An-Najah National University
Faculty of Graduate Studies

IMPACT OF PUMPING ON SALTWATER INTRUSION IN GAZA COASTAL AQUIFER, PALESTINE

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I dedicate my thesis to my beloved mother and father, my brothers and sister, and to my friends

Abdelhaleem

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Abdelhaleem I. Saleh

Nablus, 2007

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Abstract

Gaza Coastal Aquifer (GCA) is the major source of water in Gaza Strip. Recent studies show noticeable deterioration in the water quality; where chloride, nitrate, sulfate, and fluoride concentrations are exceeding the maximum contaminant levels in most of the wells in Gaza Strip. Many agricultural wells are no longer used due to the high salinity. This high salinity is an indication of a phenomenon called saltwater intrusion which appears mainly in coastal aquifers due to the excessive pumping.

This study is an attempt to find out the impact of pumping on the hydraulic head at the coastline of Gaza Strip. To do so, a groundwater flow model was developed for GCA using MODFLOW-2000 based on data from the Palestinian Water Authority (PWA). The model was calibrated based on head observations obtained form PWA and contour maps from literature. The calibrated model was used to simulate the effects of pumping, recharge, and injection on water table elevation. The results show that GCA is sensitive to the above mentioned parameters.

Pumping has a great impact on water table elevations. A small decrease in total pumping (pumping from all of the wells) results in a noticeable decline in the areas that have water table elevations below mean sea level (MSL), which is in essence an indication of saltwater intrusion. Similar results were found when decreasing municipal and agricultural pumping.

Two potential solutions were simulated; reduction in pumping and the injection of water through wells. These two options eliminated the problem of saltwater intrusion. However, a thorough future analysis should include an economic feasibility study.

Chapter1

Introduction

1 Introduction

1.1 General

Groundwater is the water that occurs in the voids between the subsurface soil particles and in the cracks. The large quantities of groundwater are found in aquifers. Groundwater is the primary source of water for human activities such as agriculture, industry and domestic drinking water especially in regions with limited annual precipitation (Todd, 1980).

Because groundwater is located at deep locations, it is less vulnerable to pollution. However, anthropogenic activities such as fertilization and other pollution sources beside over exploitation of the aquifers create serious problems to groundwater quality. These problems limit the use of groundwater and create additional problems in meeting the increasing water demand.

There are different types of pollutants that can be found in groundwater, such as nitrate, heavy metals and saltwater. Intrusion of saltwater is the most common contamination occurrence in coastal aquifers (Charbeneau, 2000). Intrusion of saltwater occurs when saltwater displaces fresh water in an aquifer. The phenomenon can occur in deep aquifers with the advance of saline waters of geologic origin, in shallow aquifers from surface waste discharge, and in coastal aquifers from the invasion of seawater (Todd, 1980). Over pumping of groundwater wells that located near the shoreline is a major cause of encroachment of saltwater into the aquifers and may lead to saltwater intrusion.

Gaza Coastal Aquifer (GCA) is the sole source of water in Gaza Strip. Recent studies show noticeable deterioration in the water quality; where chloride, nitrate, sulfate, and fluoride concentrations are exceeding the maximum contaminant levels in most of the wells in Gaza Strip (Al-Ayyam Newspaper, 12/2/2006). These studies show that about 70% of the 32 sampled wells have salinity exceeding the maximum contaminant level of 250 mg/l as Cl^-, about 50% have salinity over 500 mg/l, and about 15% have salinity of more than 1,000 mg/l. These wells are municipal and mainly used for domestic purposes including drinking. This high salinity makes the water taste bitter, salty, or metallic and interferes with the taste of foods and beverages, and makes them less desirable to consume. Also many agricultural wells are no longer used due to the high salinity. This high salinity is in someway or another, an indication of saltwater intrusion which appears mainly due to the excessive pumping (Chrbeneau, 2000). Agricultural activities in Gaza Strip also have been associated with excessive and uncontrolled use of dozens of pesticides (Shomar et al, 2005).

Another study on GCA quality (Shomar, 2006) shows that in 73 municipal and 21 private wells, only 10% of the municipal wells meet the WHO standards. Cl^-, $NO3^-$ and F^- concentrations exceeded 2–9 times the WHO standards in 90% of the wells tested with maximum concentrations of 3,000, 450 and 1.6 mg/l, respectively.

Excessive pumping to meet the increasing water demand is one of the main causes of saltwater intrusion. In addition, the locations of pumping wells near the shoreline may deepen the problem of saltwater intrusion. This causes the reduction or reversal of groundwater gradients, which permits denser saline water to displace fresh water (Todd, 1980). Another problem in GCA is the illegal wells that spread out through Gaza Strip. This is a serious problem since these wells are quite difficult to monitor and indeed contribute to the problem of saltwater intrusion.

These problems can be minimized by developing pumping strategies that entail different management actions. This necessitates the use of a groundwater flow model to simulate the impact of pumping on the saltwater intrusion problem. Thus, the overall objective of this research is to develop a groundwater flow model and to use it for assessing the pumping strategies for GCA to minimize the occurrence of saltwater intrusion.

1.2 Existing problem

It is obvious that GCA is being overexploited for the past 30 to 40 years (Khaled, 1999). This disturbed the natural equilibrium between fresh and saline water. Many water quality parameters presently exceed World Health Organization (WHO) drinking water standards.

The increasing salinity, which is often described by the concentration of chloride in groundwater, is one of the important problems that affect the usability of water for irrigation and water supply. In most areas, salinity rates are increasing with time. The expected sources of chloride in GCA are the following (Qahman, 2004):

1. Intrusion of seawater;
2. Lateral inflow of brackish water from the eastern boundary in the middle and southern areas of Gaza Strip; and

3. Presence of deep brines at the base of GCA.

Figure 1-1 shows the chloride concentrations for specific wells in GCA.

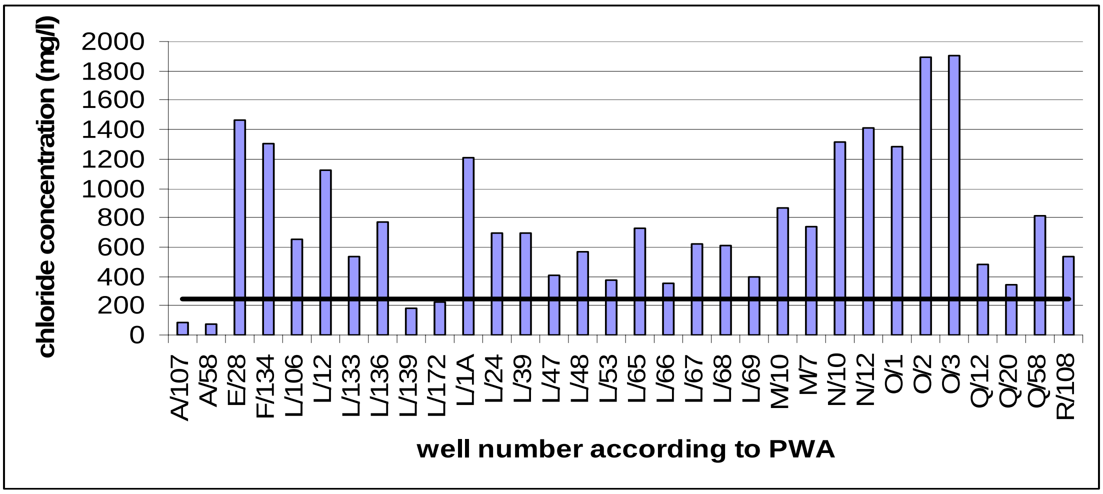


Figure 1-1: Chloride concentrations in specific wells in GCA wells in the year 2000

From the above, and knowing that GCA is the sole water source for the large and rapidly growing population of Gaza Strip, it is obvious that urgent actions ought to be carried out to eliminate the ongoing disaster. These actions include (but not limited to): (i) minimizing pumping rates, (ii) reallocating specific wells away from sea shore, and (iii) artificially recharging GCA at locations close to the shore.

1.3 Research objectives

The objectives of this research are summarized in the following:

- To determine the areas of potential saltwater intrusion;
- To specify the areas in which pumping contributes to the problem of saltwater intrusion; and

- To assess the impact of pumping on saltwater intrusion through the development and use of a groundwater flow model.

1.4 Research motivations

A groundwater flow model will be developed and used to set up pumping strategies to aid in lessening the problem of saltwater intrusion due to the following motivations:

- GCA is the only source of freshwater for the relatively big and rapidly increasing population of Gaza Strip;
- This source is facing a noticeable and evolving saltwater intrusion problem; and
- The problem of saltwater intrusion in GCA is an outcome of the complex interaction between the pumping wells and a groundwater flow model is ought to be developed and used to set up pumping strategies to help in solving the problem.

1.5 Methodology

Figure 1-2 depicts the flowchart of the research methodology which is summarized as follows:

- **Problem description and research objectives:** the ongoing problem of saltwater intrusion is described and the objectives of the research are defined.
- **Description of study area:** the study area (Gaza Strip and GCA) is studied in terms of location, population, climate, topography, land use, geology, hydrogeology, and hydraulic properties.

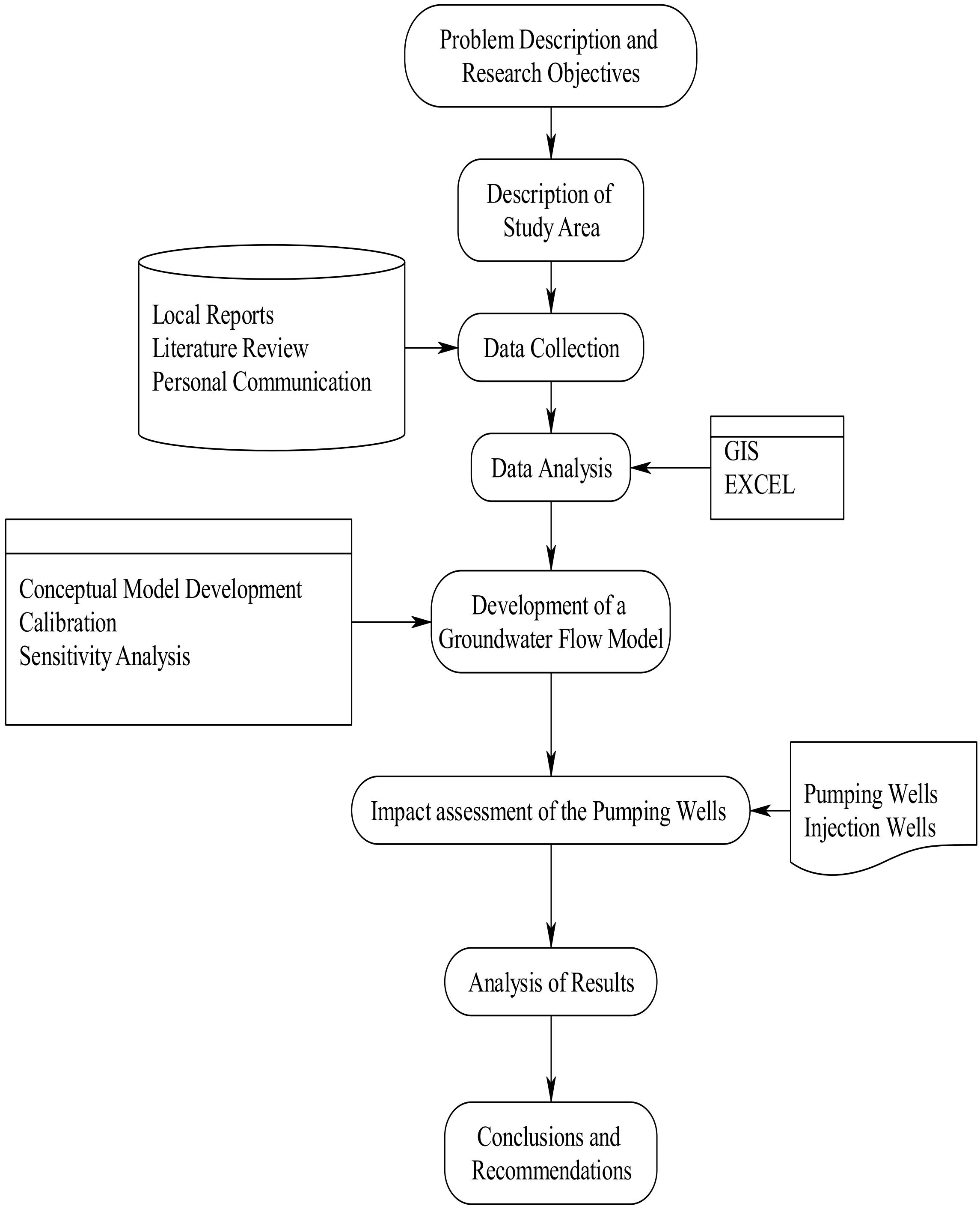


Figure 1-2: Methodology flowchart.

- **Data collection:** this step depends mainly on local reports, literature review and personal communications. The data collected are: well information, recharge information and hydraulic properties.

- **Data analysis:** the data is analyzed using computer software like spreadsheets (EXCEL) and GIS (ArcView GIS 3.2).

- **Modeling software selection:** suitable software is selected for modeling. The selected software is MODFLOW-2000 and it was chosen for the reasons stated in chapter two.

- **Calibration and sensitivity analysis:** the model is calibrated and sensitivity analysis is performed.

- **Simulation of pumping impacts:** impact of pumping is assessed using the groundwater flow model.

- **Analysis of results:** the results obtained from the model runs are analyzed, i.e. the impact of pumping and recharge on water table elevation.

- **Conclusions and recommendations:** based on the research outcomes, the conclusions and recommendations are made.

1.6 Expected outcomes

Upon the implementation of the research methodology, the following are the expected outcomes:

- A better understanding of the potential solutions (and their efficiencies) to the saltwater intrusion problem in GCA;

- A groundwater flow model; and

- A realistic pumping strategy that can be utilized by decision makers to help in the mitigation of the ongoing problem.

1.7 Thesis outline

This thesis consists mainly of seven chapters. Chapter two provides the literature review of the problem of saltwater intrusion, modeling, management options and an illustration of MODFLOW-2000. A discussion about the problem of saltwater intrusion is presented in chapter three. Chapter four gives an overview of the study area (Gaza Strip) and Gaza Coastal Aquifer (GCA). A demonstration of the groundwater flow model development is presented in chapter five. Chapter six furnishes the analysis of the model results. Finally, chapter seven provides the conclusions and recommendations.

Chapter two

Literature review

2 Literature review

Because of the importance of groundwater as a reliable source for drinking water, and the severity of the problem of saltwater intrusion in many parts of the world, several studies can be found in the literature that deal with the problem of saltwater intrusion. These studies can be classified into different categories.

