year 2000. No flow boundary conditions were considered for the northern and the southern part of the conceptual model, a constant head was considered to the eastern part with 0 m and in the western part with different elevation head based on the piezometric map of the year 2000. The conceptual model has 3600 wells with different pumping rates. The principal recharge source considered in the conceptual model is rainfall infiltration in addition to other sources like leakage pipes and irrigation return flow.

6.4 Code selection

One of the important criteria for code selection is if the code includes a water balance computation or not. This is because the water balance involves computation of inflows and outflows across the model boundaries, and from sources and sinks and storage. A water balance calculation should be integrated in every modeling software (Anderson & Woessner, 1992).

For the purposes of this study, MODFLOW-2000 was selected as the model code (Harbaugh et al., 2000). The U.S. Geological Survey modular three-dimensional finite difference groundwater flow model (MODFLOW) developed by McDonald and Harbaugh (1988) is a flexible finite difference modelling program used to develop numerical flow models. A MODFLOW model consists primarily of a set of input files that contain information on the physical properties of the modelled system such as the geometry, boundary conditions, hydrogeological properties and existing sources and sinks in the interested area. Once these files are created, the model program can be run to solve a set of equations that describe the distribution of head at discrete points within the system and the flow in response to that head distribution. The partial-differential equation of ground-water flow used in MODFLOW is (Harbaugh & McDonald, 2000)

$$\frac{\partial}{\partial x}\left(K_{XX}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

Where

Kxx, Kyy, and Kzz are values of hydraulic conductivity (L/T) along the x, y, and z coordinate axes.

h is the potentiometric head (L);

W is a volumetric flux per unit volume representing sources and/or sinks of water, W<0.0 for flow out of the ground-water system, and W>0.0 for flow in.

S_S is the specific storage of the porous material and T is time (T).

The selection of MODFLOW-2000 as the model code was based on the following criteria: use of the model code is well-documented in the academic literature, the model code has been widely used by hydrologic professionals and is generally accepted as a valid model for simulating groundwater flow, graphical user interfaces developed for the code allow for relatively simple and efficient adjustment of model parameter values, and the model code allows for automated parameter estimation based on inverse modeling techniques (Timmons et al., 2007).

The graphical user interface computer program Groundwater Modeling System (GMS) was utilized to run MODFLOW-2000. GMS is a comprehensive groundwater modelling program with a complete graphical user environment that allow users to develop ground water models and perform different groundwater simulations. GMS provides tools for every phase of groundwater model development including geological construction and site characterization, numerical model development, calibration, and results visualization. GMS permits to develop both finite element and finite difference models in 2D and 3D through wide variety of integrated model options: MODFLOW 2000, MODPATH, MT3DMS/RT3D, SEAM3D, ART3D, UTCHEM, FEMWATER, PEST, UCODE, MODAEM and SEEP2D (GMS User Manual (v8.3), 2012).

6.5 MODFLOW Model Construction in GMS

Developing MODFLOW numerical model in GMS interface requires two phase of works, the first is the input of the hydrological parameters and boundary of the study area by building many coverages and the second is the creation of a 3D Grid which represents the geological structures and hydrogeological units, by interpolating geological information scatter points.

The development of MODFLOW 3D model in GMS interface involves the following basic steps:

1. Input of boundary conditions that represent and control surface water/groundwater interactions
2. Input of hydrogeological properties of materials
3. Construction of the finite-difference grid with model layers corresponding to the regional hydrostratigraphic units
4. Calibration of the predevelopment steady-state model to predevelopment water levels and fluxes
5. Starting transient model and input of transient data
6. Calibration of the transient model by matching measured water levels over time to simulated values, then iterating between the predevelopment and transient models to arrive at a common parameter set.

6.6 Numerical model development

6.6.1 Model Domain

The first step in numerical model development is to define the outer boundary of the model. The Gaza aquifer model domain encloses an area of 365 km^2 bounded by actual political and natural borders as shown in figure (6.2).

6.6.2 **Boundary Conditions**

Boundary conditions represent hydraulic heads or groundwater fluxes at the edges of the model domain or at the intersection of the groundwater system with other systems. Different conditions were assigned to the numerical model boundary are shown in figure (6.2). The northern and the southern edge was fixed as a no-flow boundary condition (Neumann boundary) where the groundwater flow is perpendicular to the coast line. The eastern edge, where the aquifer is provided by 10 -15 x 10^6 m^3/yr as a lateral inflow, was fixed as a specific head (Dirichlet boundary conditions) with several head boundary nodes along the border which represent the different groundwater level for year 2000. These boundary nodes allow the model to simulate the head more realistically over the time and the space at the eastern edge. The western edge was fixed as a 0 m constant head near the sea.

6.6.3 Sources and sink boundary conditions

There are no significant man-made sources active in Gaza Strip. However, the aquifer is accessible by an interested number of wells. Figure (6.2) shows the spatial distribution of 3600 pumping wells over the Gaza Strip inserted in the model. All wells were identified as active pumping wells during the simulated period within the model domain. The depths of the top and bottom of well screens vary from 5 to 100 m. The open interval and pumping rate for all most wells cover more than one layer.

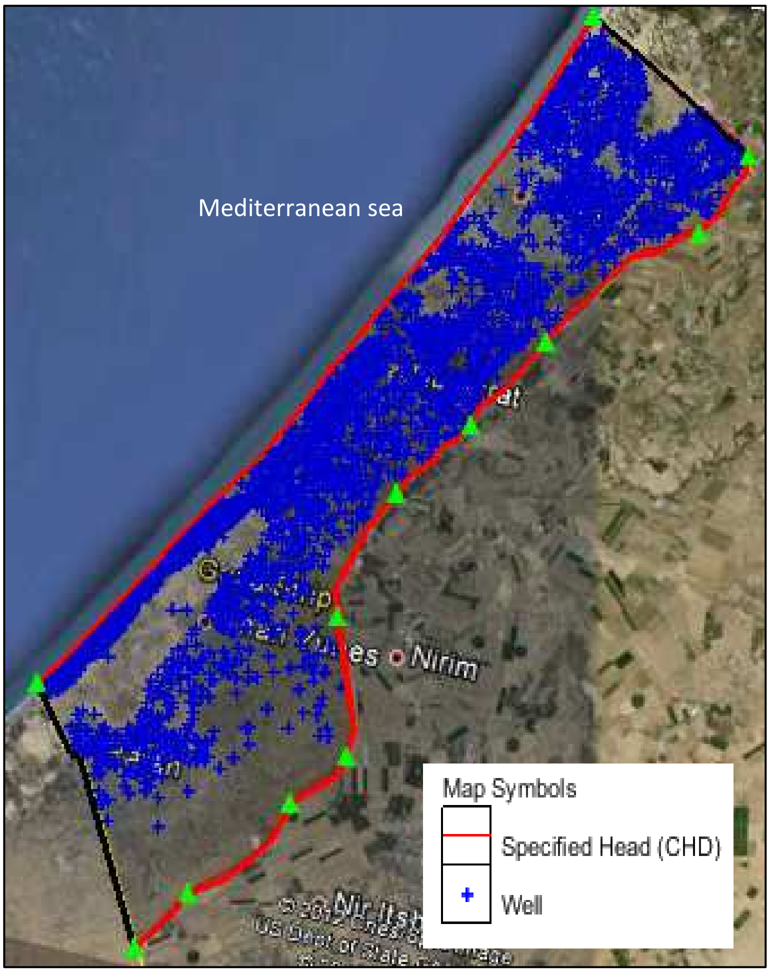


Figure (6.2) Model domain, boundary conditions and wells.

6.6.4 Hydraulic conductivity

Development of a 3D groundwater numerical model requires information on the 3D distribution of hydraulic conductivity across the hydrogeological units where the groundwater flow occurs. Based on previous studies and pumping test executed in Gaza strip, a summary of initial estimates of hydraulic conductivity values for all model hydrostratigraphic units is presented in the table (6.1). The vertical conductivity was set to 10% of the horizontal hydraulic conductivity for each hydrostratigraphic unit. Two different material types were considered, clay and unconsolidated sand and sandstone materials. The hydraulic conductivity is not constant for all layers due to presence of two different material types in the same layer; therefore, the hydraulic conductivity is linked to the material type assigned for the cell. The hydraulic conductivity for the clay varies between 0.003 m/d and 0.86 m/d, with an average of 0.3 m/d and for the unconsolidated materials varies between 20 and 80 m/d with an average of 30 m/d. Storativity varies from 0.22 to 0.27 (Aish, 2004).

H-Unit	TYPE	Thickness Range, m	Kh, Kv m/d	Ss	Sy	n
Unit 1	Aquifer	50 - 100	25 - 2.5	0.0001	0.24	0.30
Unit 2	Aquitard	10 - 1	0.3 - 0.03	0.0001	0.10	0.45
	Aquifer	1 - 1	25 - 2.5	0.0001	0.24	0.30
Unit 3	Aquifer	30 - 40	25 - 2.5	0.0001	0.24	0.30
Unit 4	Aquitard	10 - 1	0.3 - 0.03	0.0001	0.10	0.45
	Aquifer	1 - 1	25 - 2.5	0.0001	0.24	0.30
Unit 5	Aquifer	30 - 40	25 - 2.5	0.0001	0.24	0.30
Unit 6	Aquitard	10 - 1	0.3 - 0.03	0.0001	0.10	0.45
	Aquifer	1 - 1	25 - 2.5	0.0001	0.24	0.30
Unit 7	Aquifer	60 - 70	25 - 2.5	0.0001	0.24	0.30
Unit 8	Aquiclude	60 - 100	0.01 - 0.001	0.0001	0.10	0.45

Table (6.1) Hydrogeological Units thickness and hydrological characterisation used in the developed numerical model.

6.6.5 Recharge

The recharge rates assigned to the model area were based on the measurements of meteorological station in Gaza Strip for the rainfall period 1999-2000 as shown in figure (6.3). The model area was divided in polygons using the Thiessen map of regional rainfall distribution and soil types map to calculate the infiltration rate by rainfall as shown in figure (6.4).

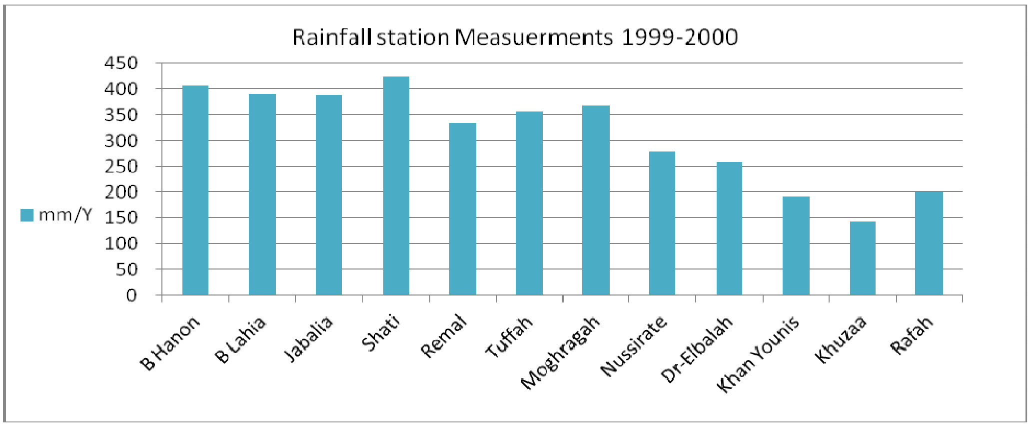


Figure (6.3) Rainfall measurements at the meteorological stations in Gaza strip for the rainfall period1999-2000.

ID	Recharge m^3/d
1	0.0001
2	0.00045
3	0.0001
4	0.00064
5	0.00046
6	0.00013
7	0.00078
8	0.00076
9	0.0002
10	0.0002
11	0.00023
12	0.00034
13	0.00011
14	0.0001
15	0.00013
16	0.00078
17	0.00023
18	0.00019
19	0.00046
20	0.00014
21	0.00011
22	0.00014
23	0.0003
24	0.00032

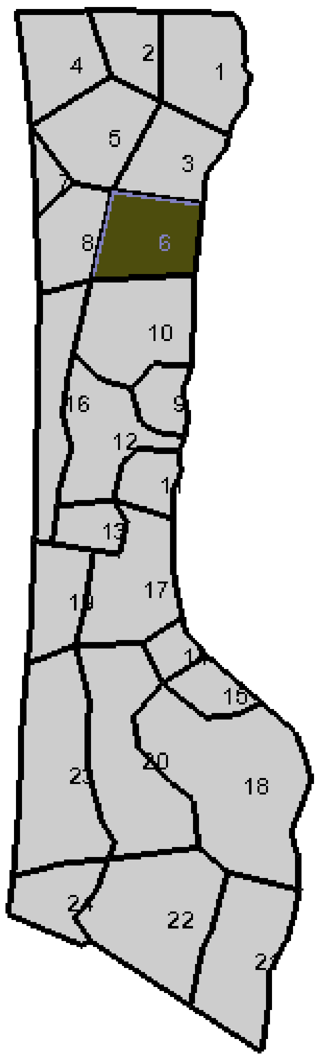


Figure (6.4) Recharge polygons and assigned rates.

6.6.6 3-D Grid Construction

In a numerical groundwater model, the continuous groundwater flow field is approximated by a discretized domain consisting of an array of grid nodes and associated grid blocks. This nodal grid forms the framework of the numerical model. MODFLOW uses a block-centered, finite-difference grid to simulate a continuous groundwater flow field (McDonald and Harbaugh 1988).

Once the MODFLOW coverages have been created with all necessary information, it is possible to start the 2D Grid generation process in order to determine the horizontal position of all cells in the three-dimensional grid while the vertical position of these cells will be determined by the conceptual model stratigraphy. The 2D horizontal grid is divided into uniform cells with size of 150x150 m. The 2D grid was rotated by -40 ° in order to simulate the realistic regional groundwater flow which is mainly westward towards the Mediterranean Sea with a grid perpendicular to the coast line and sub parallel to northern boundary of the model area. Figure (6.5) shows the generated 2D grid.