Part of these studies is field work analysis like that of Paster et al (2005). Other studies rely on the modeling of saltwater intrusion and these include Khalid (1999), Lambrakis and Kallergis (2001), Langevin (2003), and Chen et al (2004). The remainder discusses management options as in Hallaji and Yazicigil (1996), Das and Datta (1999), Mantoglou (2003), and Reichard and Johnson (2005).

Modeling of saltwater intrusion can be conducted using different simulation codes. For instance, Khalid (1999) used MODFLOW (McDonald and Harbaurgh, 1988) to model the groundwater flow, and then used BADON-3 to study the movements of the saltwater interface. Lambrakis and Kallergis (2001) used the geochemical simulation codes PHREEQE and PHREEQM (Parkhurst et al., 1980) to analyze the freshening process. Langevin (2003) used SEAWAT (Guo and Langevin, 2002) to estimate rates of submarine groundwater discharge to a coastal marine estuary. Chen et al (2004) present a two-dimensional time-independent finite difference model to simulate tidal effects on the intrusion of seawater.

It is important, when dealing with the problem of saltwater intrusion, to keep in mind that setting up management strategies is of great importance.

There are many approaches for the management of saltwater intrusion. Reichard and Johnson (2005) discuss two management options for improving hydraulic control of saltwater intrusion: increased injection into barrier wells and in lieu delivery of surface water to replace current pumpage. Mahesha (1996) studies the control of seawater intrusion through a series of injection-extraction wells. Das and Datta (1999) represent plausible scenarios for planned withdrawal and salinity control in coastal aquifers. Mantoglou (2003) used optimization to maximize the total pumping from the aquifer under a set of constraints that protect the wells from saltwater intrusion.

2.1 Modeling saltwater intrusion

Unlike constant density groundwater flow, variable density groundwater flow is difficult to model. The reasons are the limitations of computer speed, insufficiency of data, and lack of simulation tools that can minimize numerical dispersion (Langevin, 2003). Nevertheless, there are some attempts to model saltwater intrusion. This section (section 2.1) discusses some of the existing saltwater intrusion models.

Khalid (1999) analyzed the major- recent and (desired) future trends in water availability in Gaza Strip, with a special focus on saltwater intrusion and groundwater recovery for GCA. He applied MODFLOW to quantify the availability of groundwater considering the regional aquifer system and ultimately to predict the long-term groundwater behavior and the corresponding perennial yield under various strategies. Then he used the program BADON-3 to study the historical movements of the saltwater interface and the future consequences of excessive local pumping. The main objective of his study was to determine a perennial yield pumping and to determine the movement of fresh/saline water interface and the corresponding threat to both freshwater storage and deterioration of water quality.

The study of Khalid (1999) used MODFLOW to set steady and transient multiple aquifer simulation models that can be used for the assessment of groundwater availability and simulation of groundwater development scenarios. A quasi-three dimensional modeling approach is selected to represent the conceptual model of the Gaza Strip. For the purpose of model construction, the entire aquifer system is divided into aquifers separated by aquitards or leakance interfaces. The model boundaries are the physical and hydrological flow controlled boundary in the east, and the sea in the west. During calibration, the parameter values are adjusted such that sequential model results match with observed heads. The calibrated parameters for steady-state conditions were: hydraulic conductivity, vertical leakance, and aquifer recharge. For unsteady conditions, the calibrated parameters were: specific storage, porosity, well abstractions, and time dependant recharge. The results of the study revealed upward movement of the interface with time under the current practices of pumping.

Unlike the study of Khalid (1999) this research, which studies the same study area (GCA), uses different approach to study the problem of saltwater intrusion. It concentrates on the impact of pumping on the water table elevations depending on the fact that when water table elevation is below MSL, the possibility of saltwater intrusion occurrence is high.

Langevin (2003) presents an application of the SEAWAT code to estimate rates of submarine groundwater discharge to a coastal marine estuary. Discharge rates were estimated for Biscayne Bay, Florida, for the period from January 1989 to September 1998 using a three-dimensional, variable density groundwater flow and transport model.

To simulate groundwater flow to Biscayne Bay, a regularly spaced, finite-difference model grid was constructed. The regional scale model was calibrated using trial and error by matching heads, groundwater exchange rates with canals, and position of the saltwater interface. Results from the model suggest that groundwater discharges directly to Biscayne Bay and to the tidal portions of the coastal canals. Results suggest also that fresh submarine groundwater discharge to Biscayne Bay may have exceeded surface water discharge during the study period.

Lambrakis and Kallergis (2001) study the multi component ion exchange process and freshening time under natural recharge conditions for three coastal aquifers in Greece. They observed a decline in groundwater quality in most of the Greek coastal aquifers due to over-pumping and the dry years of 1980-1990. This decline is caused by a lack of reliable water resources management, water abstraction from great depths, and saltwater intrusion. The freshening process, which is a long process, shows chromatographic patterns that are due to chemical reactions such as calcite dissolution and cation exchange, and simultaneously occurring transport and dispersion process. To analyze these patterns they used the geochemical simulation codes PHREEQE and PHREEQM. The results show that when pumping was discontinued, the time required for freshening under natural conditions of two of the aquifers in the study is long and varies between 8,000 and 10,000 years. The other aquifer on the other hand, has freshening time of 15 years. Freshening time was shown to depend mainly on cation exchange capacities and the recharge rate of the aquifer.

Chen et al (2004) present a two-dimensional time-independent finite difference model to simulate tidal effects on the intrusion of seawater in either a confined or phreatic aquifer. The model considers a sloped beach face. Results show that the variation of the distance through which the seawater intrudes also oscillates with the tide, with a constant time lag of 0.25T where T is the tidal period. The shape of the aquifer also affects the intrusion of saltwater and the velocity of intrusion. The rate of seawater intrusion and the distance through which the seawater intrudes increase with the slope of the bank.

2.2 Management of saltwater intrusion

Because of the ongoing problem of saltwater intrusion in many coastal aquifers, which limits the use of fresh groundwater in many areas around the world, it is important to adopt management actions to mitigate the effects of this problem. Several management options are documented in the literature and this section discusses some of them.

Reichard and Johnson (2005), as mentioned earlier in this chapter, discuss two management options for improving hydraulic control of saltwater intrusion; increase injection into barrier wells and in lieu delivery of surface water to replace current pumpage. It was found that the second option is the most cost effective. Raising the imposed average water-level constraint at the hydraulic-control locations resulted in nonlinear increases in cost. Systematic varying of the relative costs of injection and in lieu water yielded a trade-off curve between relative costs and injection/in lieu amounts (see Figure 2-1).

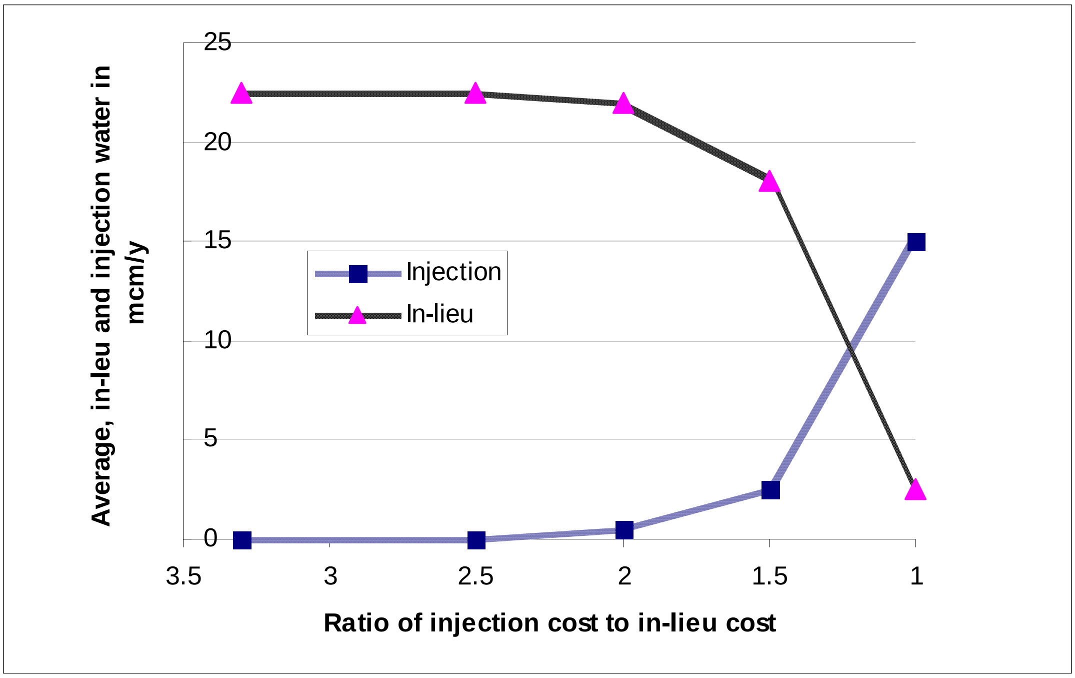


Figure 2-1: Sensitivity of optimization results to relative cost of injection and in-lieu delivery water

Mahesha (1996) studies the control of seawater intrusion through a series of injection-extraction wells. Control of seawater intrusion through an extraction barrier is one of the viable alternatives in the case of inadequate supply of freshwater for recharge. Combination of the freshwater injection with the seawater extraction is yet another viable alternative which may be more effective in preventing the intrusion. This study derives steady-state numerical solutions for the seawater-freshwater interface motion due to the extraction well system and its combination with the injection well system in coastal confined aquifers. The study found that the efficiency of the system increased as the series of the extraction wells is moved inland.

Das and Datta (1999) represent plausible scenarios for planned withdrawal and salinity control in coastal aquifers. The objectives of the study are to investigate the viability of embedding the finite-difference discretized three-dimensional density-dependent miscible flow and transport model of seawater intrusion as constraints in coastal aquifer management models; to develop embedded nonlinear optimization-based management models with multiple objectives for managing coastal aquifers for long-term use; and to demonstrate the feasibility of using the developed management models for different conflicting multiple objectives of operation, e.g., containment of seawater intrusion and supply of water for beneficial uses.

Mantoglou (2003) used optimization to maximize the total pumping from the aquifer under a set of constraints that protect the wells from saltwater intrusion. Two different constraint formulations are investigated. The first constraint called the ‘‘toe constraint’’ that protects the wells from saltwater intrusion by not allowing the toe of the interface to reach the wells. The second one is the ‘‘potential constraint’’ that protects the wells by maintaining a potential at the wells larger than the toe potential. This formulation results in a linear optimization problem which is solved using the Simplex method.

2.3 MODFLOW-2000

MODFLOW-2000 (harbaugh et al., 2000) is a computer program that solves the three-dimensional groundwater flow equation for a porous medium by using the finite-difference method. MODFLOW was designed to have a modular structure that facilitates two primary objectives: ease of understanding and ease of enhancing.

MODFLOW has undergone several revisions since 1984. This research uses the fourth version of MODFLOW, referred to as MODFLOW-2000. This version of MODFLOW is different from the previous versions in many aspects, such as:

1. It has been developed to facilitate the addition of multiple types of equations;

2. It allows definition using parameter values, each of which can be applied to data input for many grid cells; and

3. It has new multiplication and zone array capabilities, which make it much easier to modify data input values for large parts of a model. This feature facilitates the calibration and the sensitivity analysis for the developed model.

MODFLOW-2000 has been chosen for the modeling of groundwater flow of GCA due to the following reasons:

1. It is widely used in groundwater modeling;

2. It is a public domain software; and

3. Availability of technical support from the developers along with the manual and the illustrative examples.

Chapter three

The problem of saltwater intrusion

3 The problem of saltwater intrusion

Saline water is the most common pollutant in fresh groundwater. Intrusion of saline water occurs where saline water displaces or mixes with fresh water in an aquifer. The phenomenon can occur in deep aquifers with advance of saline waters of geologic origin, in shallow aquifers from surface waste discharge, and in coastal aquifers from an invasion of seawater (Todd, 1980).

Over pumping of groundwater wells that located near the shoreline is a major cause of encroachment of saline water into the aquifers and may lead to seawater intrusion. Because of its higher density, salt water goes inland under the freshwater. The interface between the salt water and the freshwater may be sharp edged or may be diffused due to diffusion process and lateral migration of the interface over time. However, the sharp edge interface approximation is mostly used because of its simplicity and usefulness in modeling saltwater intrusion (Schwartz and Zhang, 2002).

Saltwater encroachment can be either active or passive. Passive Saltwater encroachment occurs when some freshwater has been diverted from the aquifer, yet the hydraulic gradient in the aquifer is still sloping toward the saltwater-freshwater boundary. In this case, the boundary will slowly shift landward until it reaches an equilibrium position based on the new discharge conditions as depicted in Figure 3-1 (Todd, 1980).

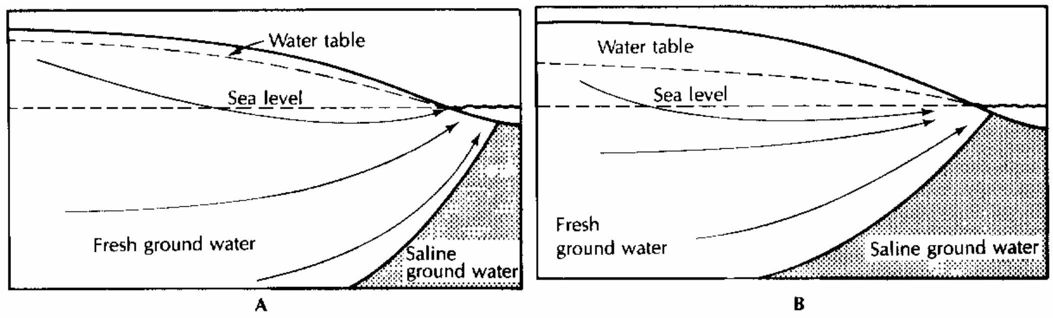


Figure 3-1: A) Unconfined coastal aquifer under natural groundwater discharge conditions. B) Passive saltwater encroachment due to general lowering of the water table

The consequence of active saltwater encroachment is considerably more severe, as the natural hydraulic gradient has been reversed and freshwater is actually moving away from the saltwater-freshwater boundary (see figure 3-2). The boundary zone moves much more rapidly than it dose during passive saltwater encroachment. Furthermore, it will not stop until it has reached the low point of the hydraulic gradient, i.e. the center of pumping.

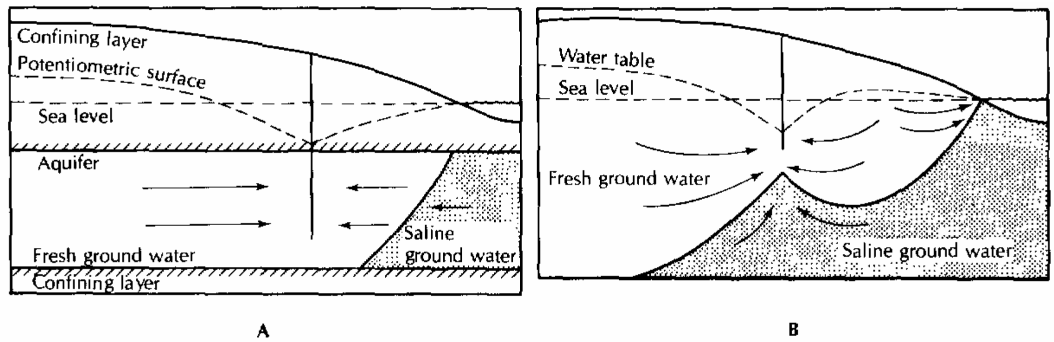


Figure 3-2: A) Active saltwater encroachment in a confined aquifer with the potentiometric surface below sea level. B) Active saltwater encroachment in an unconfined aquifer with the water table drawn below sea level

3.1 Ghyben-Herzberg approach

Ghyben (1888) and Herzberg (1901) found that saltwater occurred underground, not at sea level but at a depth below sea level of about 40 times the height of the fresh water above sea level. This distribution was attributed to the hydrostatic equilibrium that exists between the two fluids of different densities. The equation derived to explain the phenomenon is generally referred to as Ghyben-Herzberg relation after its originators.

For two segregated fluids with a common interface, the weight of a column of fresh water extending from the water table to the interface is balanced by the weight of a column of seawater extending from sea level to the same depth as the point on the interface as shown in Figure 3-3. This figure shows the idealized Ghyben-Herzberg model of an interface in a coastal unconfined aquifer.

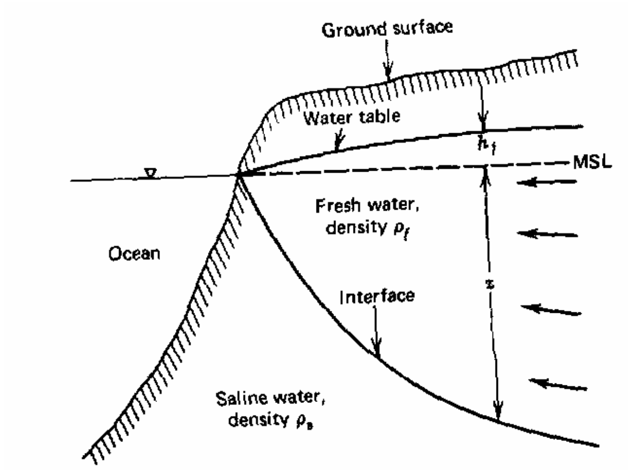


Figure 3-3: Idealized sketch of occurrence of fresh and salt groundwater in an unconfined coastal aquifer.

To derive Ghyben-Herzberg relation for any point on the freshwater-saltwater interface, the pressure at this point is the same whether approached from the freshwater side or from the saltwater side. Thus,

$$\rho_s \, g \, z = \rho_f \, g \, (z+h_f) \qquad [1]$$

where ρ_s is the density of the saltwater, ρ_f is the density of freshwater g is the acceleration of gravity, and z and h_f are shown in Figure 3-4.

So, $$z = \frac{\rho_f}{\rho_s - \rho_f} \times h_f \qquad [2]$$

The length of the saltwater interface under the hydrostatic conditions of Ghyben-Herzberg is given by the following relation:

$$L = \frac{K(1+\alpha)h_f^2}{q} \qquad [3]$$

where,

L : Length of the saltwater interface (see Figure 3-4).

K : Hydraulic conductivity.

α : $\rho_f / (\rho_s - \rho_f)$

q : The discharge per unit length of shoreline.

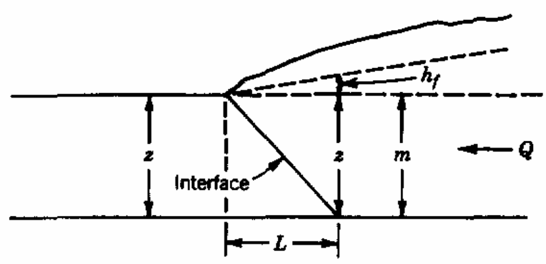


Figure 3-4: Idealized geometry to calculate the length of the saltwater wedge from the Ghyben-Herzberg relation.

3.2 Interface upconing

When pumping wells are located toward the shoreline and as a result of pumping, the interface rises towards the pumping wells. This phenomenon is called interface upconing as shown in Figure 3-5. As we can see from the figure, continued pumping causes the interface rising to successively higher levels until it can reach the well.

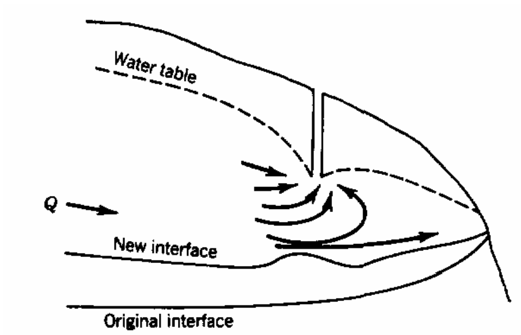


Figure 3-5: Freshwater flow to a well above the interface.

Schmorak and Mercado (1969) give an approximate analytical solution for interface upconing. Their solution gives the new equilibrium elevation to an interface in direct response to pumping as in the following equation:

$$Z = \frac{Q\,\rho_f}{[2\pi\, d\, K\,(\rho_s - \rho_f)]} \qquad [4]$$

where,

z : The new equilibrium elevation (L) (see figure 3-7).

Q : The pumping rate (L^3/T).

d : The distance (L) from the base of the well to the original (pre-pumping) interface (see Figure 3-6).

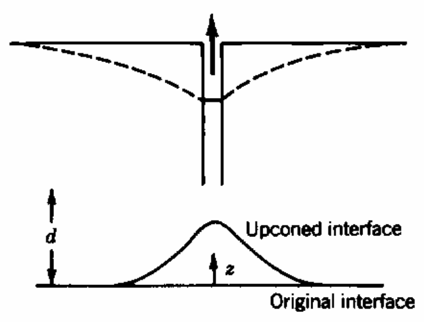


Figure 3-6: Upconing of interface in response to pumping

Also Dagan and Bear (1968) suggest that the interface will be stable for upconing heights that do not exceed one third of d given in figure 3-7. Thus, by substituting this in equation [4], the maximum permitted pumping rate should not exceed:

$$Q_{max} \leq \frac{0.6\pi\, d^2\, K\,(\rho_s - \rho_f)}{\rho_f} \qquad [5]$$

Chapter four

Gaza Strip and Gaza Coastal Aquifer

4 Gaza Strip and Gaza Coastal Aquifer

Gaza Strip is the south-western part of Palestine that is located on the south-eastern cost of the Mediterranean Sea. Its area is about 365 km^2 with a length of 45 km and a width between 6 and 12 km. It is confined between the Mediterranean Sea in the west, Egypt in the south and the occupied Palestine in 1948 in the east and the north (see Figure 4-1).

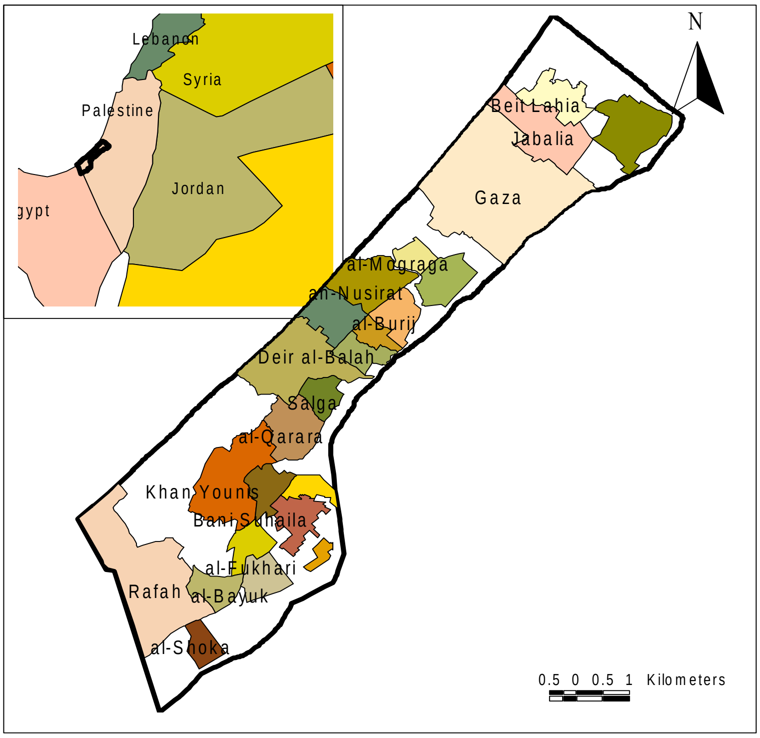


Figure 4-1: Location map of Gaza Strip

Gaza Strip is considered one of the denser places in the world where more than 1.4 million residents live in the 365 km^2 area. This population is concentrated in four cites, a few villages, and eight refugee camps with a total built-up residential area of about 80 km^2 (Metcalf and Eddy, 2000).

Gaza Strip has very limited natural resources especially in freshwater, where GCA is the only source of freshwater supply for municipal, agricultural, and industrial uses (Khaled, 1999). Knowing that this source is in a critical situation, it requires immediate efforts to improve the water situation in terms of quality and quantity. The following sections give a wider view on Gaza Strip and GCA.

4.1 Climate

Gaza Strip has a semi-arid climate. There are two well-defined seasons: the wet season starting in October and extending through March and the dry season from April to September. Peak months for rainfall are December and January. The long term annual rainfall average is 325 mm/year (Khalid, 1999) and it decreases from north to south.

The mean temperature varies from 12^{o}-14^{o}C in January to 26^{o}-28^{o}C in June. Evaporation measurements have clearly shown that the long term average open water evaporation is in the order of 1,300 mm/year. Maximum values of 140 mm/month in June, July, August, contrast with relatively high evaporation values around 70 mm/month during winter.

4.2 Topography

The topography of Gaza Strip is characterized by elongated ridges and depressions, dry streambeds and shifting sand dunes. Land surface elevations range from mean sea level (msl) to about 110 msl. There are three surface water features in Gaza Strip: Wadi Gaza, Wadi Silka, and Wadi Halib (Qahman, 2004).

4.3 Land use

A land use map of Gaza Strip is shown in figure 4-2, and table 4-1 gives the area of each land use type. Agricultural land occupies about 63% of the land surface and is the dominant economic sector in Gaza. Israeli settlements used to occupy about 5 % of the total land area, but since the summer of the year 2005 no more settlements are in Gaza Strip because of the Israeli withdrawal.

Table 4-1: Land use classes of Gaza Strip

Type	Area (Km^2)	% of Gaza Strip
Agricultural	226	63
Built-up areas	54	15
Open area	62	17
settlements	18	5

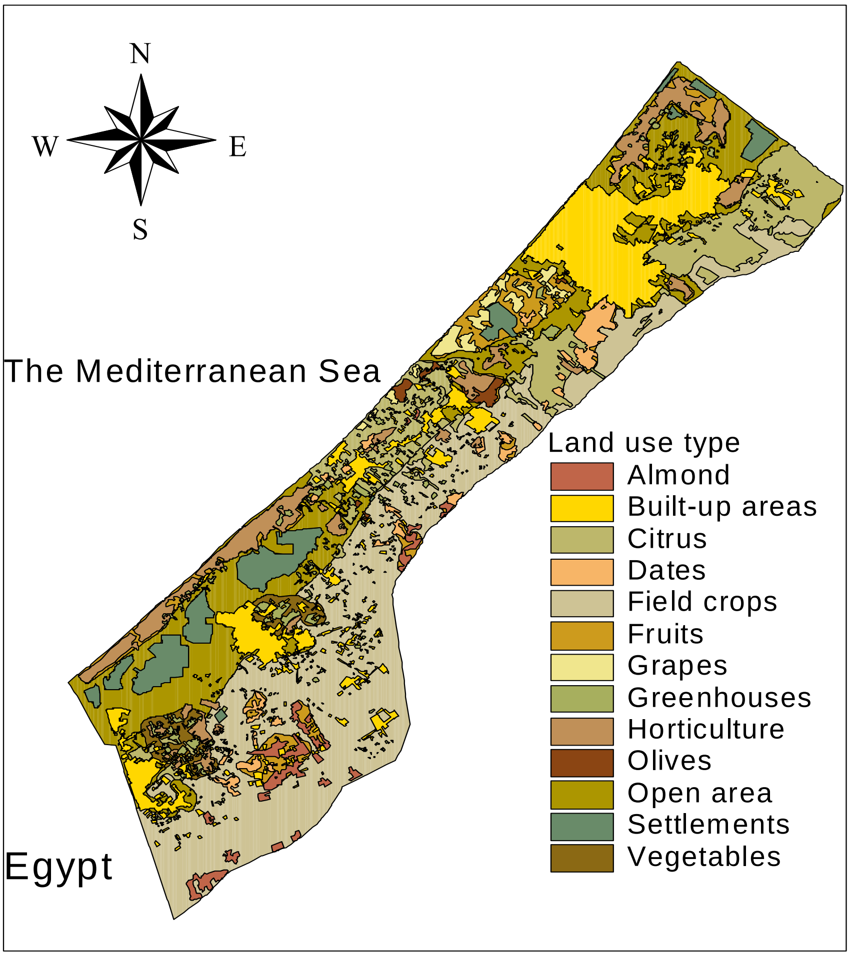


Figure 4-2: land use map of Gaza Strip

4.4 Sources of salinity in GCA

Salinity is one of the main pollutants in costal aquifers, especially in the arid and the semiarid regions, where groundwater is the sole source of water. This phenomenon threatens the quality of groundwater and as a result limits the quantity of water that can be used for different purposes especially for drinking.

An obvious example of this is GCA which is the only source of water for the residents Gaza Strip. The encountered high salinity in several pumping wells limits the use of water out of these wells and contributes to the water supply problem.

While seawater intrusion is the widely known reason of salinity in coastal aquifers, many studies have shown that other sources of salinity affect the water quality of groundwater resources in this aquifer. For example, GCA has three major sources of salinity (Vengosh et al., 2005):

1. The lateral inflow of saline groundwater from the eastern boundaries of Gaza Strip;
2. Saltwater intrusion; and
3. Anthropogenic nitrate pollution.

The lateral inflow from the eastern part is about 37 mcm/y (see table 4-2). The groundwater in this part has salinity ranges (as TDS) of 1000 to 4000 mg/l (Vengosh et al., 2005), which may contribute to the salinity problem in GCA.