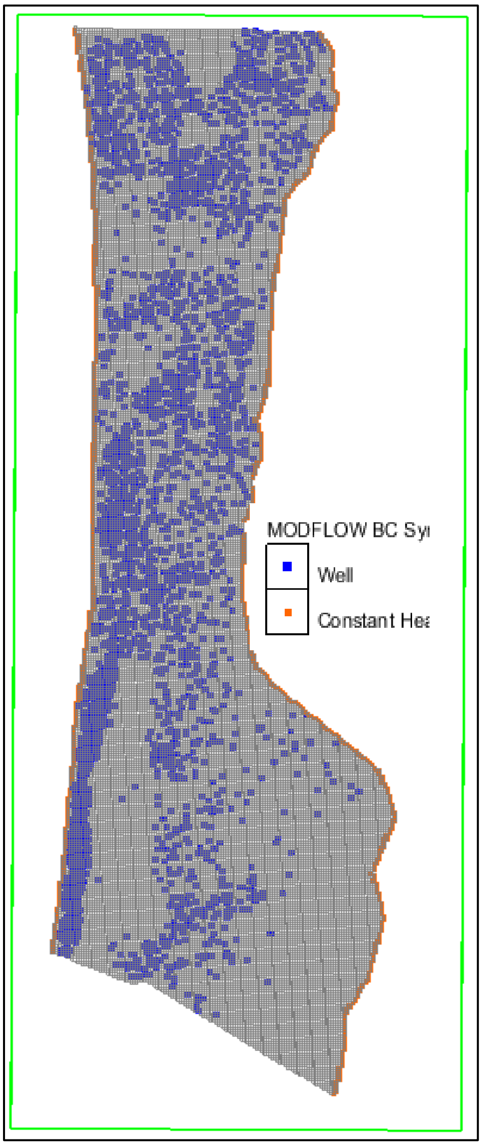


Figure (6.5) The generated 2D grid of the numerical model.

6.6.7 Geologic sitting reconstruction and layers interpolation

The geology of a site should be characterized through the existing geological data like well logs, geologic maps, and cross sections. Cross sections can be constructed from information contained in drilling logs and geological reports. Structural features, such as faults, fractures, fissures, impermeable boundaries or other subsurface features that might provide preferential pathways for the flux should be delineated.

A 3D geological model for the Gaza aquifer including important geological formations was developed. The DEM of Gaza Strip with resolution of 300*300 m and 20 schematic vertical cross section distributed all over Gaza Strip perpendicular to the coast line and boreholes lithology information were used in the model construction (Appendix 1 and 2).

The 300*300 m DEM of Gaza Strip was used to interpolate the surface elevation of the first layer. Vertical cross sections and boreholes lithology information were interpreted to identify the hydrogeological units position by the creation of a scatter points file for each hydrogeological unit using GIS environments. The scatter point files were used in the development of the Gaza geological framework which consists mainly of 8 hydrogeological units. The 3D grid model shown in figure (6.6) has 669200 cells and 758736 nodes. Layers stratigraphy slope horizontally towards the sea. Hydrological characterisations and thickness of hydrogeological units has been presented previously in table (6.1).

As mentioned in chapter 2 the geology of Gaza strip consists primarily of Pleistocene age Kurkar Group deposits including calcareous and silty sandstones, silts, clays, unconsolidated sands, and conglomerates. The aquifer layers are alternated by 3 coastal marine clay aquitard with variable extension (2-5) inland depending upon location. Figure (6.7) and (6.8) show the position and the extension of the coastal clay layers in the geological cross section of Gaza aquifer structure. The basic unit of the coastal aquifer model present the Saqiyah formation of Neogene's age which is formed of impervious clay shale rocks. The model end at -180 m under sea level.

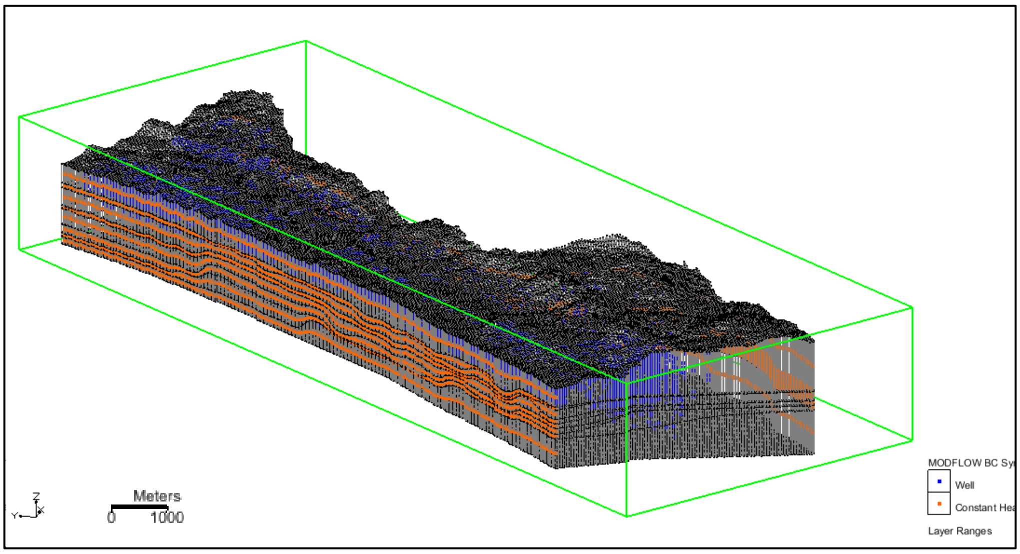


Figure (6.6) The 3D grid of the Gaza numerical model.

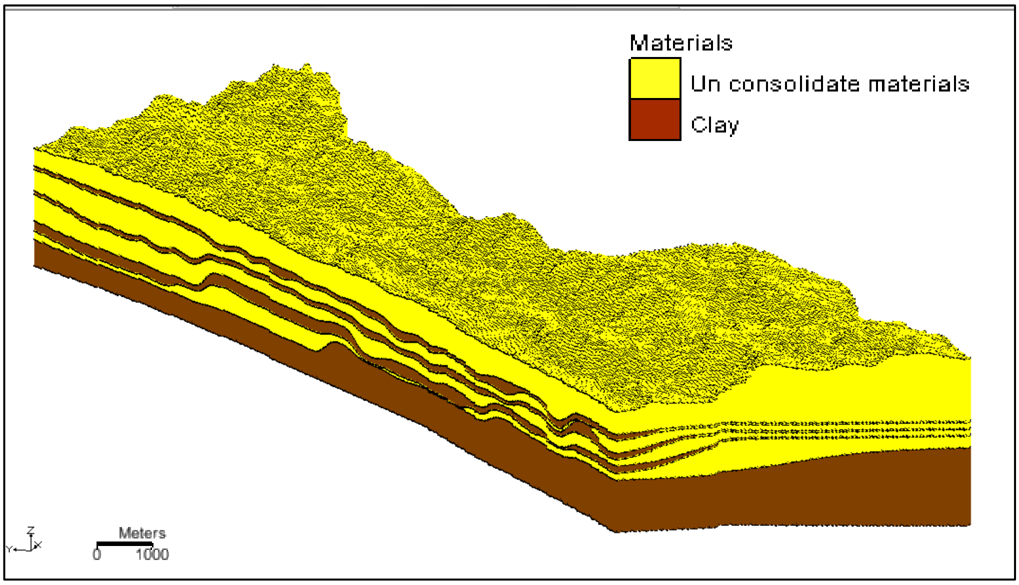


Figure (6.7) Layers stratigraphy of Gaza hydrogeological model.

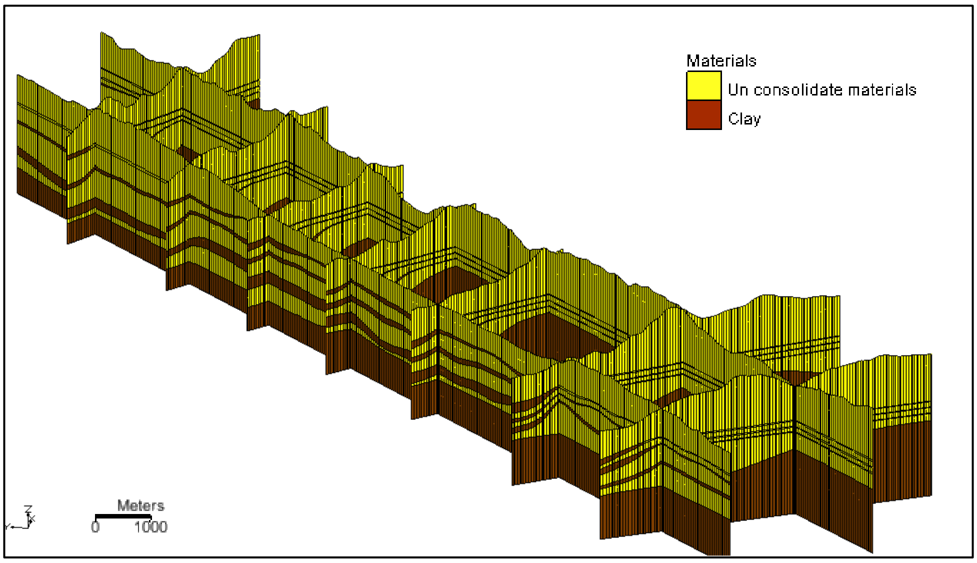


Figure (6.8) Geological cross section of Gaza aquifer.

6.6.8 Initial Condition

An initial condition was assigned to internal model domain to give the starting ground water level for the model. It is important to note that the initial head condition affects the speed at which the steady state solution is reached. Based on the ground water level measurements of the year 2000, the starting head was interpolated into the MODFLOW layers. Figure (6.9) represents the spatial distribution of starting head.

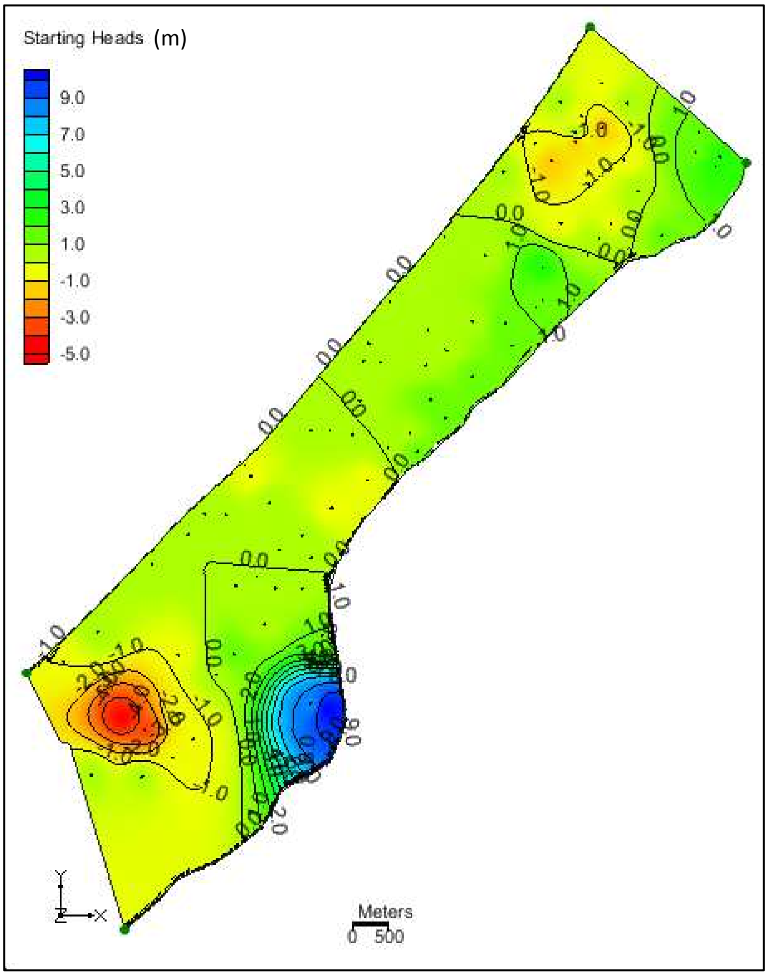
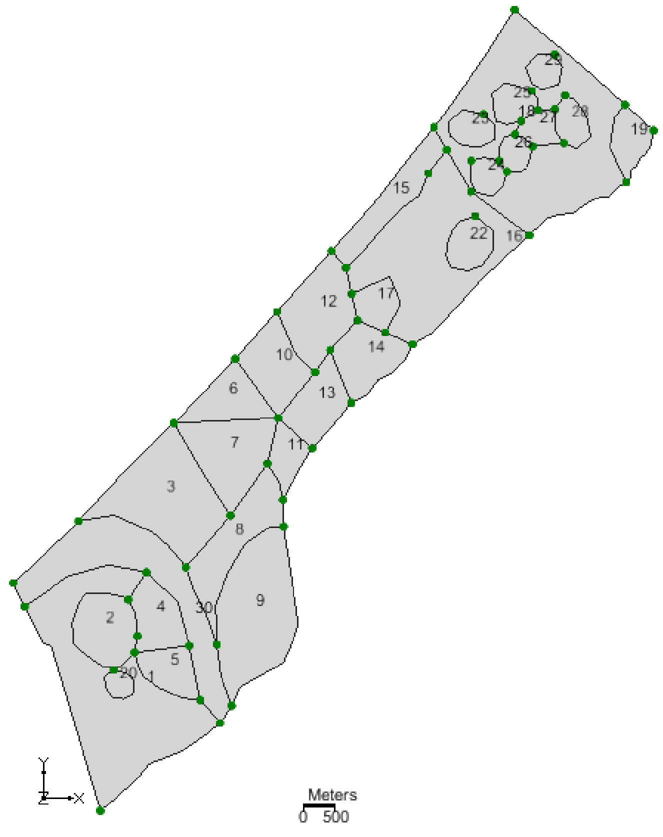


Figure (6.9) Spatial distribution of starting head.