The second source of salinity in GCA is seawater intrusion which caused mainly by over pumping of groundwater wells that are located near the shore.

The third source is anthropogenic nitrate pollution. Recent studies have shown high nitrate concentrations in the most of Gaza Strip wells (Al-Ayyam Newspaper, 12/2/2006). This pollution is mainly due to agricultural return flow and wastewater.

This research is focusing on the second source of salinity, which is seawater intrusion caused by the over pumping.

4.4.1 Ion ratios

The chemical composition of groundwater is of great importance in monitoring the aquifers. As for saltwater control, each source of salinity has distinguished ion ratios. Knowing that, and knowing the chemical composition of the water, can help in identifying the source of salinity. Table 4-2 (Ghabayen et al., 2006) gives the chemical composition of the potential salinity sources in GCA.

Based on data from the Palestinian ministry of health and the Palestinian ministry of agriculture in the year 2000 for 108 pumping wells in GCA, the ion ratios for GCA can be prepared as shown in Table 4-3. Comparing the average values of the ion ratios in Table 4-3 with the sources of salinity in Table 4-2 shows that seawater intrusion is the main source of salinity. Table 4-3 shows also the significant variation between the minimum and the maximum values of ion ratios.

Since the ions concentrations changes per time, as a results, the ion ratios changes per time also. To show these changes, the time series of the ion ratios of three representative wells, W1 in the north, W2 in the middle, and W3 in the south of Gaza Strip (see Figure 4-3a) were prepared (Hydrological data book of Gaza Strip, 1995). These time series are shown in Figure 4-3 b, c, and d. This figure shows the temporal and spatial differences in water quality in Gaza Strip. Each location has characteristic time series of the ion ratio depending on different factors. Theses factors include hydrogeologic properties and sources of contamination.

Table 4-2: The chemical composition of potential salinity sources in GCA

	Seawater intrusion	Flow from Eocene rocks	Deep brines upconing	wastewater seepage	Agricultural return flows
Na/Cl	0.86-1	1-1.8 1.23 ~ 0.86	~<0.8 <0.86 0.5-0.8	1.1	
So_4/Cl	0.05	0.05-0.12	~ 0.05	0.09	>> 0.05
Br/Cl	0.0015	0.0014-0.0015	0.0014-0.0016	0.0005	0.02
B/Cl	0.0008	0.0018 0.0087	0.002 0.0015-0.0018	0.002-0.005	0.005
K/Cl	0.019		<0.019		
Ca/(HCO_3+SO_4)	0.35-<1		>1		
Mg/Ca	>5	0.5-0.7	>1		

Table 4-3: Ion ratios in GCA

	Minimum	Average	Maximum
Na/Cl	0.4379	0.9877	1.9273
So_4/Cl	0.0848	0.3748	1.0226
Br/Cl	0	0.00542	0.008901
K/Cl	0.0033	0.173	0.2005
Ca/(HCO_3+SO_4)	0.0516	0.2371	0.7061
Mg/Ca	0.1383	0.9362	2.3115

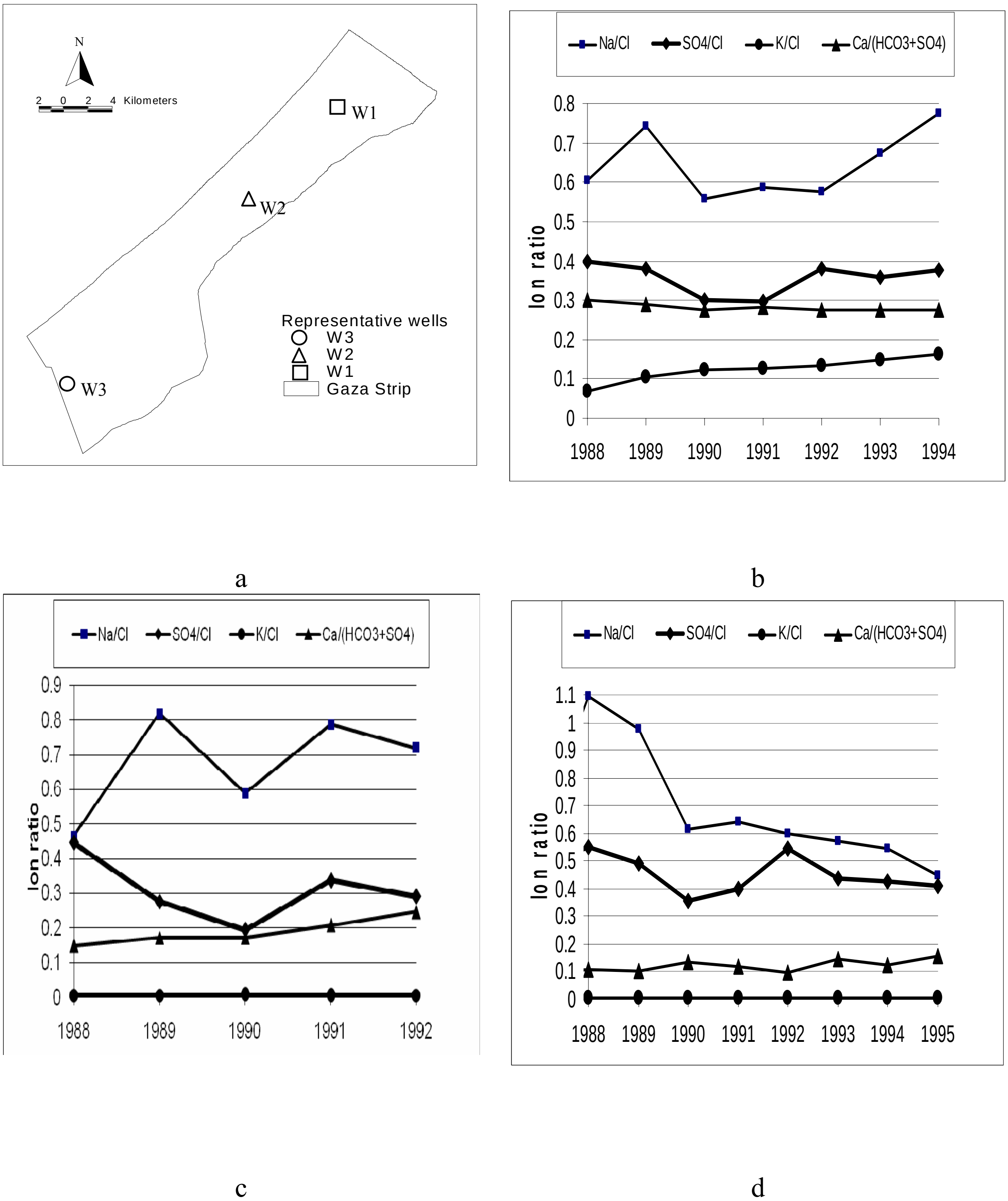


Figure 4-3: a) Representative Wells locations. b) Time series of ion ratios in well W1. c) Time series of ion ratios in well W2. d) Time series of ion ratios in well W3.

4.5 Gaza Coastal Aquifer

4.5.1 Geology, hydrogeology, and hydraulic properties

GCA consists of the Pleistocene age Kurkar Group (Gvirtzman, 1969) and recent (Holocene age) sand dunes. The Kurkar Group consists of marine and aeolian calcareous sandstone ("kurkar"), reddish silty sandstone ('hamra'), silts, clays, unconsolidated sands, and conglomerates. The dune sands (and loess soils) which overlie the Kurkar Formation consist of mostly fine, well-sorted sands of aeolian origin.

The layered stratigraphy of the Kurkar Group within the Gaza Strip subdivides the coastal aquifer into 4 separate subaquifers near the coast. Subaquifer A is unconfined, whereas subaquifers B, AB, and C become increasingly confined towards the sea (Baalousha, 2003). Figure 4-4 is a typical hydro geological section for GCA. Table 4-4 is a lithological column in GCA (Khaled, 1999).

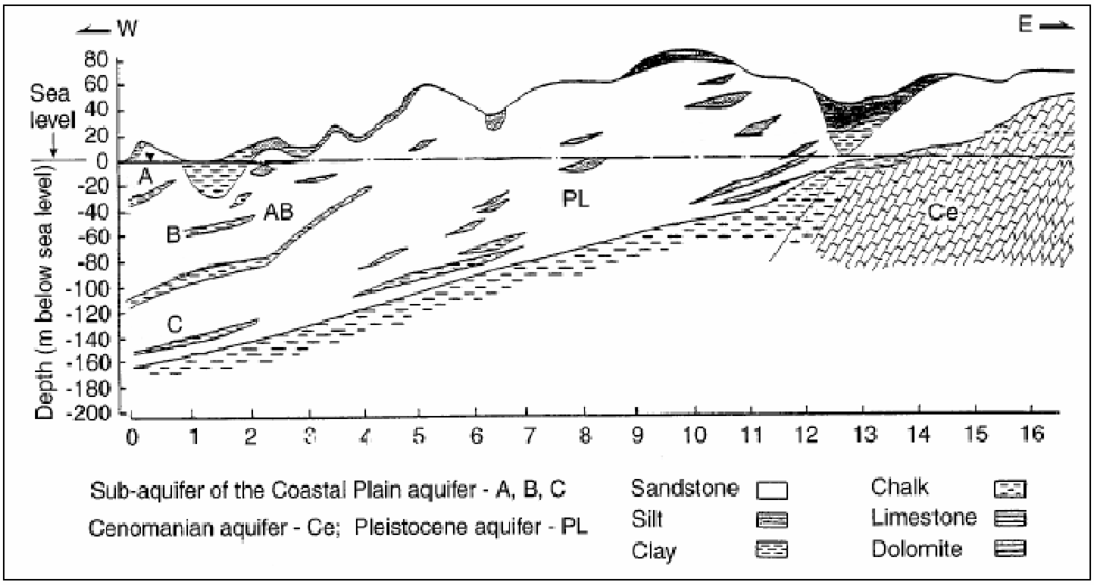


Figure 4-4: Typical hydro geological section in GCA

Table 4-4: Lithological column in GCA

Cainozonic	Age	Lithology	Thickness (m)	Hydro-stratigraphic
Quaternary	Recent Epoch	Soil + coarse sand	10	Land surface
	Holocene	Silt + clay	5	Usually dry
	Pleistocene	Medium sand + chalk + pebbles	10	Shallow aquifer (dug wells)
		Fine sand + chalk	40	Upper aquifer
		Marine clay + silt	10	Aquitard
Tertiary	Pliocene	Micro-conglomerates + coarse sand + chalk	40	Meddle aquifer
		Compact clay + silt	15	Aquitard
		Mixed (Kurkar) + Calcareous sand	40	Lower aquifer
	Miocene	Saqyieh clay	200	Aquiclude

As a result of aquifer tests carried out in Gaza Strip, the following hydraulic properties are known:

- Transmissivity values range from 700 to 5,000 m^2/day.
- hydraulic conductivity values range from 20 to 80 m/day.
- specific storativity value is about 10^{-4} m^{-1}

4.5.2 Existing wells

There are more than 3,000 wells within the Gaza Strip (PWA). The majority of these are privately owned and used for agricultural purposes. Only 92 wells are owned and operated by individual municipalities and are used for domestic supply. Figure 4-5 shows the locations of all the known licensed wells.

Total groundwater abstraction in the Gaza Strip in recent years is estimated at 120-140 mcm (Metcalf and Eddy, 2000). In 1999, municipal abstraction totaled about 50 mcm from 84 wells. Almost 50% of the municipal abstraction takes place in Gaza City and Jabalya. In the same year, agricultural abstraction is estimated to be 80-85 mcm (+/- 10%).

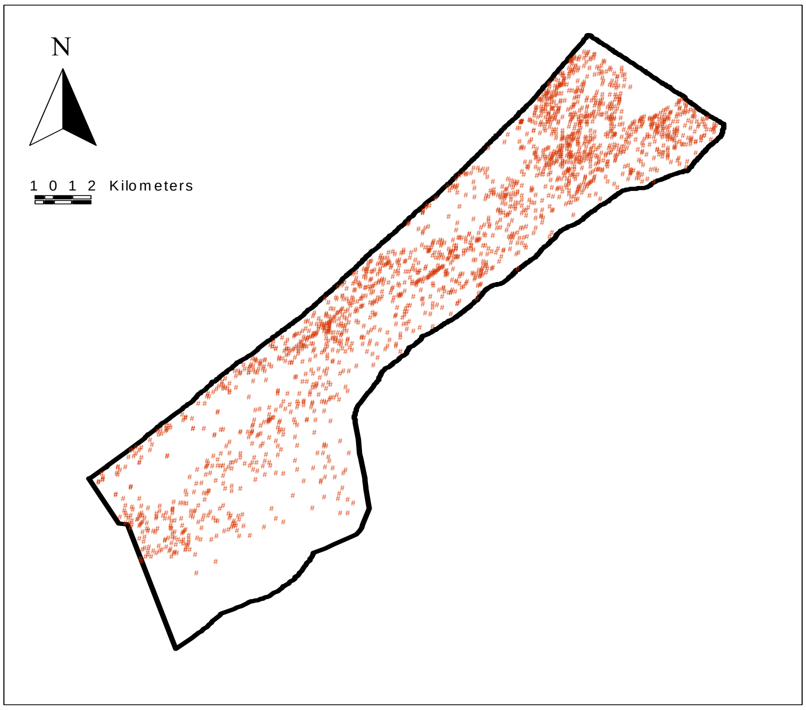


Figure 4-5: Well locations in GCA

4.5.3 Groundwater quality

Recently, PWA has published a report about water quality in Gaza municipality pumping wells (Al-Ayyam Newspaper, 12/2/2006). The report shows a serious deterioration in water quality, mainly in wells that are located at the shoreline proximity.

The report shows that about 70% of the 32 sampled wells have salinity exceeding the maximum contaminant level of 250 mg/l as Cl^-, about 50% have salinity over 500 mg/l, and about 15% have salinity more than 1,000 mg/l. For nitrate, the report reveals that about 75% of the wells have nitrate concentrations above 100 mg/l (the maximum contaminant level is 45 mg/l).

According to the PWA report, only three of the 32 sampled wells meet the standards in terms of chloride (salinity) and nitrate concentrations. Also in specific wells, high concentrations of sulfate and fluoride were observed. Figures 4-6 and 4-7 show the chloride and nitrate concentrations, respectively in specific municipal wells in Gaza Strip. It is clear from these figures that most of these wells have chloride and nitrate concentration above the maximum contaminant levels (MCL) which are 250 mg/l for chloride and 50 mg/l for nitrate (as NO_3^-).