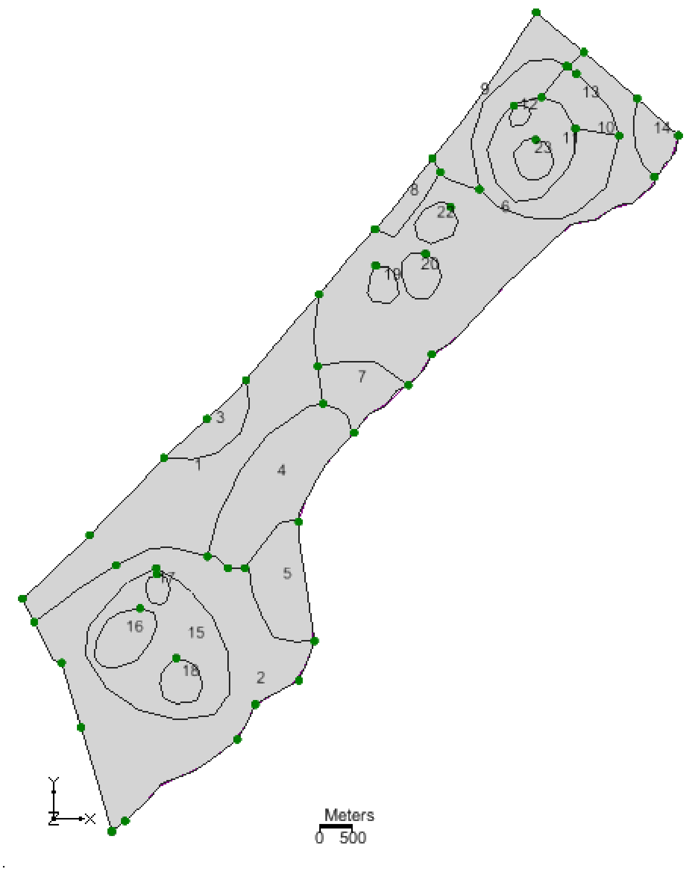
6.7 Calibration

Model calibration is the adjustment process of model parameters to reach a good matching between simulated observations and estimated observations. The calibration was based on the input data discussed in the previous subsection. Calibration of the flow model was achieved by manual trial and error adjustment of model input parameters. Many iterations have been done to meet the convergence criterion of 0.5 m for the groundwater flow equation (groundwater head). The developed model was calibrated for the ground water level of the target year 2000 by using 50 observation wells. Hydraulic conductivities and recharge are changed to improve the fit between simulation results and measurements. In order to perform these changes in the model parameters the Gaza Strip polygon was divided into small polygons for the recharge and the hydraulic conductivities coverages as shown in figures (6.10) and (6.11). Major adjustments of these subsoil parameters were needed to satisfactorily calibrate the system. The calibrated groundwater head is shown in figure (6.12).



ID	Recharge m/d	ID	Recharge m/d
30	0.0001	15	0.0025
1	0.0001	16	0.002
2	0.00001	17	0.00008
3	0.0005	18	0.00069
4	0.00001	19	0.0015
5	0.00099	20	0.0003
6	0.00004	22	0.0005
7	0.0008	23	0.0001
8	0.00001	24	0.0001
9	0.0001	25	0.0001
10	0.0005	26	0.003
11	0.00001	27	0.0001
12	0.0015	28	0.0029
13	0.0001	29	0.002
14	0.001		

Figure (6.10) Calibrated recharge values.



ID	Kh	Kv
1	30	3
2	1	0.1
3	60	6
4	1	0.1
5	5	0.5
6	30	3
7	20	2
8	10	1
9	100	10
10	5	0.5
11	70	7
12	1	0.1
13	100	10
14	5	0.5
15	10	1
16	1	0.1
17	0.5	0.05
18	40	4
19	60	6
20	60	6
22	60	6
23	100	10

Figure (6.11) Calibrated hydraulic conductivity values .

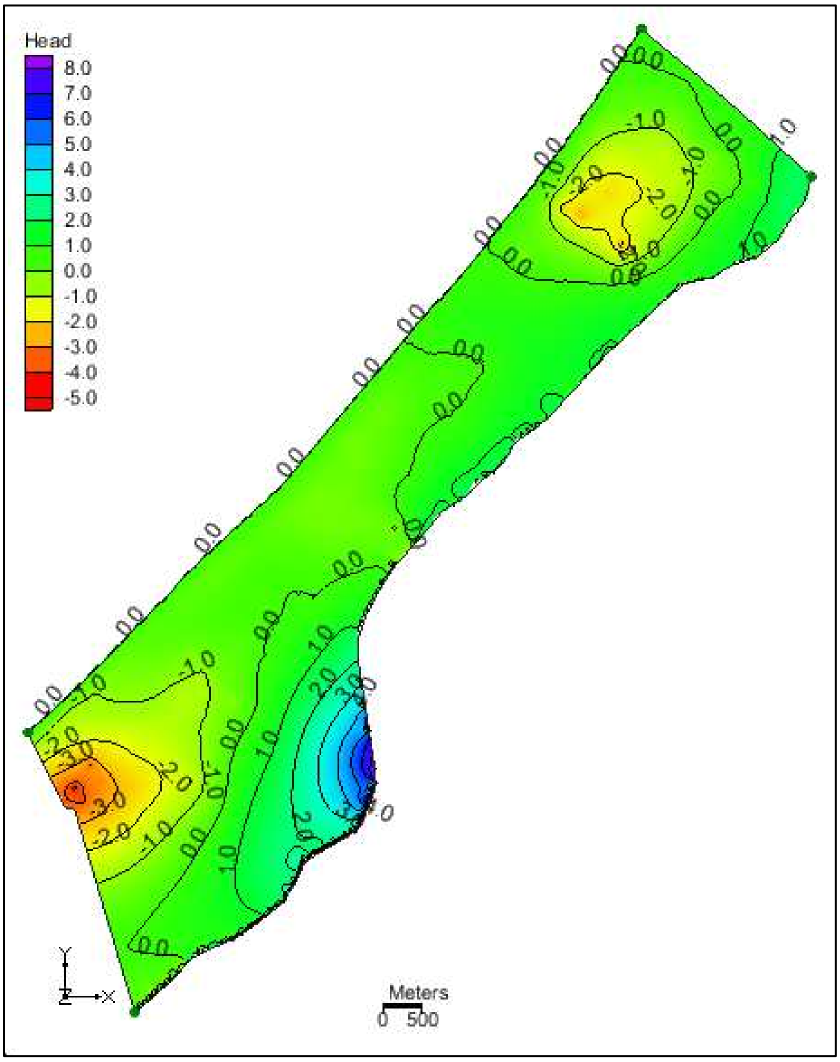


Figure (6.12) Calibrated groundwater head for year 2000.

The results of the steady-state (head) calibration were evaluated both qualitatively and quantitatively. Model calibration results were evaluated qualitatively by comparing contoured maps of calibration target water level to the model head solution. The error in the model head solution was also quantified by determining the mean error, mean absolute error, standard deviation, and sum of squares for the model residuals. The calibrated steady-state head solution has a residual mean of 0.07 m, an absolute residual mean of 0.45 m, a root mean squared error residual of 0.75 m, and a residual sum of squares of 151.79 squared m. The statistical measurements and the contoured water level maps show that the calibrated steady-state head solution reasonably matches the water levels in the target wells. Scatter plot of measured against simulated heads was used to show the calibrated fit. The scatter plot of computed and observed values is shown in figure (6.13). Table (6.2) presents Steady state groundwater budget for the entire model. The recharge rate is 207801.4598 m3/d and the abstraction by wells is 265592.8331 m^3/d.

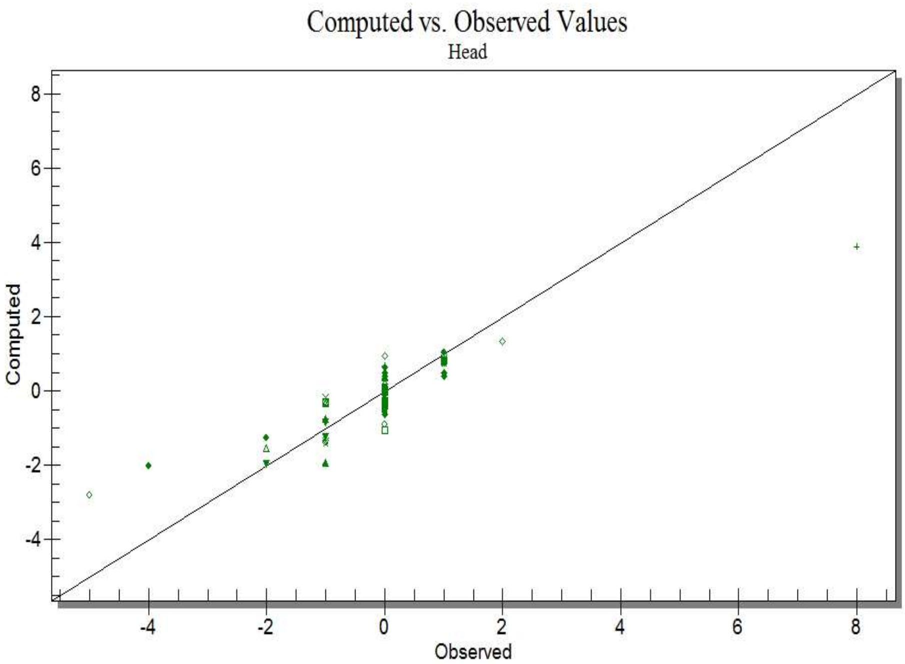


Figure (6.13) Scatter plot of computed and observed values.

Budget term	Flow m^3/d
IN:	
Constant heads	317283.5608
Wells	0
Recharge	207801.4598
Total IN	525085.0207
OUT:	
Constant heads	259492.1872
Wells	265592.8331
Recharge	0
Total OUT	525085.0203
SUMMARY:	
IN - OUT	0.000395326

Table (6.2) Steady state groundwater budget for entire model.

6.8 Transient model development

The development of the transient model of Gaza strip was based on the previously explained steady state model. The model has a nine stress period, each one aggregated in ten time steps. The EXCEL spreadsheet was used to generate the MODFLOW well and recharge files for the target period simulation from 2001 to 2009. Pumping rates for municipal wells increase year by year while the pumping rate for agricultural wells does not change.

6.8.1 Transient model calibration

Transient calibration was conducted for the 2001–2009 target period, using the calibrated steady state results as an initial condition. The transient model was run in a trial and error fashion to calibrate the recharge and storativity parameters. All other parameters are in agreement with the parameters used in the steady-state model. Calibration was accomplished by starting with a uniform storativity for all model cells. The calibrated values of specific storage range from 0.0001 to 0.1 %. The calibrated transient head solution has a residual mean of - 0.3 m, an absolute residual mean of 0.57 m, a root mean squared error residual of 0.72 m, and a residual sum of squares of 591.55 squared m. Figure (6.14) shows the scater plot of measured against simulated heads and the calibration fit. Satisfactory agreement between the simulated and observed groundwater levels was achieved at the majority of observation points as shown in figure (6.15).

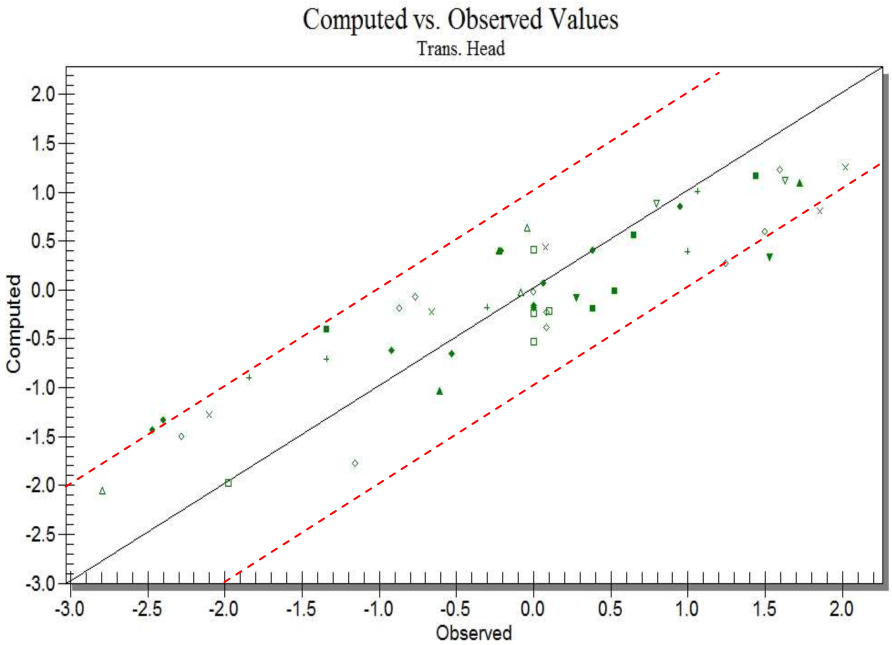
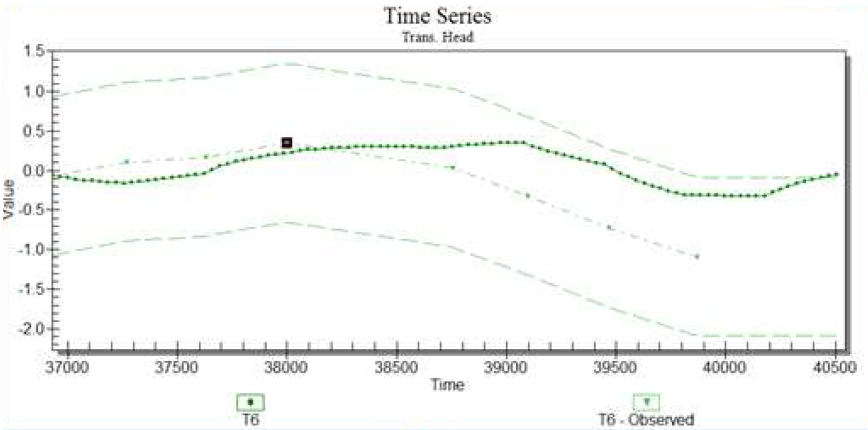


Figure (6.14) The scatter plot of the simulated heads.



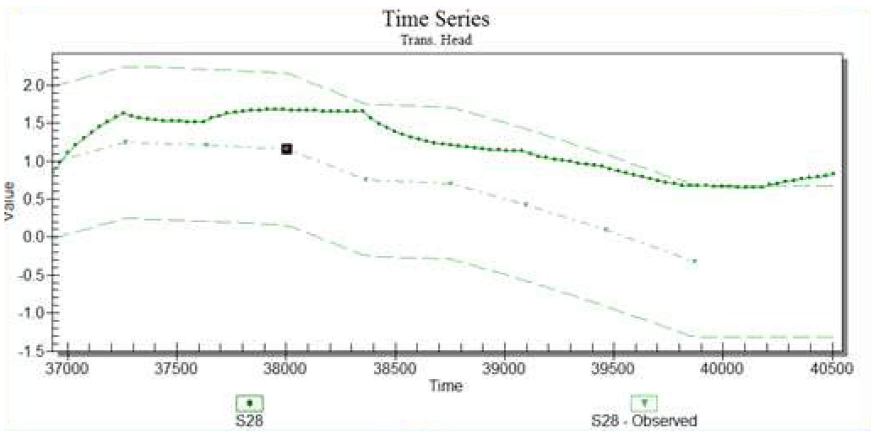
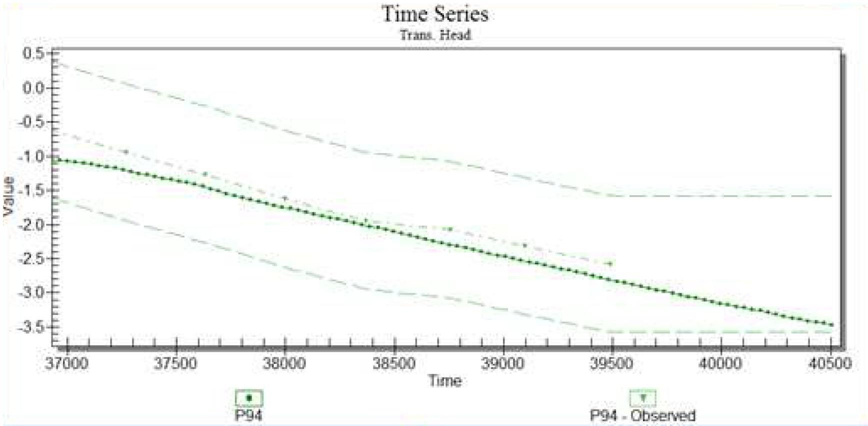


Figure (6.15) Measured and simulated heads for some observation wells.



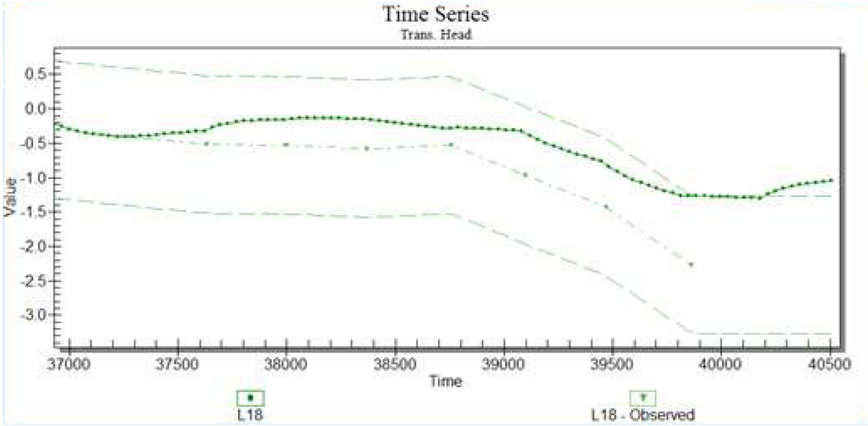


Figure (6.15) Measured and simulated heads for some observation wells.

Chapter 7

Management Scenarios

Chapter 7: Management Scenarios

7.1 Introduction

The Gaza transient flow model successfully simulates the groundwater flow patterns for the 2001-2009 period. The model was calibrated according to the criteria previously described. Calibration of the transient model for the past conditions was an essential step in order to forecast the future groundwater levels.

In coastal aquifers, groundwater level is an important parameter for monitoring the sea water intrusion since a groundwater level below MSL is a significant indicator of seawater. Over exploitation of ground water in Gaza strip has created a heavy depletion of the groundwater level in many zones and consequently a great potential risk of seawater intrusion occurrences. Groundwater level declined by several meters in southern and northern regions of Gaza strip forming deep depressions. The present management scenarios are aimed to find the suitable solution to manage withdrawal and sea water intrusion control in coastal Gaza aquifer.

7.2 Scenario Development Process

The development of scenarios generally begins with the characterization of the current situation (Gallopin, 2002). This means the identification of the principal issue to be studied. The central issue to be addressed in this study is the impact of continuous pumping on the groundwater level and using of additional water recourses (treated waste water) to control the sea water intrusion. Current conditions have been characterized in the previous chapters of this thesis.

Transient model simulations were run for three scenarios as following:

1) Increasing pumping rates from 2010 to 2030.

2) Decreasing the abstraction from the aquifer by closing wells localized on the depression zones and shoreline.

3) Using treated wastewater by injection wells localized on the depression zones and shoreline.

Development of these management scenarios was based on the Coastal Aquifer Management Plan (CAMP) adopted by Palestinian Water Authority for the next 20 years. The CAMP was based on the three driving forces identified as critical to developing the groundwater resources of the Gaza aquifer which are population growth, sustainable uses and using of additional water recourses. While these three factors cannot account for all of the potential variability in future groundwater use, they are believed to be the factors that will impact groundwater levels most substantially over the next 20 years. The future water consumption adopted by the CAMP was based on the population growth projected for the next 20 years. The projected domestic and agricultural demand for the next 20 years is presented in table (7.1). In this table domestic demand includes net demand for domestic, industrial, public customers, livestock water supply, water losses through transmission pipeline and water distribution system are included (Yaqubi, 2006). The future agricultural demand was planed considering the future land use changes where the urban areas will expand onto agricultural land, resulting in a decreasing agricultural demand through the next 20 years as illustrate in table (7.1). Generally, the overall water demand in Gaza Strip is estimated to increase from 2000 146 x 10^6 m^3/yr to about 260 x 10^6 m^3/yr in 2020 (Yaqubi, 2006). Treated wastewater and desalination are considered as additional water resources in CAMP with 63 x 10^6 m^3/yr and 57 x 10^6 m^3/yr respectively in 2020 (Yaqubi, 2006). Table (7.2) presents the total water consumption from 2000 to 2020 from different available water recourses.

Year	Population	Agricultural water demand	Municipal water demand	Total	Available resources	Gap
2000	1167359	91	55	146	109	-37
2005	1472333	92	100	192	131	-16
2010	1871144	88	125	312	137	-76
2015	2241206	86	152	238	145	-93
2020	2617823	80	182	262	155	-107

Figure (7.1) The projected domestic and industrial demand for the next 20 years. (source: PWA, all data are x 10^6 m^3).

Water resource	2000	2005	2010	2015	2020
Coastal aquifer	55	92	100	119	148
Brackish ground water	51	35	32	20	0
Wastewater re- use	0	23	34	48	63
Desalination	0	24	47	55	57
Storm water recharge	3	4	5	6	7
Israel	5	10	10	10	10
Total	114	188	228	258	285

Figure (7.2) Total water consumption in 2020 from different water recourses available. (source: PWA, all data are x 10^6 m^3).

The applied scenarios are based on the following assumptions:

1- Current pumping rate for year 2009 is 150 x 10^6 m^3. Pumping rates are planed to increase in municipal wells gradually based on table (3). For all scenarios, from 2020 until 2030 the pumping rates are kept fixed since the population growth is predicted to decrease after 2020, so the water consumption will not increase. The pumping rate of the agricultural wells in 2009 is kept fixed for all the investigated period because there are no significant changes predicted for the investigated period as planned in CAMP.

2- No climate changes are considered for all the simulation period. This is due to two primary reasons. First, there exists great uncertainty regarding any application of global climate models to regional and localized conditions. Second, the time period under investigation from 2009 to 2030 is not long enough to see the full effects of global climate change as an important factor that will influence future water supply and demand in the area.

3- For each scenario, results are presented in terms of changes in groundwater levels.

7.3 Scenario 1

The first scenario simulate the impact of continuous increasing of pumping rates without any use of additional water resources for the target simulation period from 2010 until 2030. The simulation results indicate that continuous pumping without sustainable management would increase obviously the groundwater level decline already present in the aquifer in 2009 relative to pre-development conditions. The areas of additional groundwater level decline localised in the pre-existing depression zones in the north and south of the model. Simulation results are shown in figures (7.1), (7.2) and (7.3) for years 2010, 2020, and 2030 respectively. The figures reflect the aquifer behavior under continuously increasing pumping rates for the next 20 years.

The simulation results indicate that continuous pumping will result in total groundwater level decline relatively to predevelopment conditions that exceeds 5 m. The greatest additional water level decline occurs in the southern region of the Gaza strip, with an additional groundwater table decline from -12 m to more than -16 m below MSL. The other significant additional groundwater level decline extends over the northern region of the strip, where the groundwater table decline from is - 5 to more than - 9 m below MSL. The groundwater level change in the middle regions of the strip remains of smaller magnitude for all the investigated period and decreasing from east to west with some local lowering related to high pumping rates.

The pre-existing depression zones in the north and in the south of the Gaza strip represent a realistic concern in the future management of Gaza aquifer. These zones are characterized by a high potential sea water intrusion risk for the next 20 years and should be managed sustainably to control sea water intrusion.

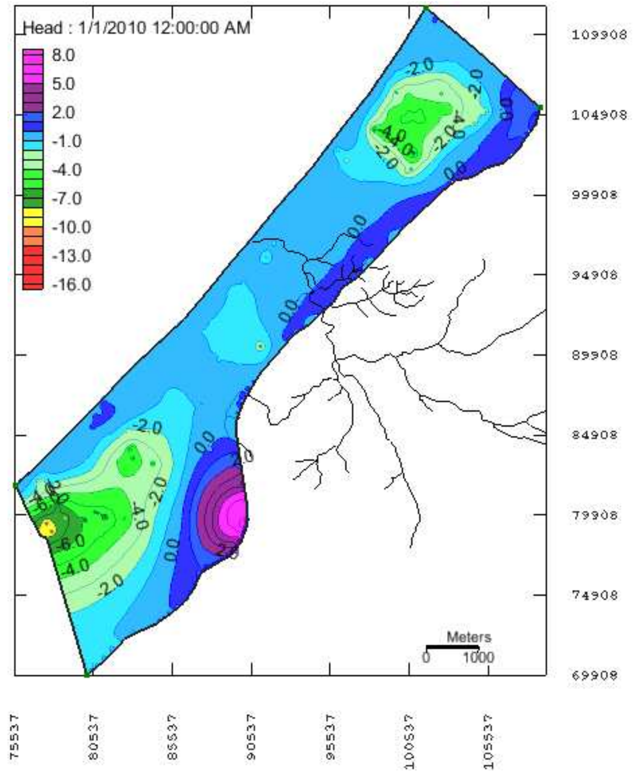


Figure (7.1) Simulated ground water level for the year 2010 under increasing pumping effect (Scenario 1).

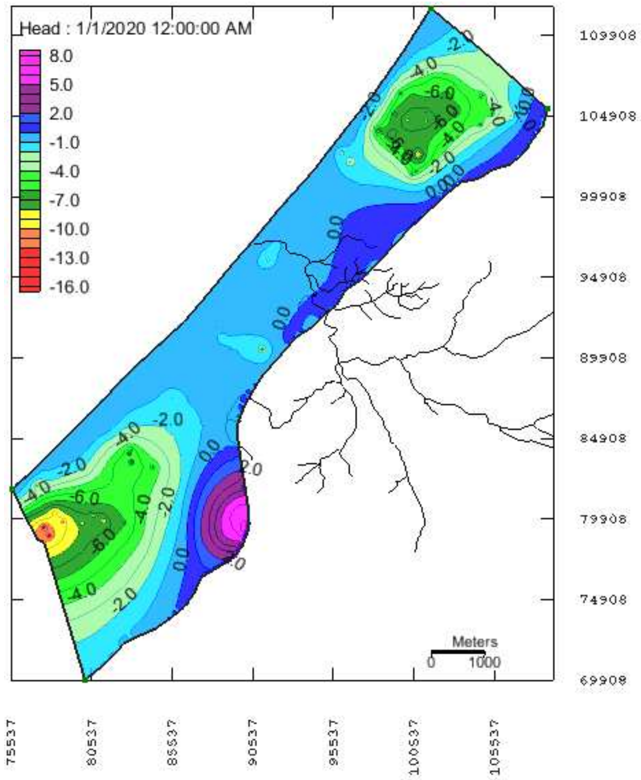


Figure (7.2) Simulated ground water level for the year 2020 under increasing pumping effect (Scenario 1).

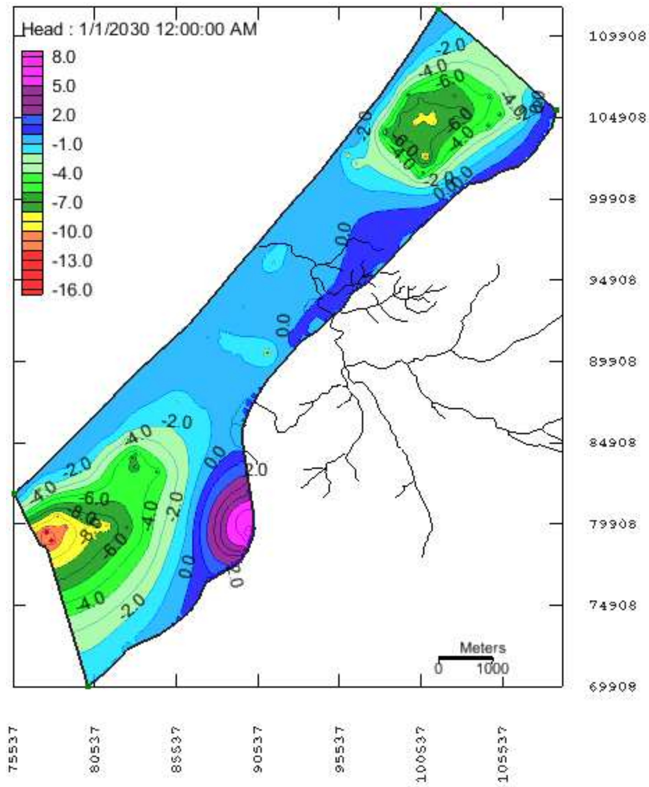


Figure (7.3) Simulated ground water level for the year 2030 under increasing pumping effect (Scenario 1).