Nitrates level in excess of 150 mg/l poses an extreme risk to infant's health in the form of blue baby syndrome (methaemoglobinaemia) .Moreover; high nitrates may have carcinogenic effects for adults. While the presence of chlorides may not be as harmful as that of nitrates, the salinity it causes makes the water unacceptable for drinking. Therefore, low level of chlorides is critical for customer satisfaction (Agha, 2005).

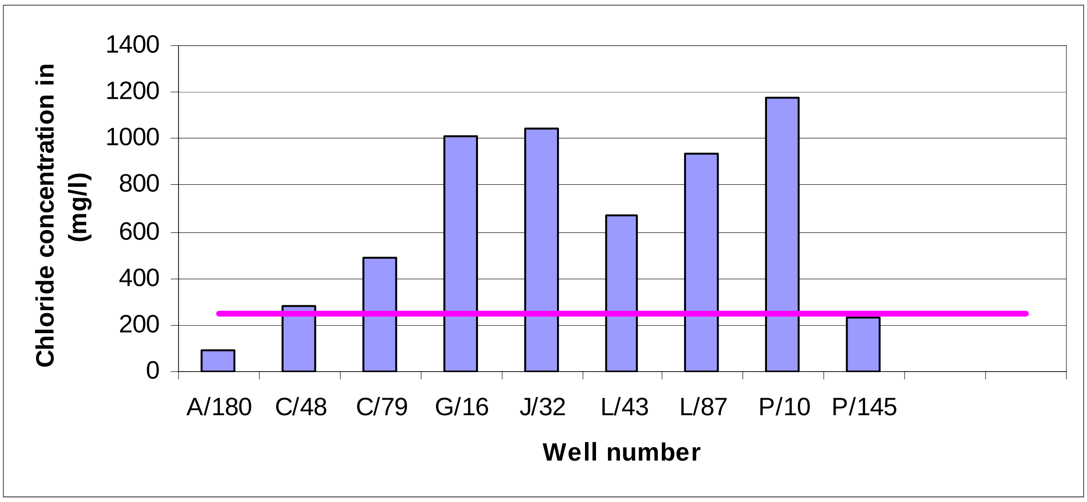


Figure 4-6: Chloride concentration in specific municipal wells in Gaza Strip in the year 2000.

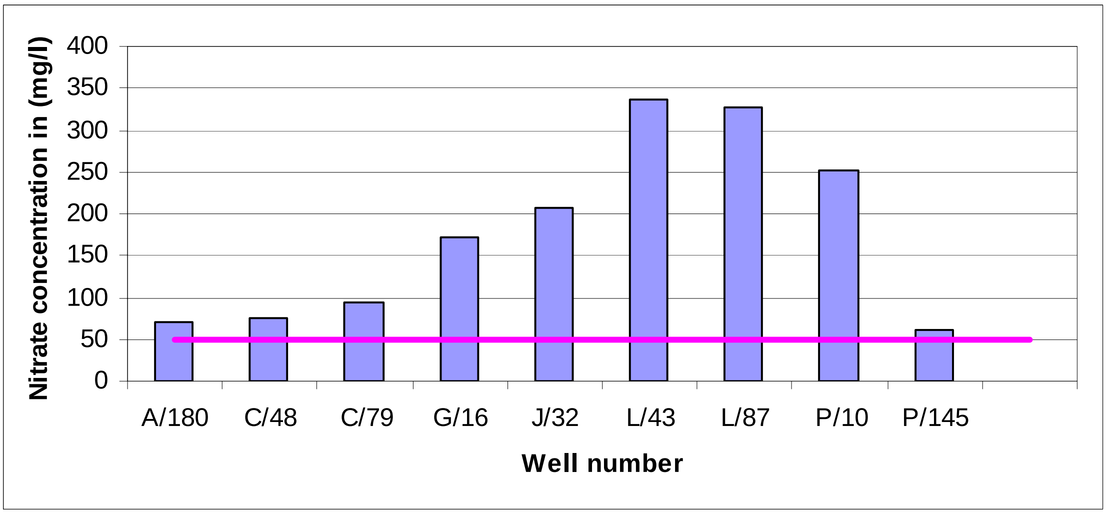


Figure 4-7: Nitrate concentration in specific municipal wells in Gaza Strip in the year 2000.

4.5.4 Groundwater vulnerability

Intrinsic vulnerability of an aquifer can be defined as the ease with which a contaminant introduced into the ground surface can reach and diffuse in groundwater (Antonakos and Lambrakis, 2006). Based on the idea that specific land areas are more vulnerable to groundwater contamination than others, groundwater vulnerability maps provide useful information to protect groundwater resources (Almasri, 2007).

There are many vulnerability assessment methods. The DRASTIC method developed by Aller et al. (1985) is one of the most widely used methods to assess intrinsic groundwater vulnerability to contamination (Almasri, 2007). The acronym DRASTIC stands for the parameters included in the method: **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone, and hydraulic **C**onductivity of the aquifer. DRASTIC indexes calculated are roughly analogous to the likelihood that contaminants released in a region will reach ground water, higher scores implying higher likelihood of contamination. GIS is considered an adequate tool to use in the application of the DRASTIC methods (Hamza et al., 2006).

The equation for determining the DRASTIC index is (Almasri, 2007):

$$DI = D_wD_r + R_wR_r + A_wA_r + S_wS_r + T_wT_r + I_wI_r + C_wC_r \quad [1]$$

where D, R, A, S, T, I, C represent the seven hydrogeologic factors, r designates the rating, and w the weight. DI represents a relative measure of groundwater vulnerability. The higher DI, the grater the vulnerability of the aquifer to contamination.

For GCA, the DRASTIC index was prepared by processing the data available from PWA and the results of the groundwater flow model developed in this research (Chapter 5). The depth to water table (D) was computed using GIS by subtracting the water table elevation from the ground surface elevation. The distribution of recharge (R) was computed as stated in section 5.3. As for the aquifer media (A), it was evaluated based on the lithological well logs (hydrogeological data book of Gaza Strip, 1995). The soil media (S) was assessed based on PWA data. The topography (T), which represented by the percentage slope of ground surface, was computed by processing the DEM using GIS. The impact of vadose zone (I) was considered based on the lithological well logs (hydrogeological data book of the Gaza Strip, 1995). The aquifer hydraulic conductivity (C) was computed based on data from PWA. After obtaining all of the parameters in equation [1], these parameters where categorized and then the corresponding rates were assigned accordingly.

Figure 4-8 shows the distribution of the DRASTIC index for GCA. Comparing this distribution with similar studies (Almasri, 2007) shows a good match. It is clear from this figure that high vulnerability areas are concentrated near the seashore.

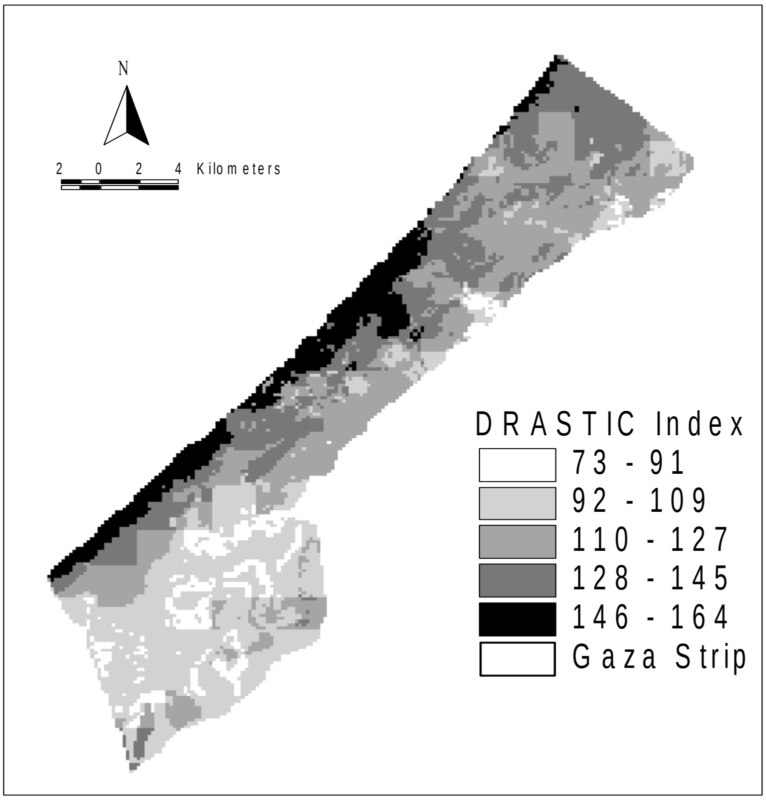


Figure 4-8: The map of vulnerability to contamination for GCA

4.5.5 Groundwater balance

Based on the estimates of all water inputs and outputs to GCA, a water balance can be developed as shown in table 4-5 (PWA) for the year 2004-2005.

Table 4-5: Water balance in 2004-2005 of the Gaza Strip

Inflows (mcm)		Outflows (mcm)	
Rainfall recharge	42	Palestinian wells abstraction	150
Lateral inflow	37	Israeli wells abstraction	4.3
Return flow	52	Lateral outflow	9
Salt-water intrusion	30		
Sum	161		163.3

From table 4-5, it is clear that there is a deficit in the groundwater budget in GCA. This deficit results in lowering the water table, and so, contributes to the problem of saltwater intrusion.

Chapter five

Development of the groundwater flow model

5 Development of the groundwater flow model

Model development is the process in which hydrological and geological data are simulated mathematically using a code such that MODFLOW-2000. MODFLOW-2000 simulates groundwater flow by using the finite difference method. Model outcomes are mainly groundwater heads and water budget. After model development, the calibration process takes place. In this process, hydraulic properties of the aquifer are modified so that the simulated values of groundwater heads approximately match the observations. The last step in the model development is the sensitivity analysis, in which the effects of different parameters on water table elevations are studied.

5.1 Model set-up

The finite-difference grid in MODFLOW consists of two sets of parallel lines orthogonal to each other and the cells are formed by the intersection between these lines. The model of GCA has uniform cell sizes of 200 m by 200 m. This discretization level allows a proper capturing of the different properties and insures a smooth simulated potentiometric head. The model domain contains 336 rows, 280 columns and one layer with a total of 94,080 cells. This number of cells includes all the active and inactive cells. However, the number of active cells (cells within the model domain) is 39,774. Figure 5-1 depicts the model domain of GCA.

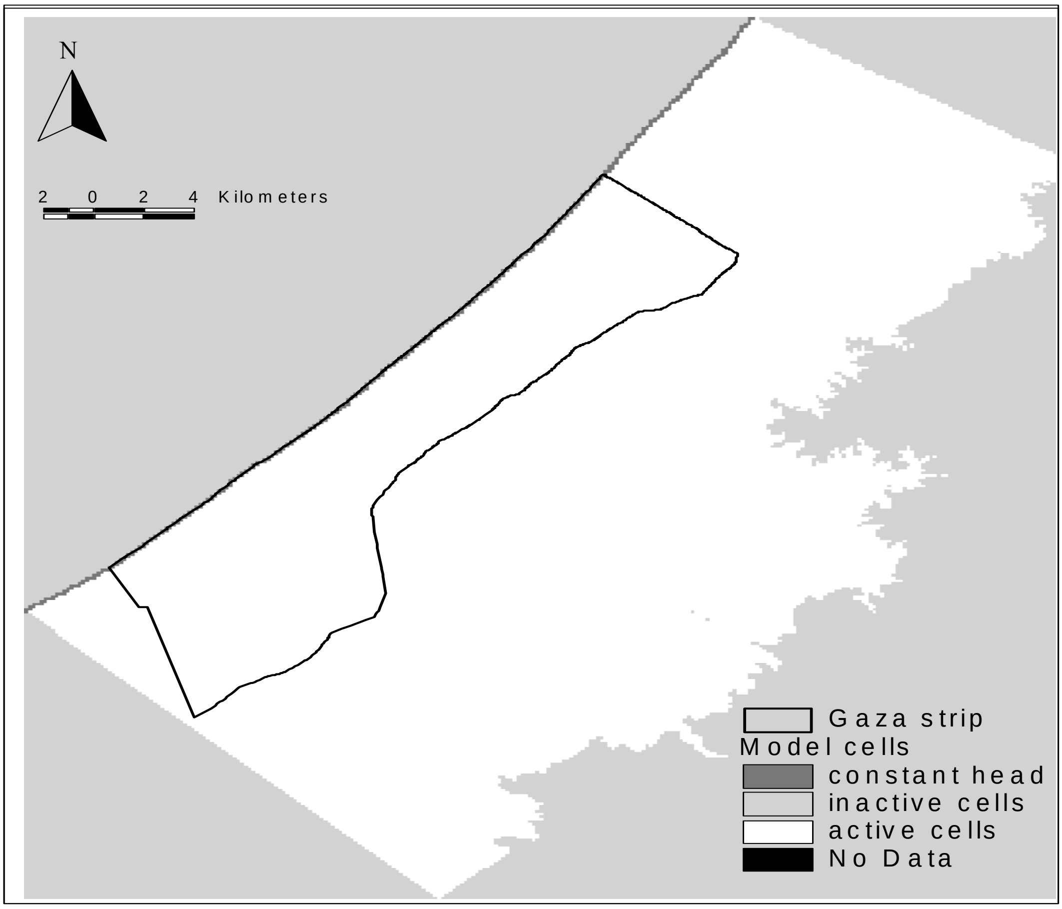


Figure 5-1: The Model domain and boundary conditions.

As shown in Figure 5-1, the model domain is larger than Gaza Strip. The reason for this is to assign a no-flow boundary to the model domain except for the shoreline. In this way, the model can simulate the lateral inflow to Gaza Strip more realistically.

Although the hydrogeological section (Figure 4-4) indicates that there is more than one sub-aquifer in the vertical direction, this study uses a single layer model. This is because the majority of the pumping wells are abstracting from the first layer.

5.2 The boundary conditions of the study area

There are two types of boundaries in this model: The physical boundary in the east and the seashore boundary in the west. The western boundary is modeled as constant head cells, while the remaining boundaries are modeled as no-flow boundaries. The representation of the boundaries by MODFLOW has been carried out by assigning specific indicators to the cells according to the type of the boundary as shown in figure 5-1.

5.2.1 No-flow boundary

The cells in this boundary are assigned the value “0” to be inactive cells (Figure 5-1). These cells have no flow into or out of the cell during the entire simulation. The number of these cells is 54,306 cells.

5.2.2 Constant-head boundary

The constant-head boundary simulates the coastline (Figure 5-1). The cells in this boundary are assigned the value “-1” to indicate that they have a constant head. The number of theses cells is 423.