7.4 Scenario 2

The second scenario intends to simulate the impact of decreasing abstraction rates from the aquifer on the ground water level. Based on the results of the first scenario, it was possible to identify the future extent of the two critical groundwater level decline zones in the Gaza aquifer. In this scenario all pumping wells are considered as active wells except theses located on the verified depression zones and at the shoreline, which have been considered as inactive for all the target simulation period. Figure (7.4) shows inactive selected wells inside the black polygons. This scenario reflects the aquifer response in case of no pumping under normal recharge condition. Figure (7.5), (7.6), (7.7) depict the aquifer remediation particularly, in the northern and southern depression zones for the simulation years 2015, 2020 and 2030, respectively. The groundwater level increased by more than 10 m. In the north, the groundwater level reached 6 m above MSL while in the south the groundwater level reached 3 m above MSL by 2030. The simulation results indicate that the pumping wells play a substantial role in the aquifer depletion and decreasing groundwater level. Closing wells placed in these zones eliminated all the negative head zones in the Gaza aquifer and remediate the groundwater level by several meters above MSL. This indicates that the pumping from these zones has a great influence on the ground water levels. Therefore, pumping rates should be planned in the future to be reduced in order to remediate the groundwater level and avoid the intrusion of seawater in the aquifer.

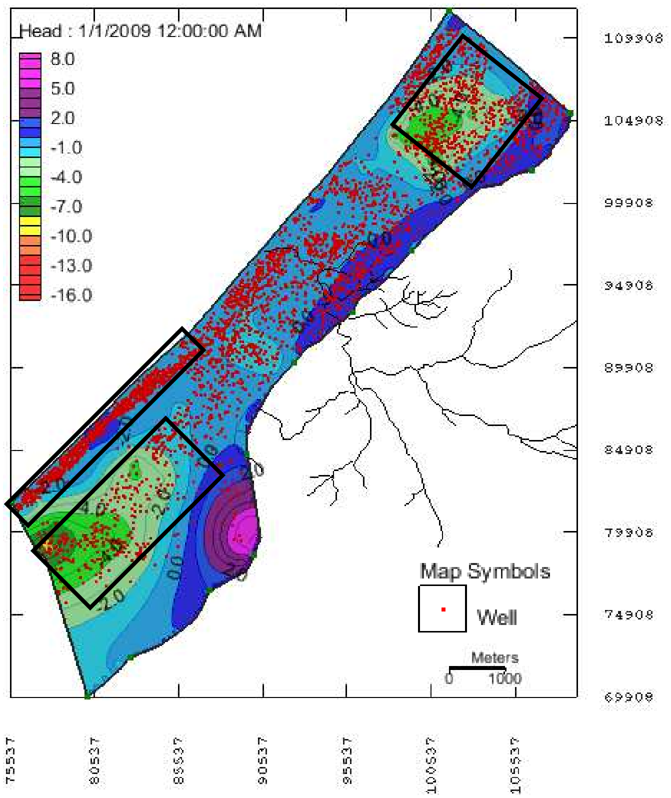


Figure (7.4) Inactive selected wells inside the black polygon (Scenario 2).

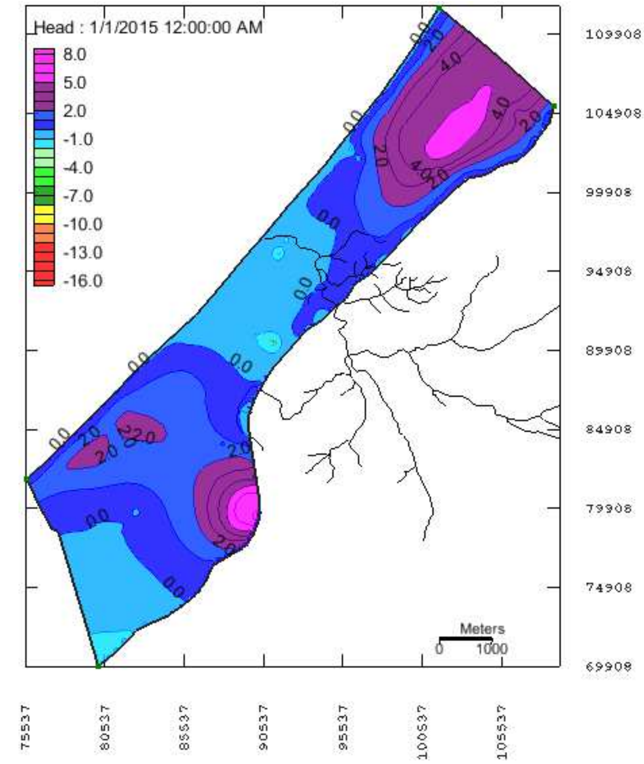


Figure (7.5) Simulated groundwater level for the year 2015 under pumping reduction (Scenario 2).

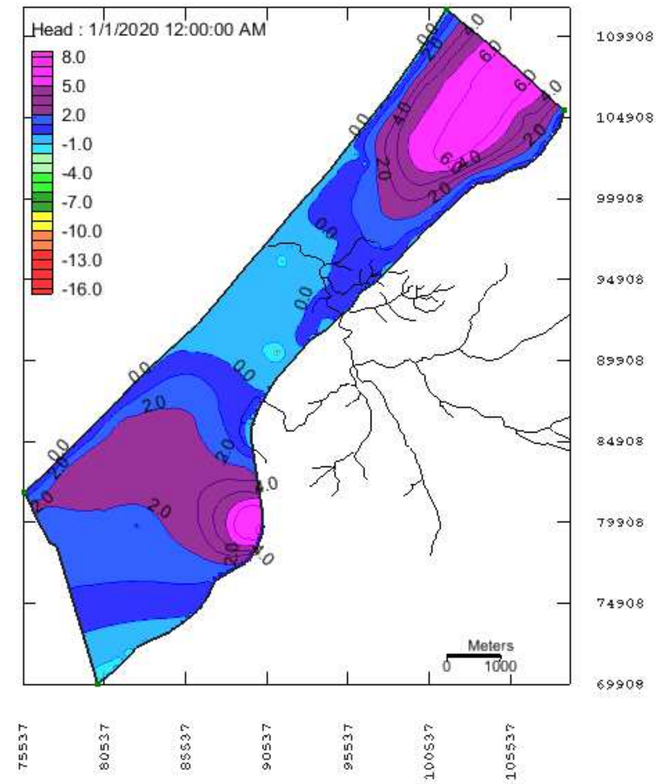


Figure (7.6) Simulated groundwater level for the year 2020 under pumping reduction (Scenario 2).

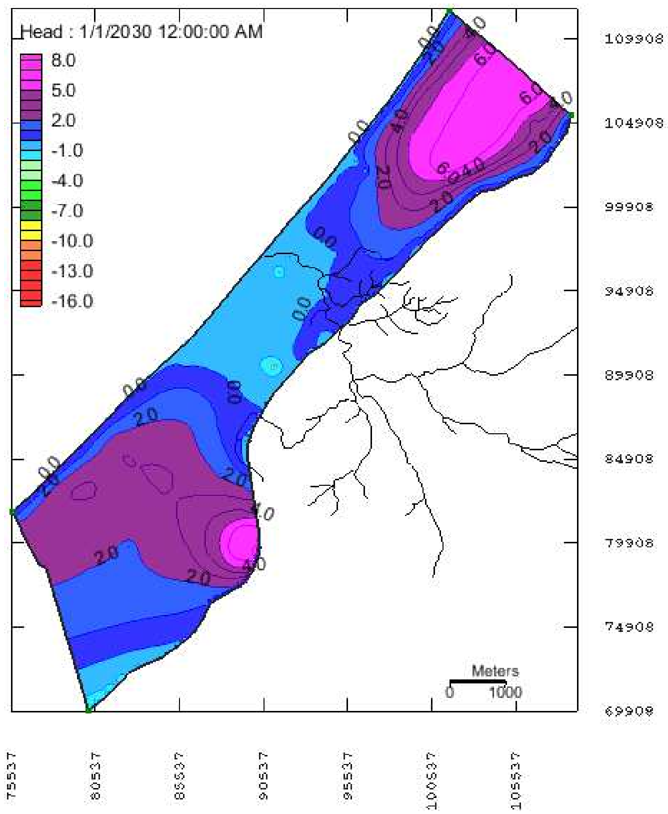


Figure (7.6) Simulated groundwater level for the year 2030 under pumping reduction (Scenario 2).

7.5 Scenario 3

This scenario investigated the use of additional water resources to remediate the groundwater level and control sea water intrusion in the study area, under continuous increasing pumping rates. The treated wastewater is one of the main options that can be used in the management of the water resources in the Gaza Strip as it represents an additional renewable and reliable water source (Afifi, 2000). The quantity of treated wastewater used in this scenario is based on the projected use of treated wastewater by PWA for the future as shown in table (7.2) for the investigated period. The treated wastewater added for the model by injection wells located on the verified depression zones and at the shoreline as shown in figure (7.7). The total treated wastewater used for the investigated period increased gradually from 40 MCM in 2010 to 60 MCM in 2020. From 2020 until 2030 the recharge rate was fixed at 60 MCM/yr. In this scenario all pumping wells were considered active wells for all the investigated period.

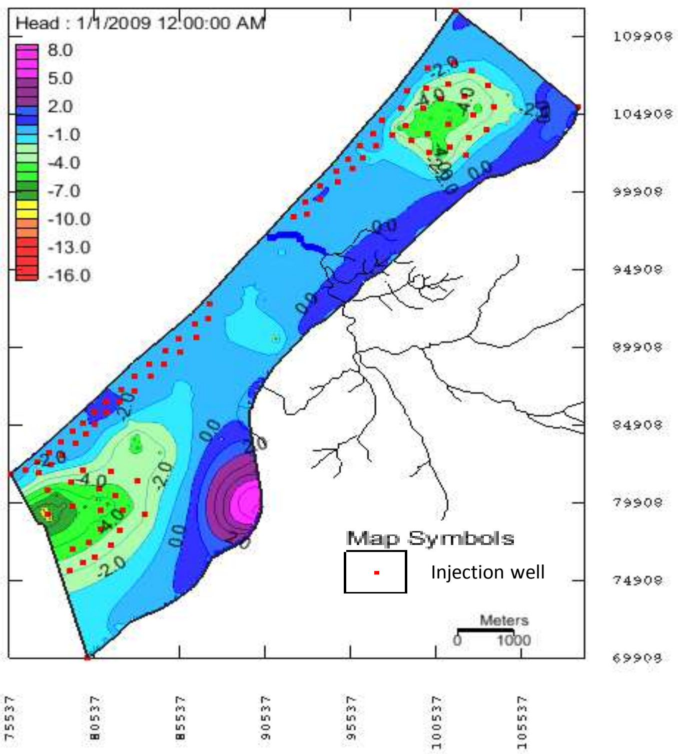


Figure (7.7) Location of the injection wells added to the model.

Figure (7.8), (7.9), (7.10) and (7.11) demonstrate the simulation results for years 2015, 2020, 2025 and 2030 for the target simulation period, respectively. The simulation results show a slowly increase in the groundwater level from 2010 to 2020. The groundwater level remediated by several meters in the north, south and at the shoreline. Areas that have groundwater levels within or/and above MSL, were increased specially at the shore line and in the northern part of the wadi Gaza, the two depression zones in the north and south were remediated by 1 and 3 m respectively, however the ground water level remain below MSL. This is because the aquifer in this period was under the control of the continuous increase of pumping rates which kept the ground water level under the MSL in these zones. From 2020 until 2030 the groundwater level remediates considerably by more than 5 m in the north and in the south. In this simulated years the aquifer response was more positive to the injection wells, this is because the pumping rate was fixed for this simulated years because the population growth is predicted to decrease after 2020, so the water demand will not increase.

Simulation results show that the use of treated wastewater has eliminated the negative head in the northern region by 2030 and decreasing the area with negative head in the southern region. Injection wells at the shoreline have a notable positive impact where the groundwater level increase by more than 2 m. This will creates a sufficient pressure to push the sea water interface towards the sea. Increasing the aquifer recharge by using treated wastewater appears as a practical and convenient solution to remediate groundwater level and prevent seawater intrusion.

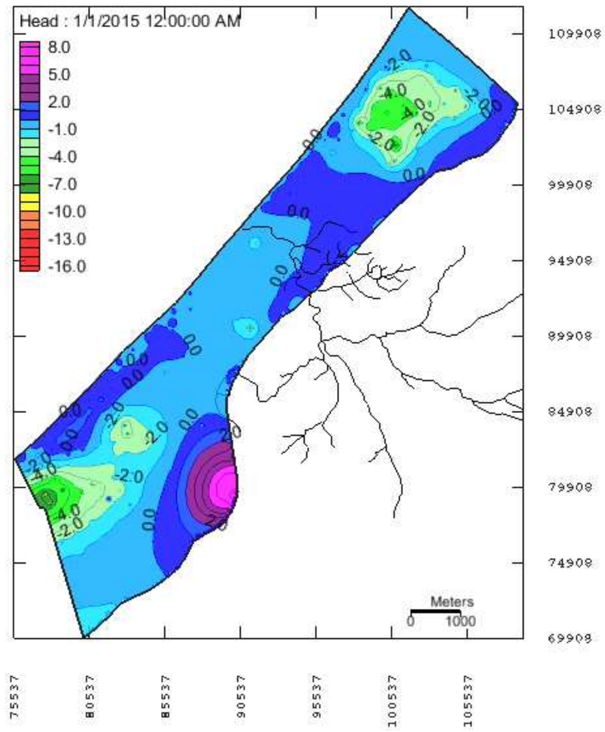


Figure (7.8) Simulated ground water level for the year 2015 under increasing recharge (Scenario 3).