5.3 Groundwater recharge

Groundwater recharge is the replenishment of an aquifer with water. For GCA, the sources of the recharge are recharge from rain, recharge from irrigation, wastewater recharge and Water supply network losses recharge (Metcalf and Eddy, 2000).

Recharge from rain is the main source of recharge. The rainfall is based on data from 15 rainfall stations; 9 inside and 6 outside Gaza Strip. Infiltration coefficients were assigned to be 0.15, 0.15, and 0.6 for clay, loess, and sand respectively.

The recharge from irrigation has three components:

1. Irrigation directly from rainfall, which is taken into account when calculating the recharge from rain.
2. Irrigation from wells, where 25% of the pumped water is assumed to return to the aquifer.
3. Recharge from wastewater reuse network at the far east of the model domain.

Wastewater recharge consists of physical losses from wastewater network, septic tanks, recharge from unpiped wastewater, and recharge from piped wastewater.

The final component of the recharge is water supply network losses recharge, which are the physical losses in the network. For the model domain the value of recharge is about 217 mcm.

The Recharge Package of MODFLOW was used to simulate the spatial distribution of the recharge to GCA.

5.4 Abstraction wells

As stated in section 4.5.2, there are more than 3,000 wells within the Gaza Strip. The majority of these are privately owned and used for agricultural purposes. Only 92 wells are owned and operated by individual municipalities and are used for domestic supply. These wells are distributed over the districts of Gaza strip with obvious concentration in the areas that have high population density as shown in Table 5-1 (PWA). These areas are: Gaza City, Jabalia Camp and Beit Lahia in the north; Deir Al-Balah in the middle; and Rafah and Khan Younis in the south. Table 5-1 depicts the wells that located in the districts only. The rest of the wells are located in the open areas and settlement locations.

Because the model domain is larger than Gaza Strip (Figure 5-1), some of the wells are located outside Gaza Strip boundary. The number of these wells is about 600 and they abstract about 53 mcm.

From Table 5-1 we can see that the depth of the wells varies considerably in each district. This should be taken into consideration in the modeling of GCA as a multiple layer model. But in the groundwater flow model in this research (see section 5.1) it is assumed for GCA to be a single layer model. The reason for this assumption is because of the lack of the data available and because the objective of model development is to find out the impact of pumping on saltwater intrusion rather than the well depth.

Table 5-1: Distribution of wells over Gaza Strip districts

District	Area (km^2)	Number of Municipal Wells	Depth range (m)	Number of Agricultural Wells	Depth range (m)	Total Pumping (mcm)
Abasan Al-	5.91	0	-	12	-5~-71	0.64
Abasan Al-	3.19	0	-	6	-9~-20	0.32
Al-Bayuk	4.68	0	-	4	-15	0.21
Al-Burij	5.35	1	-16	30	-5~-53	1.61
Al-Fukhari	5.14	0	-	3	-15	0.16
Al-Maghazi	2.88	1	-15	10	-8~-15	0.54
Al-Mograga	3.15	0	-	45	-6~-47	2.41
Al-Msadar	4.13	1	-13	14	-7~-55	0.75
Al-Qarara	8.63	0	-	42	-6~-28	2.25
Al-Shoka	3.57	0	-	0	-	0
An-Nusirat	9.71	2	-14~-15	101	-6~-62	5.42
Az-Zawida	6.94	0	-	60	-5~-72	3.22
Bani Suhaila	5.02	0	-	8	-9~-26	0.43
Beit Hanoun	11.44	5	-9~-54	134	-5~-71	9.34
Beit Lahia	6.80	8	-8~-68	88	-5~-53	9.15
Deir Al-Balah	16.98	7	-11~-20	155	-6~-80	11.07
Ga'a Al-Grain	4.50	0	-	2	-15	0.11
Gaza	45.86	20	-6~-67	260	-5~-50	31.06
Jabalia	12.96	19	-6~-65	213	-5~-66	24.87
Johr Al_Diek	6.48	0	-	56	-5~-52	3.00
Khan Younis	16.25	7	-17~-82	70	-5~-51	7.72
Khuza'a	1.36	0	-	3	-14~-15	0.16
Rafah	28.94	8	-16~-58	122	-5~65	10.98
Salga	4.03	0	-	9	-6~-21	0.48
Sum	223.9	79		1447		125.9

In MODFLOW, the Well Package is used mainly to simulate the outflow through pumping wells and inflow through injection wells. Wells are identified in MODFLOW by specifying their locations (i.e. layer, row, and column) and the corresponding pumping rates.

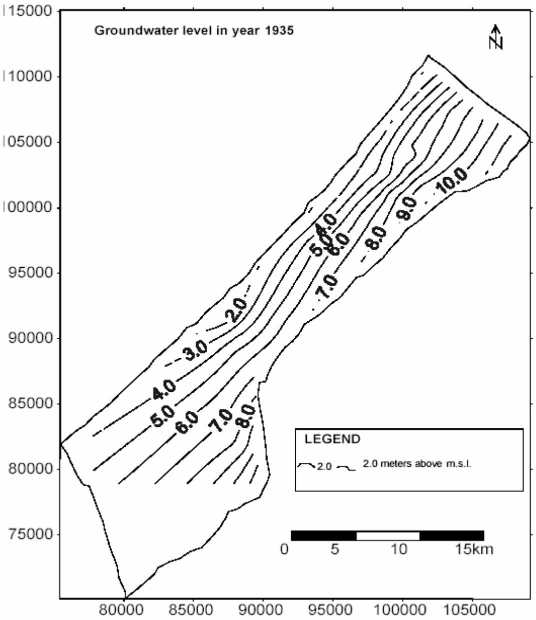
Figure 5-2 shows the spatial distribution of the pumping wells in Gaza Strip. The annual long-term average abstraction from GCA is about 226.6 mcm.

Figure 5-2: The Spatial Distribution of the wells in Gaza Strip

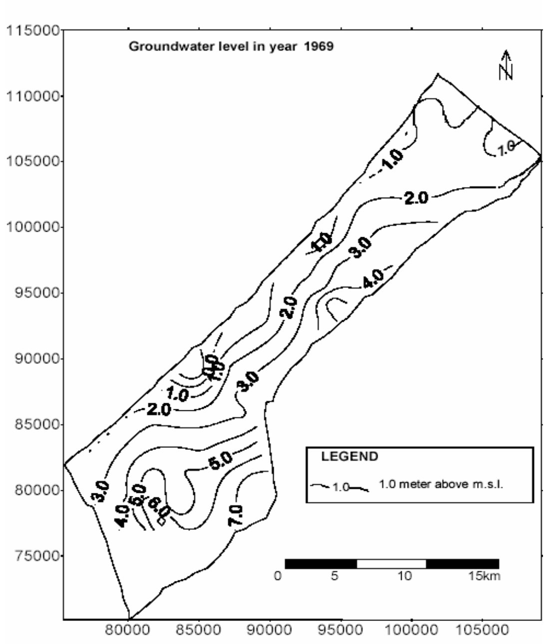
5.5 Groundwater elevation

Groundwater elevation is an important parameter for monitoring the groundwater system. For example, if groundwater levels decline with time, this is an indication of an imbalance between recharge and discharge. Also, a groundwater level below MSL is an indication of saltwater intrusion.

Figure 5-3 is a contour map of the ground water elevation in the years 1935, 1965, and 2000 (Qahman, 2004).



a



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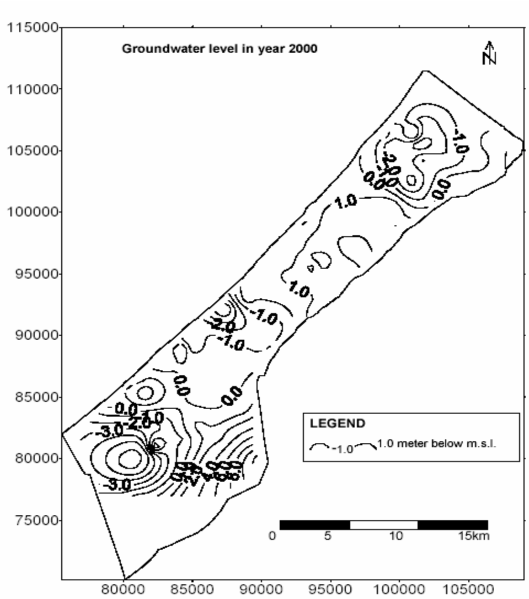


c

Figure 5-3: Contour map of water table elevation for GCA: a) In year 1935.b) In year 1965. c) In year 2000

As indicated in figure 5-3 the groundwater elevation is declining with time. In the year 2000, there are three zones where groundwater elevation is below MSL; Zone 1, 2 and 3. The effect of pumping from theses zones will be discussed later in section 6.5.

5.6 Compilation of data for model formulation

After collecting all the needed data for developing the conceptual model, these data were used in formulating the numerical model using MODFLOW. In order to use MODFLOW, initial conditions, hydraulic properties, and stresses must be specified for every model cell in the finite-difference grid. MODFLOW has a modular structure where it is divided into pieces called packages. The packages which were utilized in developing MODFLOW are summarized in Table 5-2.

Table 5-2: Summary of Packages Used in the Development of MODFLOW for GCA

Package Name	Key Data
Name (NAM)	Input and output packages used in model simulation
Basic (BAS6)	Model boundary and initial head
Block-centered flow (BCF)	Hydraulic conductivity Values
Well (WEL)	Well locations and pumping rates
Recharge (RCH)	Recharge distribution
Preconditioned Conjugate Gradient (PCG)	Method for solving the groundwater flow equation along with all the settings
Discretization (DIS)	Provides the number of rows, columns, and layers
Output control (OC)	Output options

5.7 Model calibration

As mentioned earlier, calibration is the process where hydraulic properties and boundary conditions are modified so that the simulated values of groundwater heads approximately meet the observed ones. The model was calibrated under steady-state conditions. The values of well abstractions are based on the available data from PWA. For the purpose of the steady-state calibration, a set of observation wells were selected to represent the target elevations as shown in Figure (5-4) based on PWA data in 2005. Also, recent contour maps for groundwater elevations (Figure 5-3) where used for calibration.

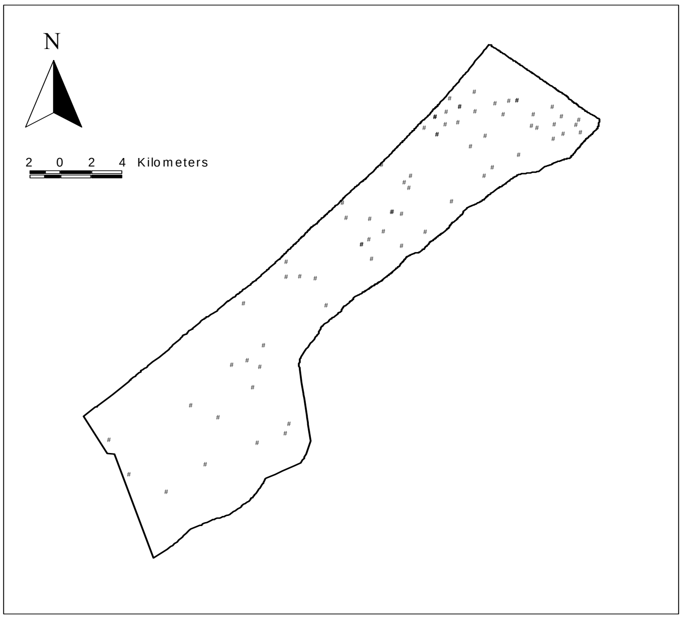


Figure 5-4: Spatial distribution of observation locations

The traditional method of calibration is based on the trail-and-error process where the simulated heads at the designated points and the water budget are compared to the observed ones. This method was carried out sequentially by adjusting the model parameters until the computed values approximate the observed values.

To facilitate model calibration, the model domain was divided into zones as shown in Figure 5-5. This made it easier to alter the hydraulic conductivity values at selected locations and to observe the corresponding effect on the values of the water table and the water budget after running the model.

After different changes in input parameters using the trail-and-error process, the distribution of the calibrated hydraulic conductivity values for GCA is shown in Figure 5-6.

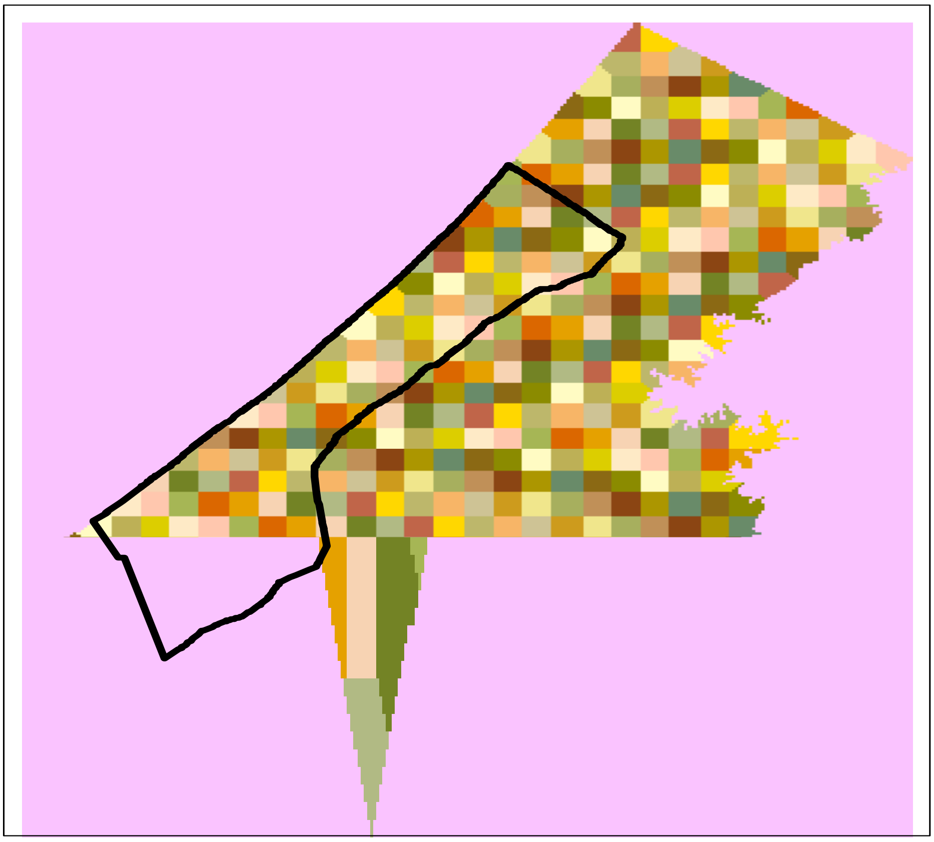


Figure 5-5: Hydraulic Conductivity Zones Utilized in Calibration.