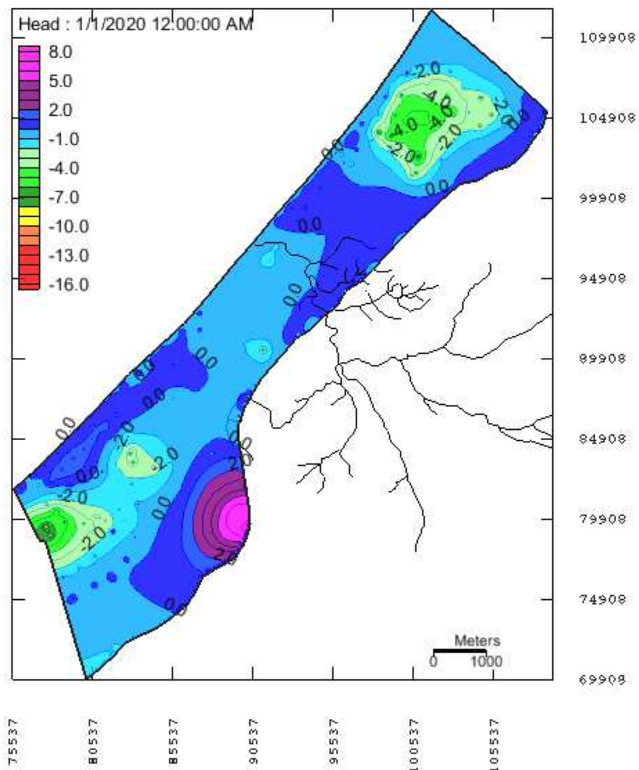


Figure (7.9) Simulated ground water level for the year 2020 under increasing recharge (Scenario 3).

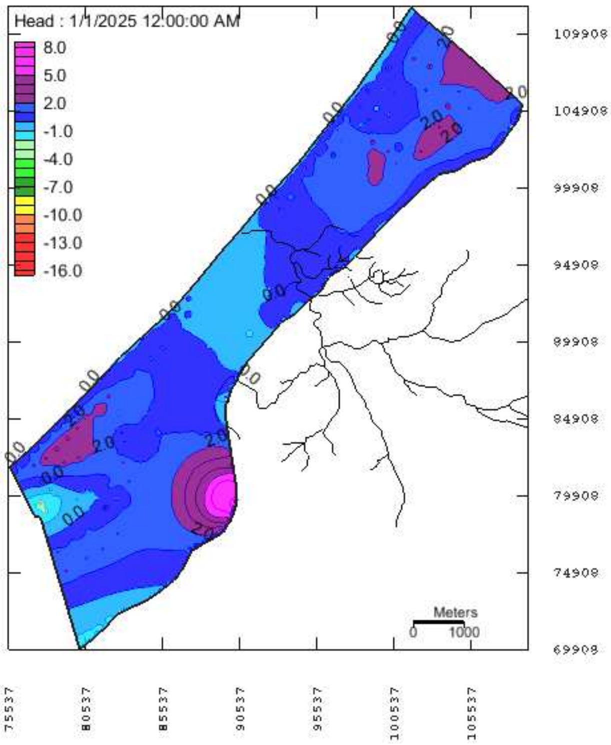


Figure (7.10) Simulated ground water level for the year 2025 under increasing recharge (Scenario 3).

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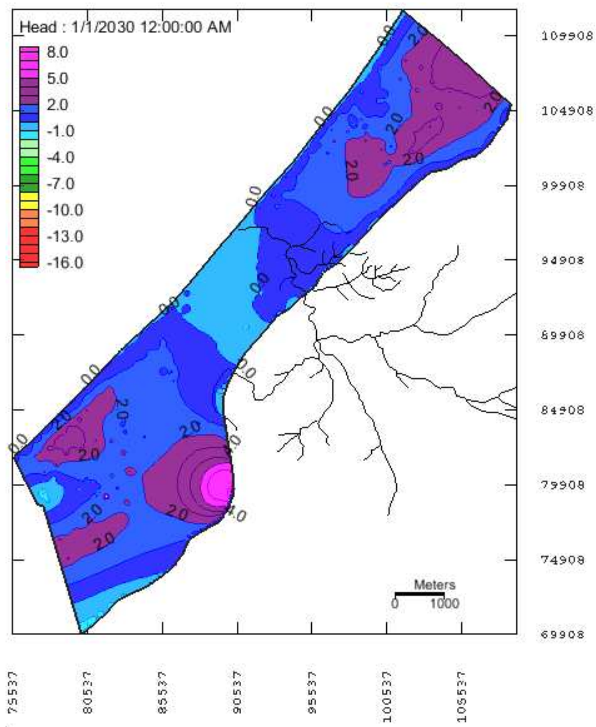

Figure (7.11) Simulated ground water level for the year 2030 under increasing recharge(Scenario 3).

7.6 Discussion

Three potential management scenarios where discussed in this chapter: continuous increasing of pumping rates, reducing the pumping rates from the aquifer and injecting water into the aquifer. While the first scenario shows the impact of continuously increasing pumping rates on the groundwater level and sea water intrusion, the two other scenarios are hydraulically successful in solving these problems.

The simulation results indicate that the pumping wells play a substantial role in replacing groundwater level in the aquifer, therefore, should there be considered as a critical factor in the aquifer management and seawater control.

Closing pumping wells placed on the depression zones and at the shoreline in order to remediate the groundwater level and prevent the sea water intrusion, give the best results as the groundwater level remediate by several meters above MSL. However, this solution involving research for other fresh water resources to cover the water quantity pumped by these wells, makes this solution unpractical and costly being is the main problem of Gaza strip the water scarcity.

Using of treated wastewater under continuously increasing pumping rates through injection wells shows good benefits all over the aquifer. Ground water level increases several meters above MSL in the north while in the south the groundwater increases by several meters but still lower below the MSL. The treated wastewater represents an additional renewable and reliable water source that can be used in the management of the water resources in the Gaza Strip. Using treated wastewater in groundwater remediation and seawater intrusion controlling appears as the more practical and convenient solution.

Conclusions and recommendations

7.7 Conclusions

The Gaza aquifer is an active dynamic groundwater system where considerable changes in hydraulic components occur continually. The preexisting equilibrium condition between fresh and saline water has been disturbed by large scale pumping. The aquifer has been overexploited for the past 50 years.

Data analysis applied in this thesis and recent studies indicate that there are ongoing problems of aquifer withdrawal and saltwater intrusion in the Gaza strip. The continuous groundwater level lowering and the high salinity are the main indicators of these problems.

The Gaza aquifer vulnerability to sea water intrusion is predicted to increase in the future due to the occurrence of these problems.

The developed numerical model was applied to evaluate the overall regional impact of pumping and recharge variation on the aquifer for three future management scenarios. The first scenario is to pump from the aquifer continuously until the year 2030 when the pumping rate reaches 260 x 10^6 m^3/yr; the second scenario is to decrease the pumping rates from the aquifer and the third scenario is to inject the treated wastewater progressively to the aquifer, starting at 40 x 10^6 m^3/yr in the year 2010, to 60 x 10^6 m^3/yr in the year 2030 through injection wells. It is predicted that between years 2010 and 2030, the first scenario will induce a considerable decrease in ground water levels and consequently a high potential risk of sea water intrusion occurrence. The second and the third scenarios will solve the problem of aquifer withdrawal and control the sea water intrusion.

The results of these scenarios confirm the efficiency of CAMP adopted by PWA for the next 20 years to improve the quantity and quality of the Gaza coastal aquifer by integrating many alternatives which lead to aquifer, and reduction of the seawater intrusion.

7.8 Recommendations

The following recommendations can be presented as a result of the present study:

- Appropriate investments should be made to ensure that each of the major components of the hydrological water budget are adequately quantified, understood, and incorporated into the regional groundwater model.

- Random and illegal agricultural wells must be closed or used as injection wells to release the stress on the aquifer, particularly at the shoreline and in depression zones.

- Existing wastewater treatment plants must be developed to increase their capacity and efficiency in order to treat the wastewater adequately to be injected in the aquifer.

- Improving the wastewater network to reduce the aquifer contamination on the hand and on the other hand to increase the treated water quantity that can be used in agricultural or injected to the aquifer.

- Improving the water supply network to reduce pumping requirements and pipe seepage.

- Agricultural sector should be managed more efficiently through stopped the use of some pumping wells and use alternative water resources like low water quality and treated wastewater.

- PWA must go ahead in implementing the strategic plan for using of additional water resources to cover the future water demand.

- Development of a 3D coupled numerical model to simulate the seawater intrusion process in coastal aquifer. This model will be a helpful tool to identify the position of seawater interface and upconing.

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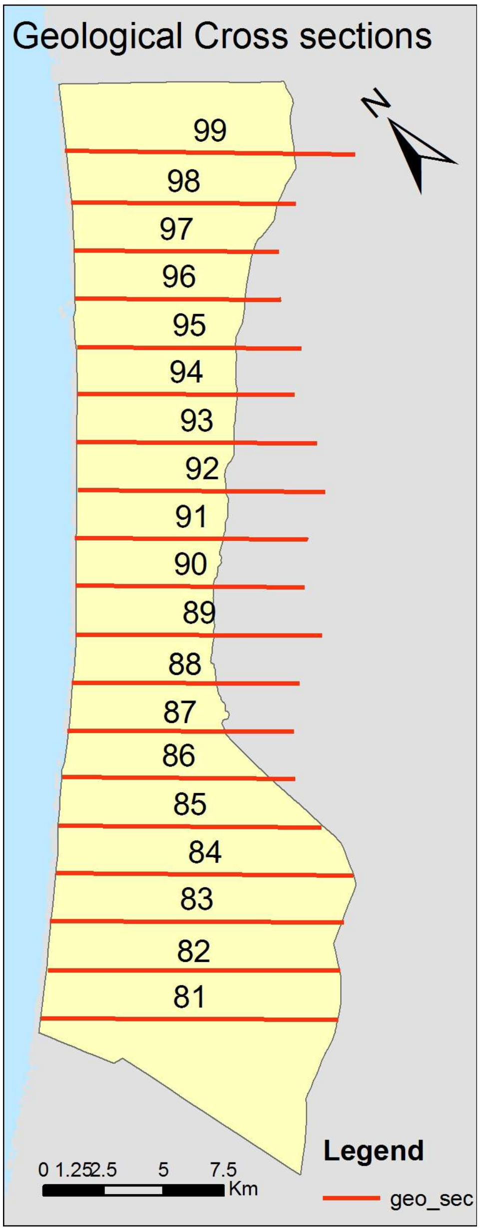
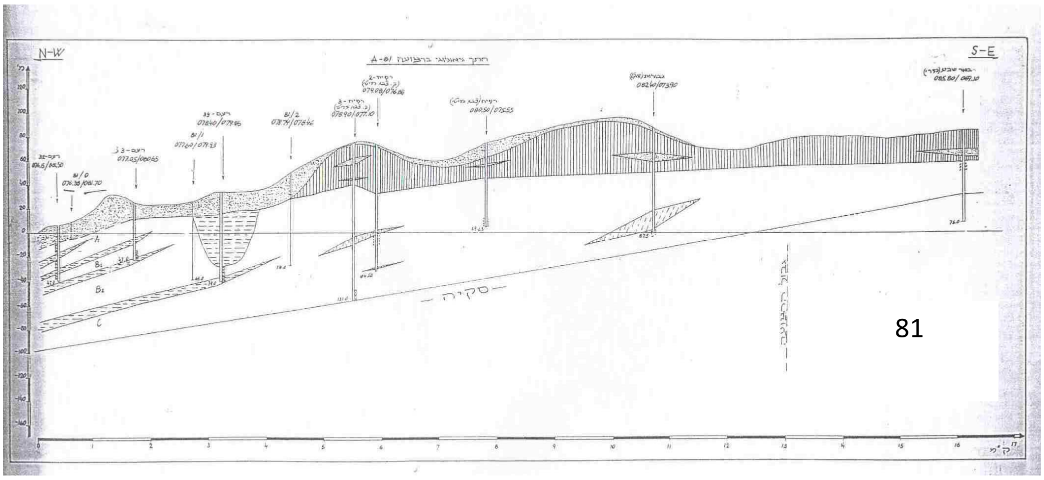
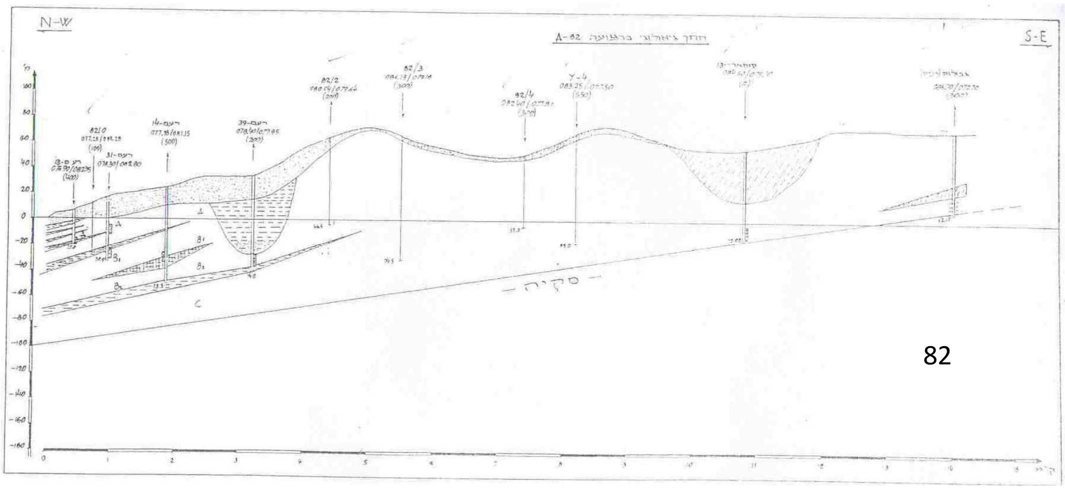
Appendix

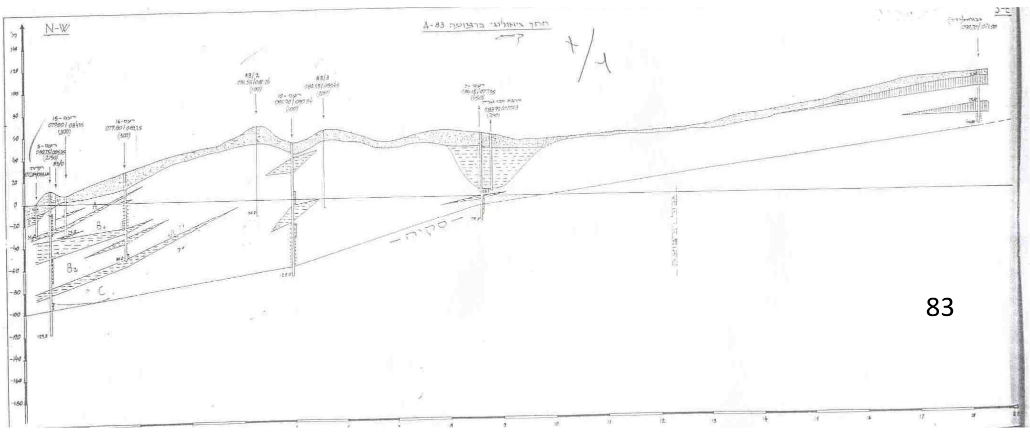
Appendix 1 Map of Geological cross sections distribution.