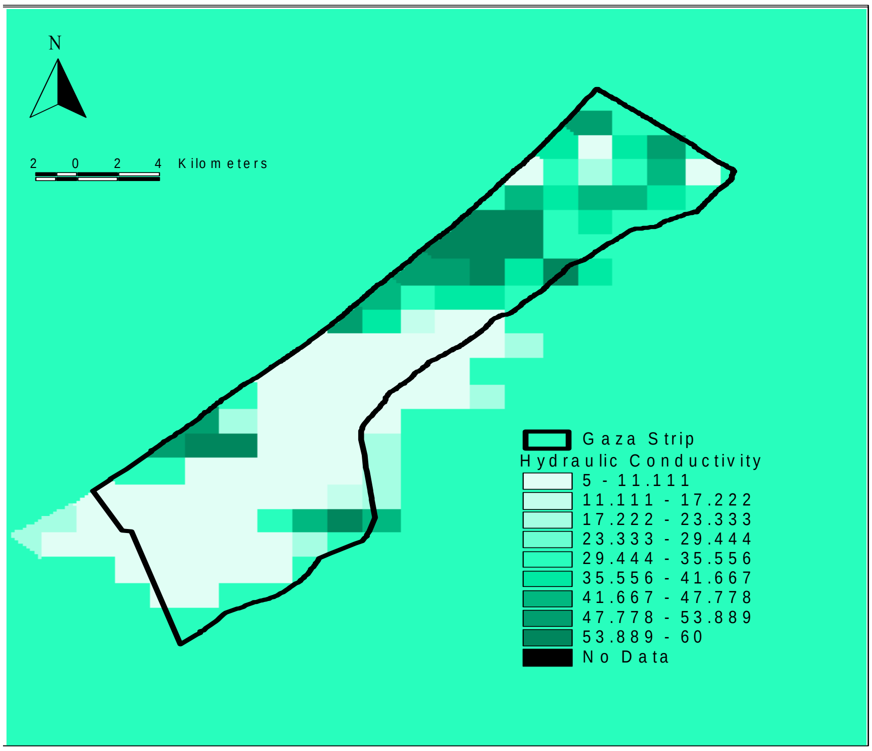


Figure 5-6: The Spatial Distribution of the Simulated Hydraulic Conductivity Values

The calibrated contours of water table elevation as simulated by MODFLOW is shown in Figure 5-7. Compared to Figure 5-3 c, the water table contours in Figure 5-7 shows a good match to the contours in the year 2000. Also in this figure (Figure 5-7), the areas that have water table elevations below MSL (zones 1, 2 and 3) are observed.

Figure 5-7: The Contours of the Simulated Water Table Elevations of GCA

The scatter plots of the simulated and observed heads at the calibration locations are depicted in Figure 5-8 and show a good match. The correlation coefficient between the observed data and the simulated data is 0.85 and the root mean square error is 2.19 m. Root mean square error is a statistical measure of the magnitude of a varying quantity, it is the square root of the mean of the squares of the values of errors.

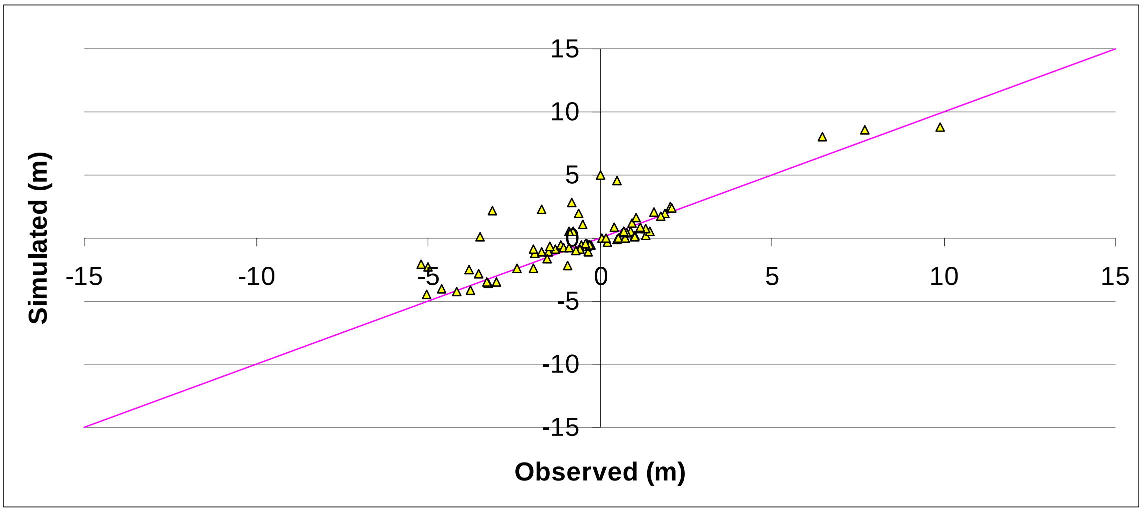


Figure 5-8: Simulated Versus Observed Water Table Elevations of GCA at the Calibration Locations

Table 5-3 summarizes the simulated water budget for GCA. Under the steady-state conditions, the average inflow to the system is approximately 217 mcm as recharge. About 227 mcm leaves the model domain through abstraction wells. Differences between the inflow and the outflow are due to the numerical approximation by MODFLOW.

Table 5-3: Annual Steady-State Water Budget for the Model Domain

Inflow/Outflow Component	Inflow (m^3/yr)	Outflow (m^3/yr)
Wells	0.0	226,596,352
Constant-head Boundary	34,558,576	25,494,956
Recharge	217,246,976	0.0
Total	**251,805,552**	**252,091,312**

Based on the simulated water table elevations (Figure 5-7), and according to Ghyben-Herzberg approach (section 3.1), a contour map of the freshwater/saltwater interface was derived. This contour map is shown in Figure 5-9. This figure indicates the distance between the mean sea level and the freshwater/saltwater interface. It is clear from this figure that the saltwater reaches the sea level in the areas that have water elevations below MSL.

To show the cross-sections of the saltwater intrusion interface, two sections (1-1 and 2-2 in Figure 5-9) were taken in the north and the south of Gaza Strip. The results are shown in Figures 5-10 and 5-11. These figures show that saltwater is in the MSL for significant distance from the shoreline (9 km and 4 km in the north and the south respectively) because the water table in these locations is below MSL (see Figure 5-7).

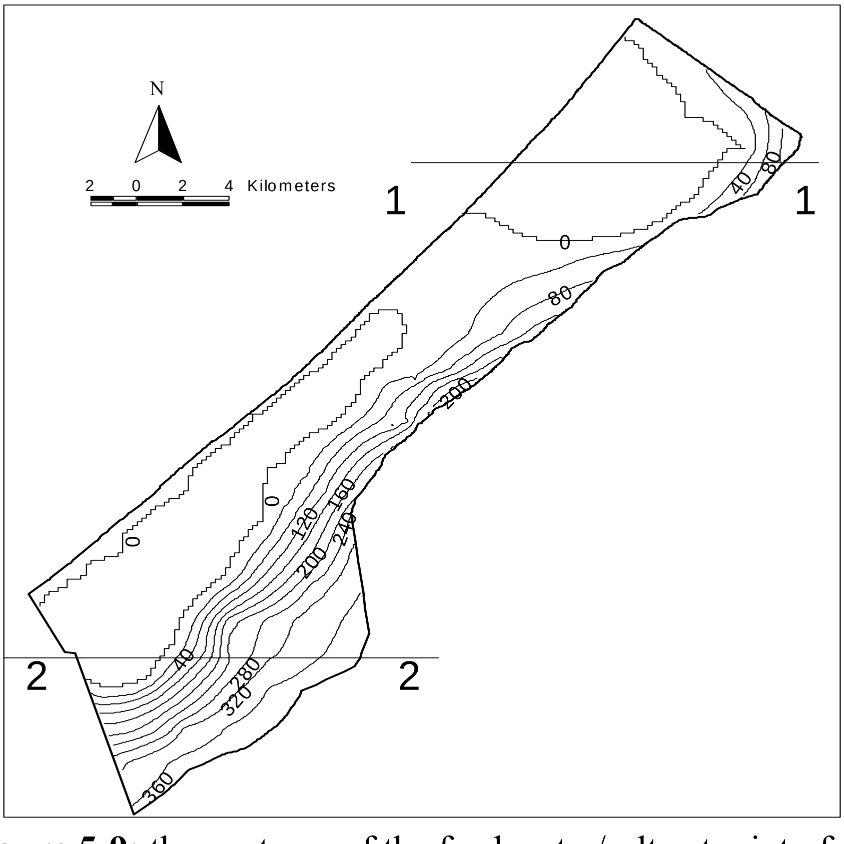


Figure 5-9: the contours of the freshwater/saltwater interface

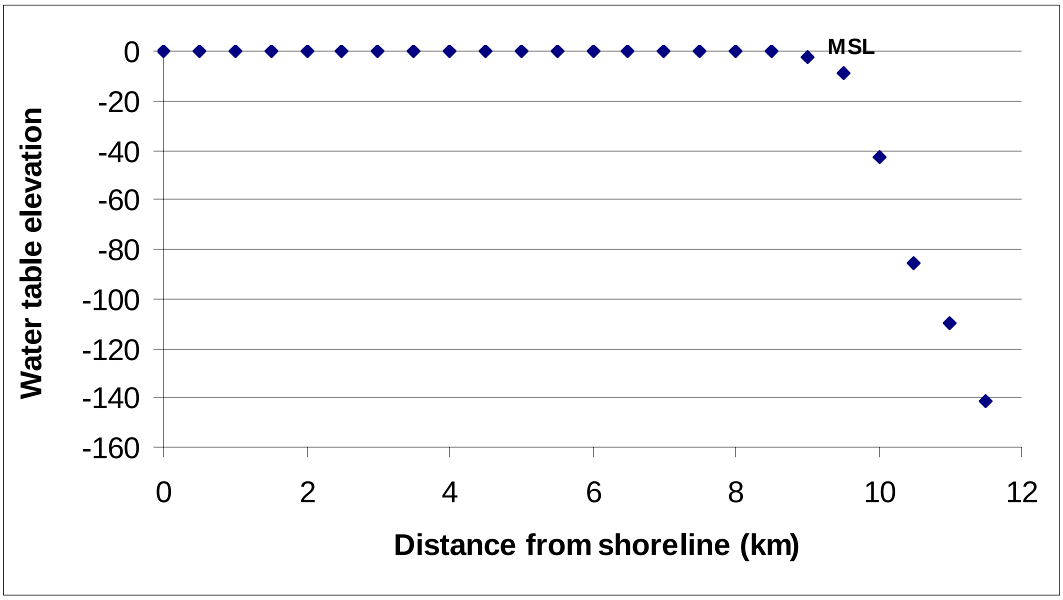


Figure 5-10: A cross-section in the freshwater/saltwater interface in the north of Gaza Strip (section 1-1 in Figure 5-9)

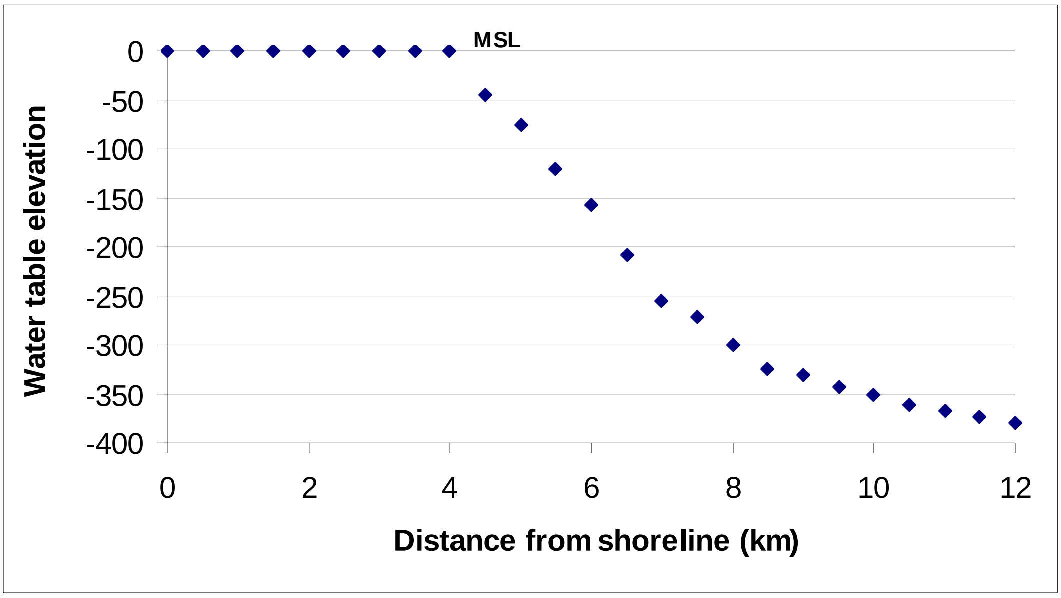


Figure 5-10: A cross-section in the freshwater/saltwater interface in the south of Gaza Strip (section 2-2 in Figure 5-9)

Also by subtracting the water table elevation (Figure 5-7) from the ground surface elevation for Gaza Strip, a distribution of the depth to water table can be derived as shown in Figure 5-12. This figure shows that the depth to water table is low near the shoreline, and the largest values of this depth are in the eastern part of Gaza Strip.

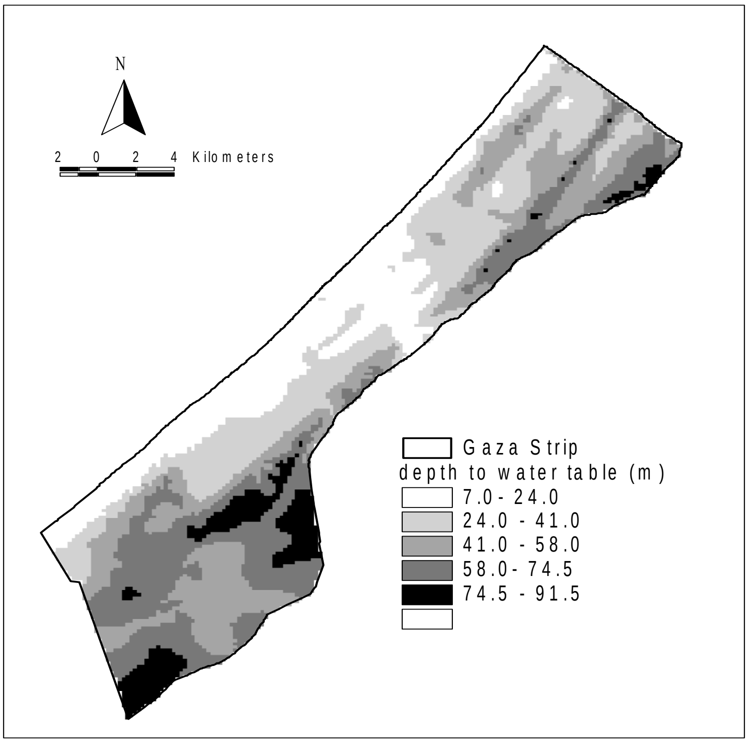


Figure 5-12: Depth to water table

5.8 Sensitivity analysis

In the sensitivity analysis, the effects of different parameters on water table elevations are studied. A sensitivity analysis is an essential step in model development. The parameters tested in the sensitivity analysis are the hydraulic conductivity and the recharge. The sensitivity tests were conducted by varying the above-mentioned parameters by specific amounts from the calibrated values.