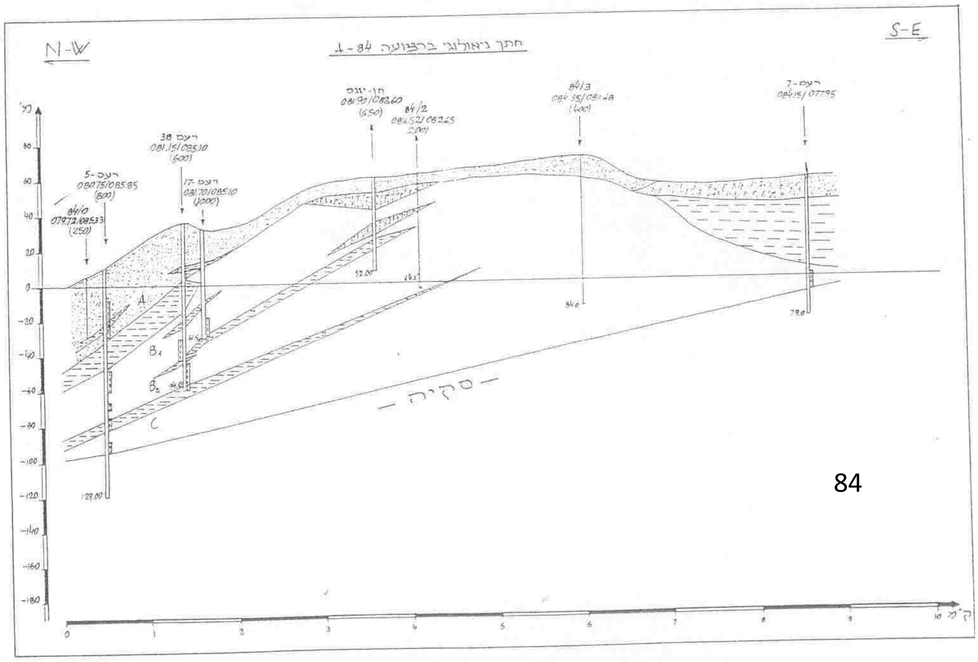


Appendix 2 Geological cross sections used in the model layer reconstruction.









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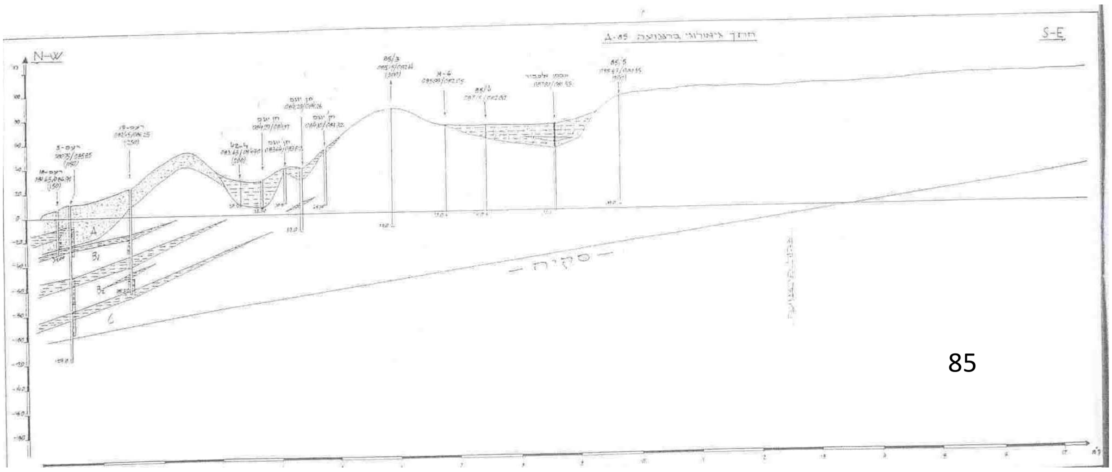

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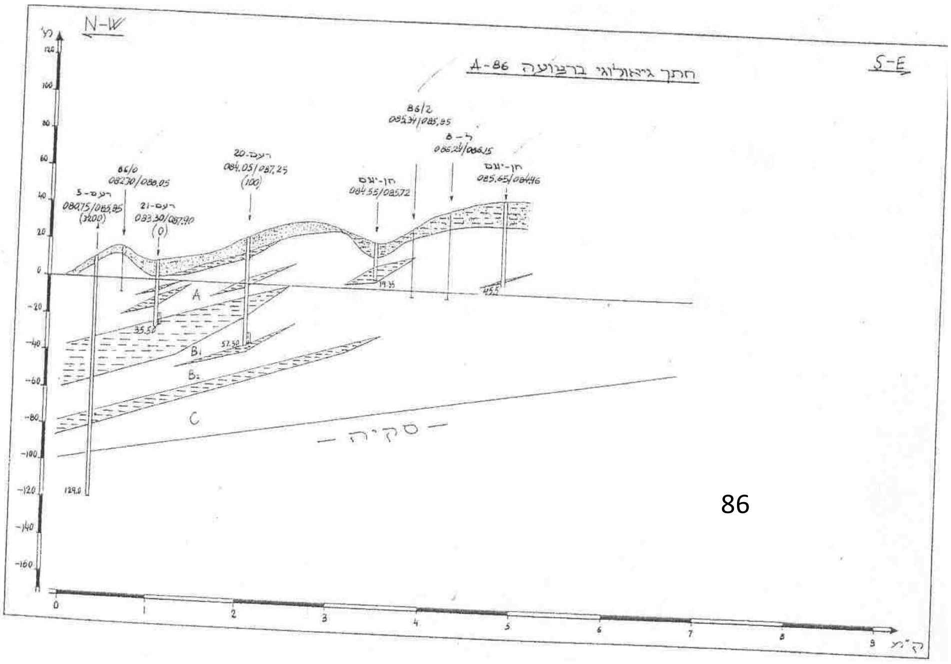

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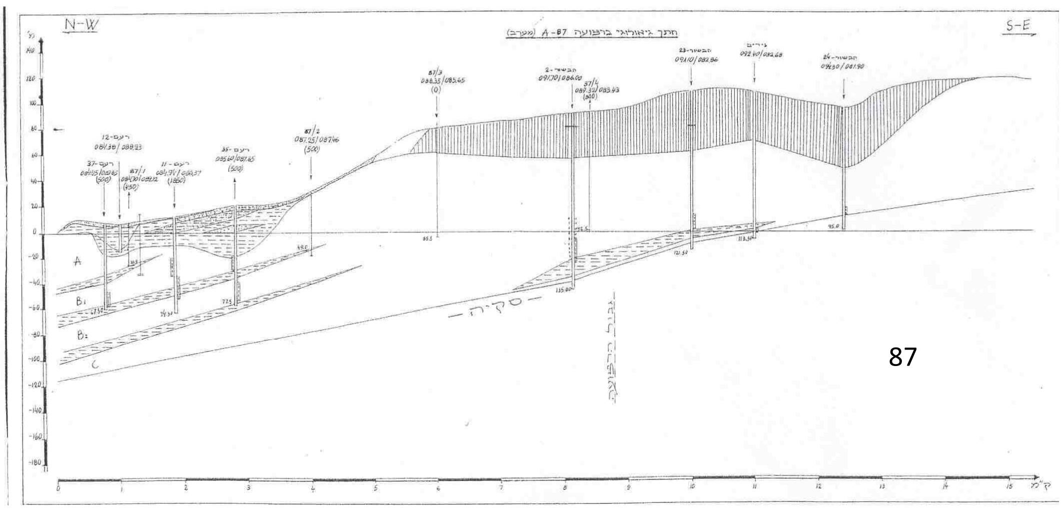

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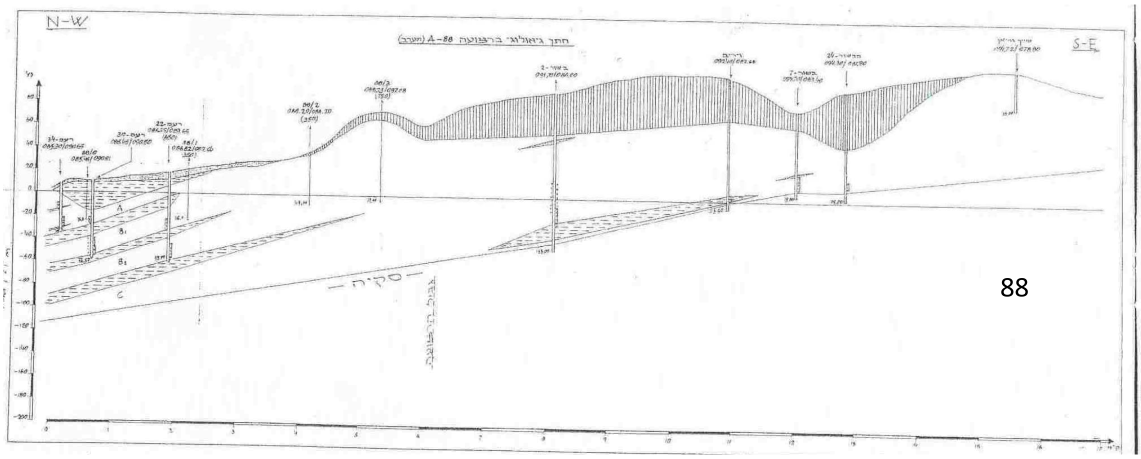

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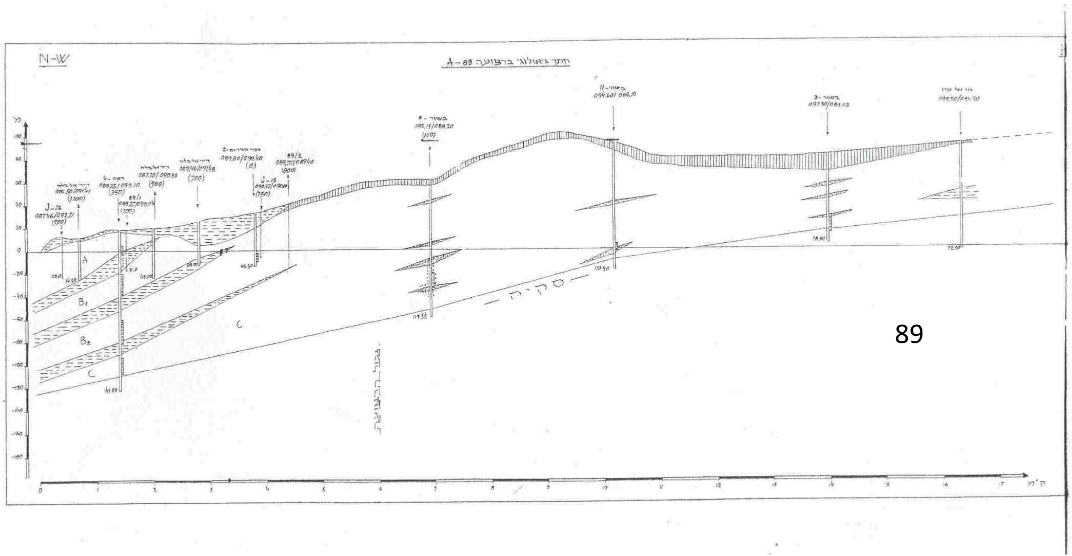

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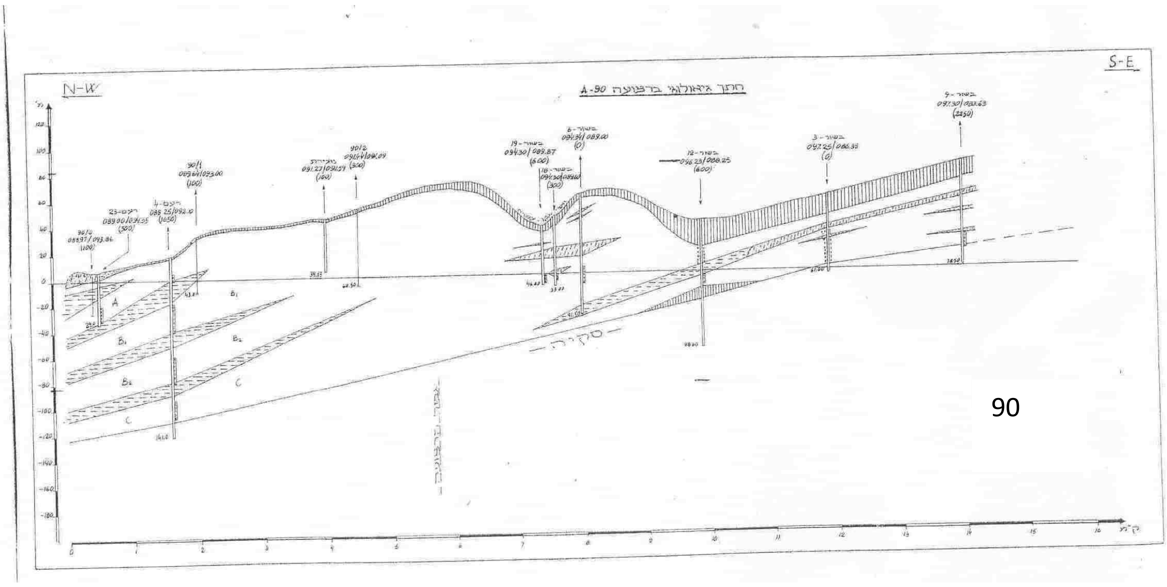
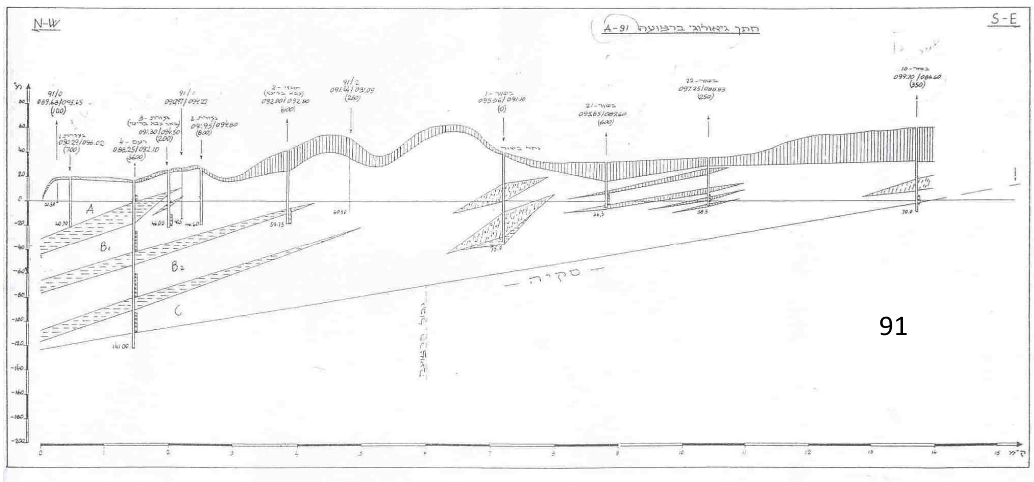

N-W
S-E
חתך גיאולוגי ברצועה A-90
A
B1
B2
C
סקיה

90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S-E
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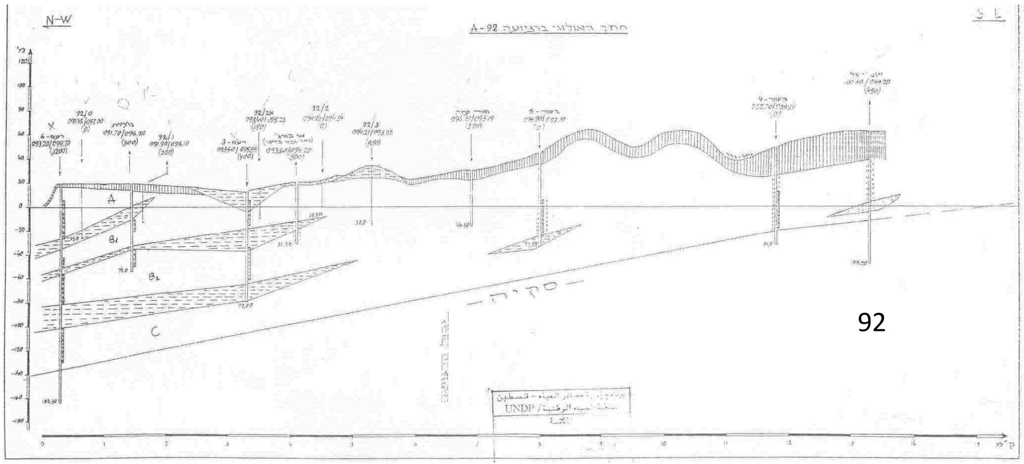
A
B1
B2
C
סקיה

91



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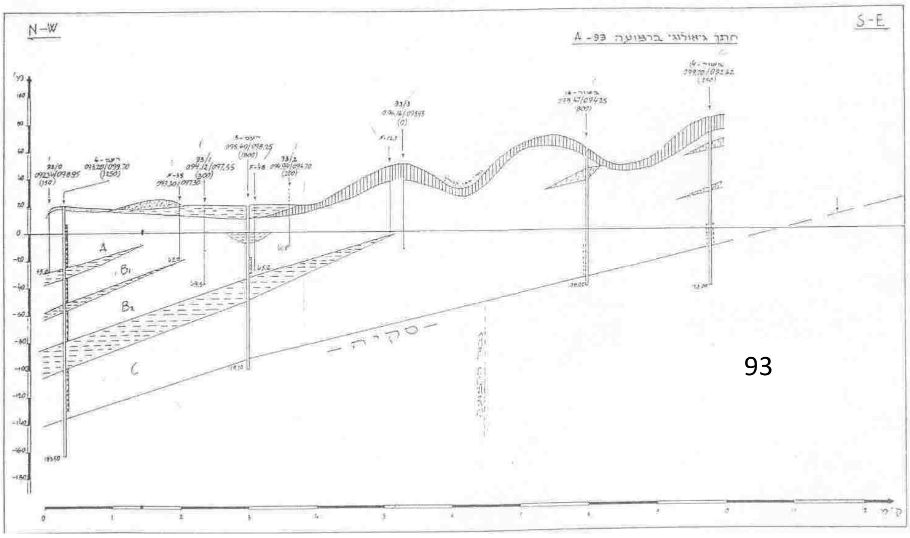

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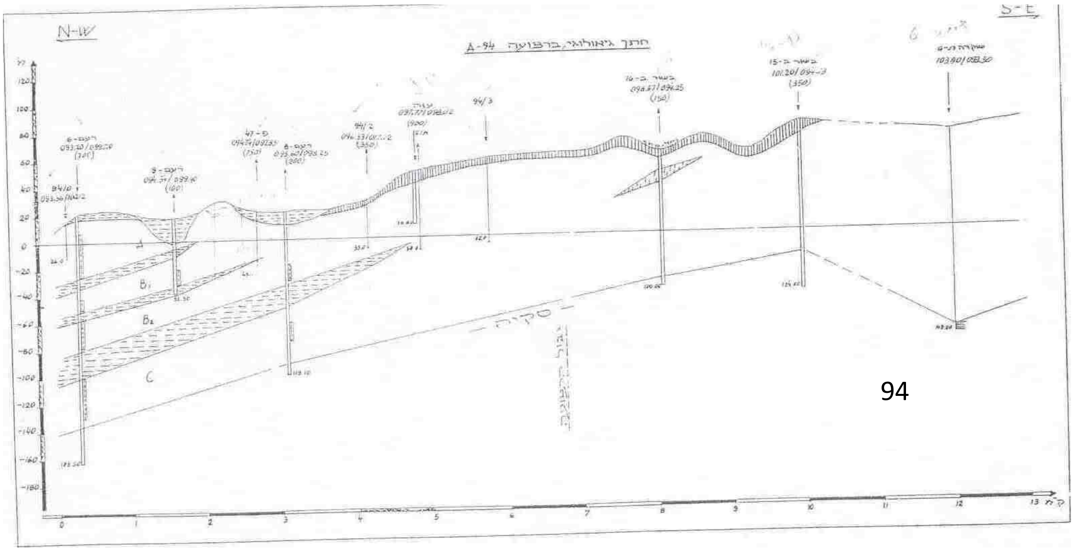

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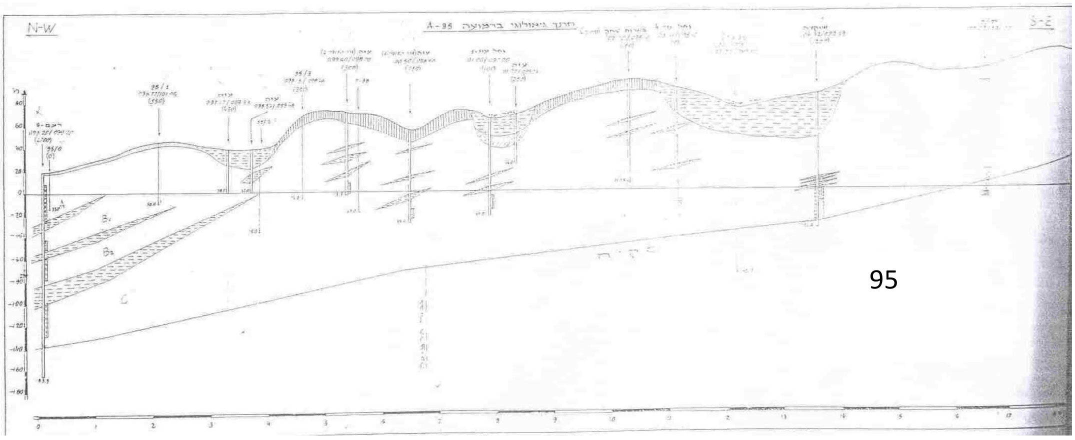

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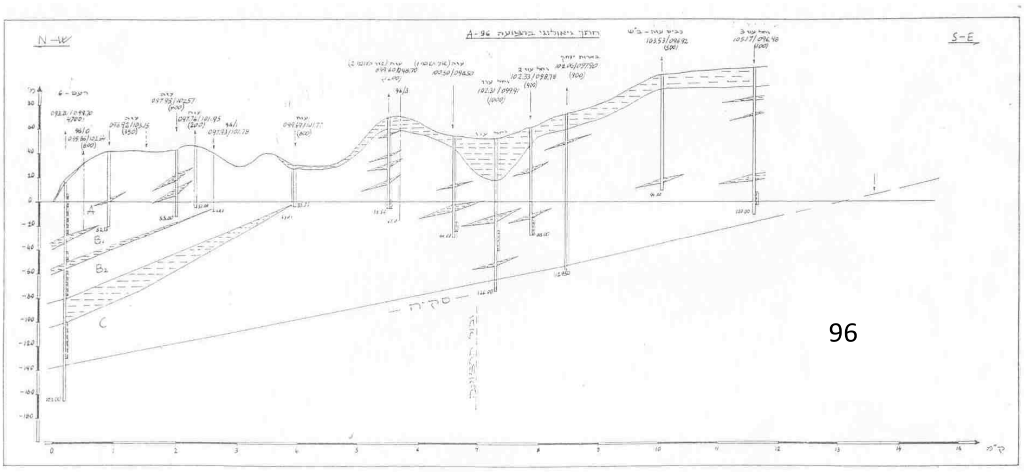

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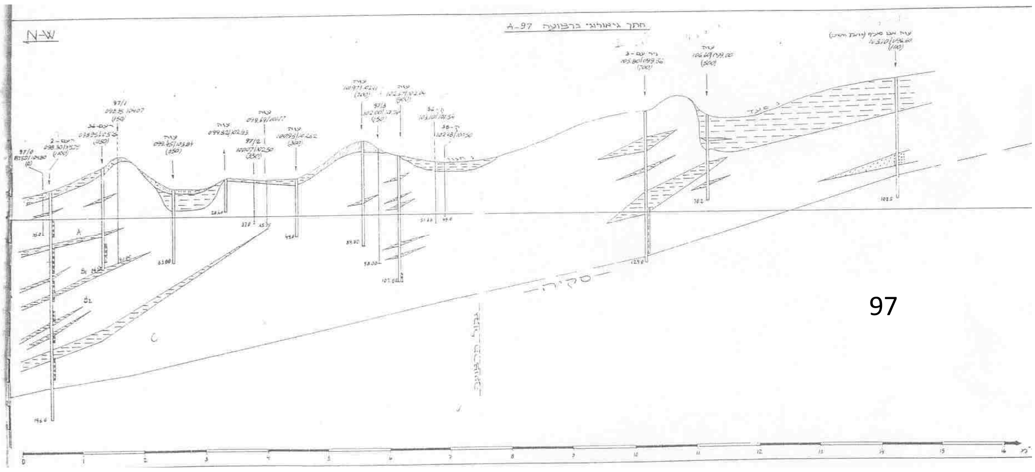

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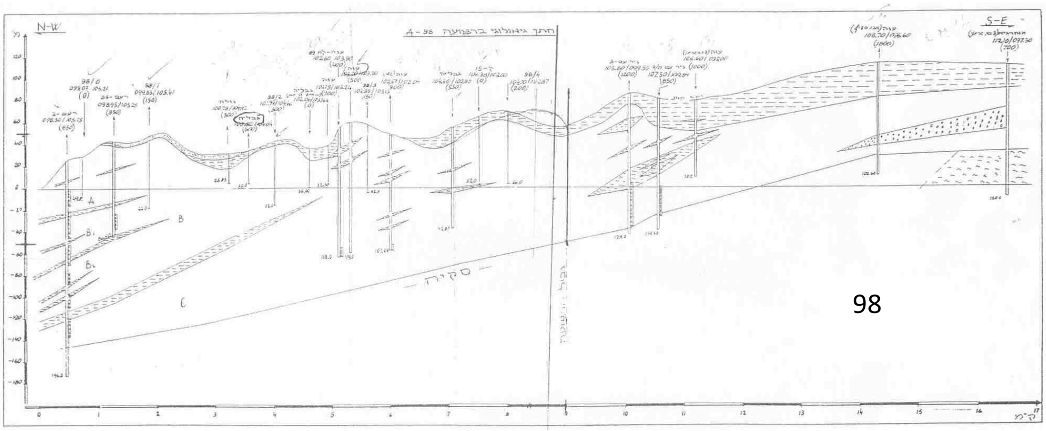

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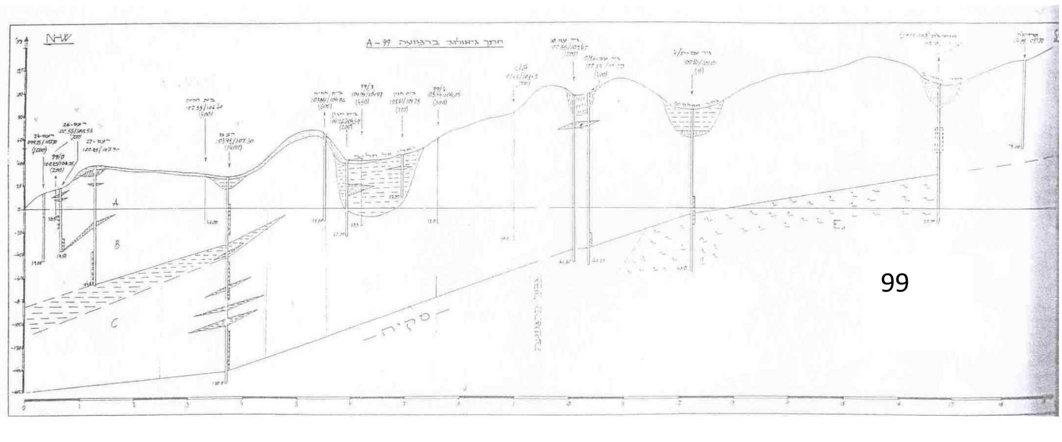

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