The sensitivity analysis results are presented as plots of areas that have water table elevations below MSL. The changes in hydraulic conductivity and recharge were made by changing the multiplication factor in the BCF6 and RCH Packages, respectively.

5.8.1 Model sensitivity to hydraulic conductivity

Model output was found to be sensitive to changes in the steady-state calibrated hydraulic conductivity. An increase in the hydraulic conductivity causes a lowering in the total areas that have water table elevations below MSL. Figure 5-13 shows the effect of hydraulic conductivity on water table elevation.

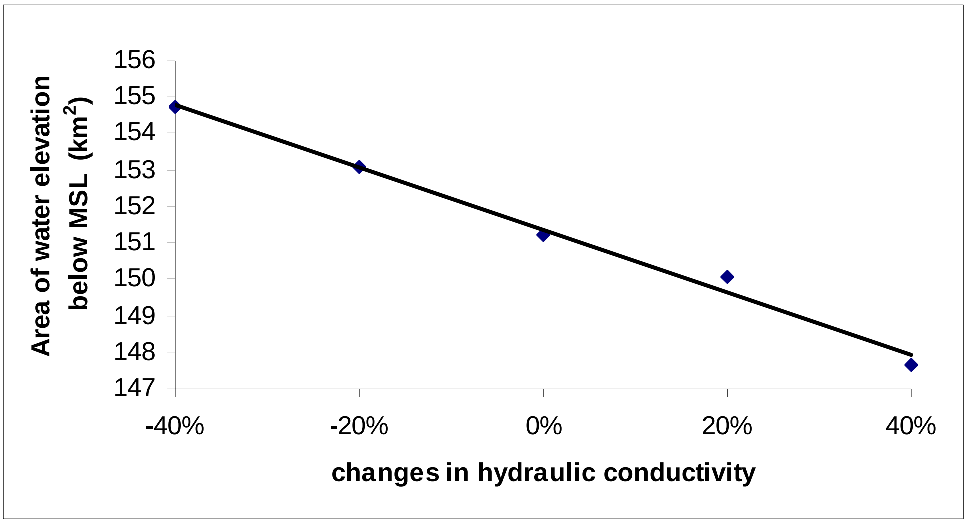


Figure 5-13: The impact of hydraulic conductivity on water table elevation

From Figure 5-13 we can see the linear relationship between the changes in hydraulic conductivity and the area of negative water table (R^2 = 0.99). By knowing the equation of this line (equation [1]) it will be easy to extrapolate the impacts of other potential changes in hydraulic conductivity on the area that has negative water table elevation.

Area of negative water table (km^2) = -8.58(%change in K) + 151.35 [1]

5.8.2 Model sensitivity to recharge

The model shows a high sensitivity to changes in recharge. As expected, an increase in the recharge causes an increase in the simulated heads which yields a decrease in the areas that have water table elevations below MSL. Figure 5-14 shows the effect of changing recharge on water table elevation.

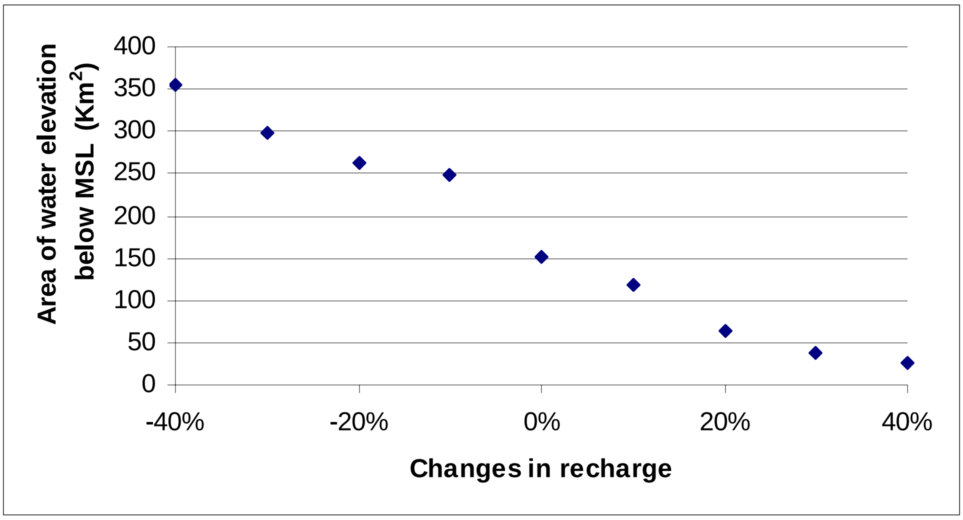


Figure 5-14: The impact of recharge on water table elevation

It is clear from Figures 5-13 and 5-14 that the model is more sensitive to recharge than hydraulic conductivity. A +40% change in hydraulic conductivity decreases the area that has water table elevation below MSL by only 3.6 Km^2. while the same percentage on change in recharge decreases that area by 124.4 Km^2.

Chapter six

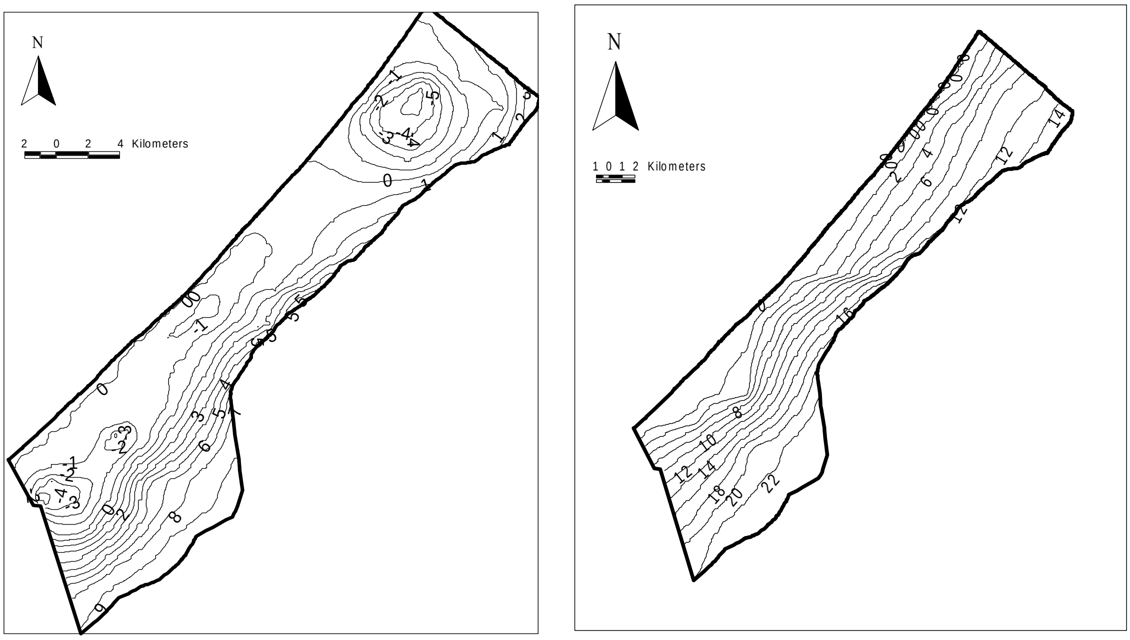
The impact of pumping and recharge on saltwater intrusion

6 The impact of pumping and recharge on saltwater intrusion

The groundwater model of GCA was executed several times to check the impact of total pumping, municipal pumping, agricultural pumping and annual recharge on the water table elevations of GCA. Then the effects of pumping from the three zones in Gaza Strip where the water table elevation is below MSL were investigated. After that, the effect of injection wells as an alternative solution was investigated. The results of these runs are depicted in the following sections.

6.1 The impact of total pumping

To investigate the impact of total pumping from all the wells in the Gaza Strip, the groundwater model was executed several times by reducing the pumping by 10% each time. Figure 6-1 shows the contour lines of water table elevations in two cases; the current situation (100% pumping) and the no pumping situation



a b

Figure 6-1: a- Water table elevation contours under the current situation.
b- Water table elevation contours under the no-pumping scenario.

From figure 6-1 we can see that the current water table contours shows a serious drawdown in three locations; Gaza and Jabalia in the north, Deir El-Balah in the middle, and Rafah and Khanyounis in the south. These three locations have the largest population, and as a result, the greatest pumping rates. A detailed discussion related to these zones is provided in section 6.5. On the other hand the contour lines in the no-pumping situation show a uniform gradient from the sea to the eastern boundary except for the southern part where hydraulic conductivity is low. Also the annual recharge in the southern part is less than that in the north.

Figure 6-2 shows the significant decrease of the areas that have water table elevations below sea level with the reduction in total pumping. From this figure it is apparent that when reducing the pumping by almost 50%, there are no negative heads. This connotes that there will be no hydraulic gradient toward the aquifer from the sea and there is no occurrence of saltwater intrusion.

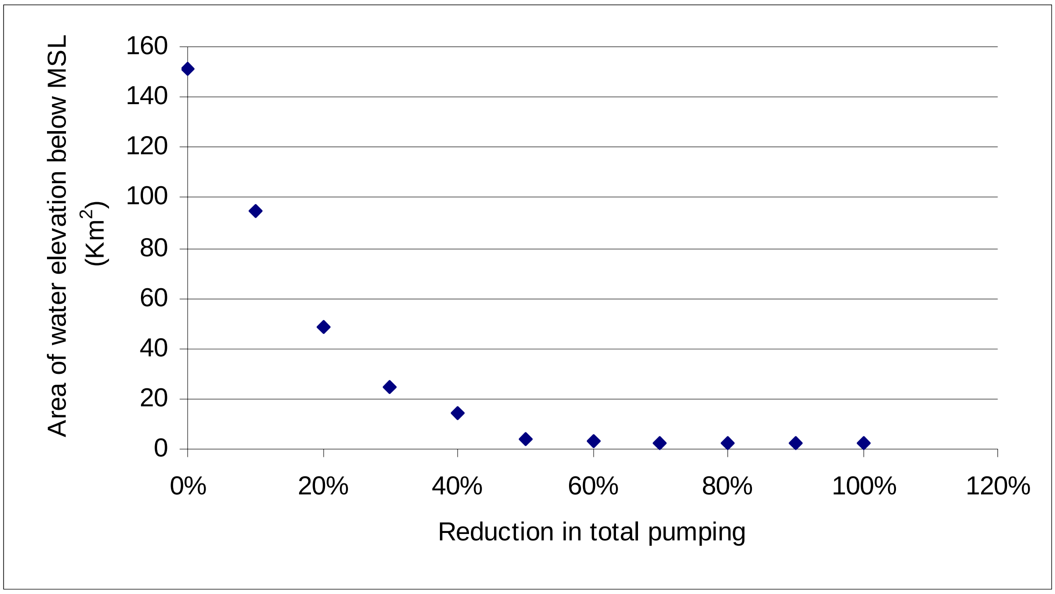
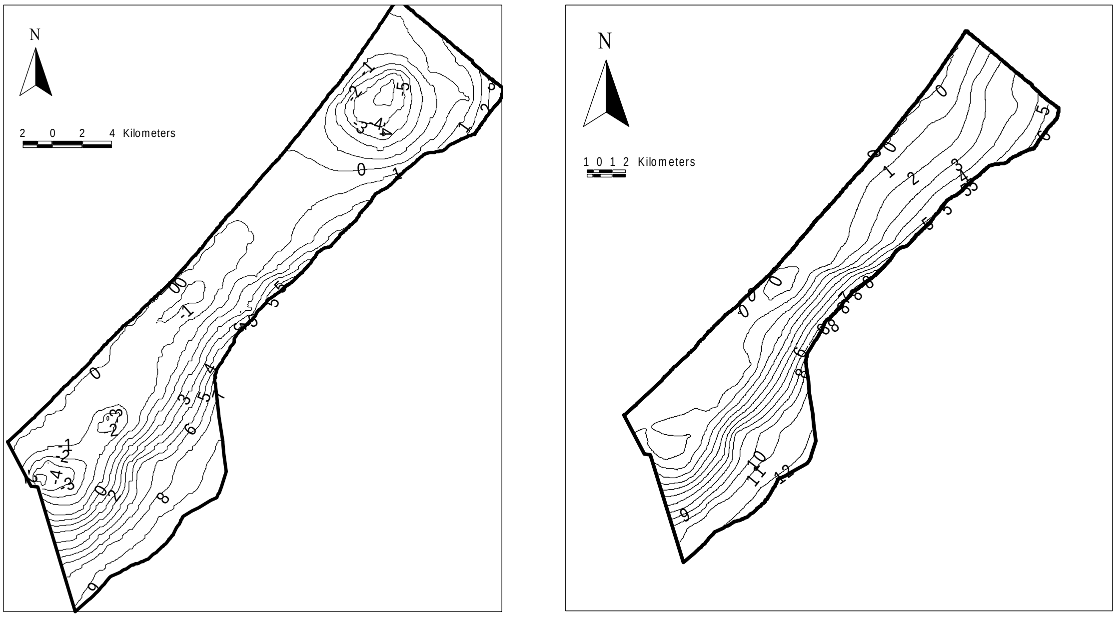


Figure 6-2: The relationship between the areas that has negative head and the reduction in total pumping

6.2 The impact of municipal wells

The pumping through the municipal wells is about 64 mcm or 28 % of the total pumping although the number of these wells is only 92 (less than 5% of the wells). Figure 6-3 shows the contour lines of water table elevations for two scenarios; the current situation (100% pumping) and the no-municipal pumping situation.



a b

Figure 6-3: a- Water table elevation contours under the current situation. b- Water table elevation contours under the no-municipal pumping scenario.

Figure 6-3 indicates that when we shut off the municipal wells, most of the areas that have negative water table elevations will be eliminated. And so, there is no danger of saltwater intrusion.

Figure 6-4 shows the decrease of the areas that have water table elevations below MSL due to the reduction in municipal pumping. This indicates the high effect of pumping from municipal wells on water table elevation despite the small number of those wells. This means that these wells should be taken into consideration when developing management plans.

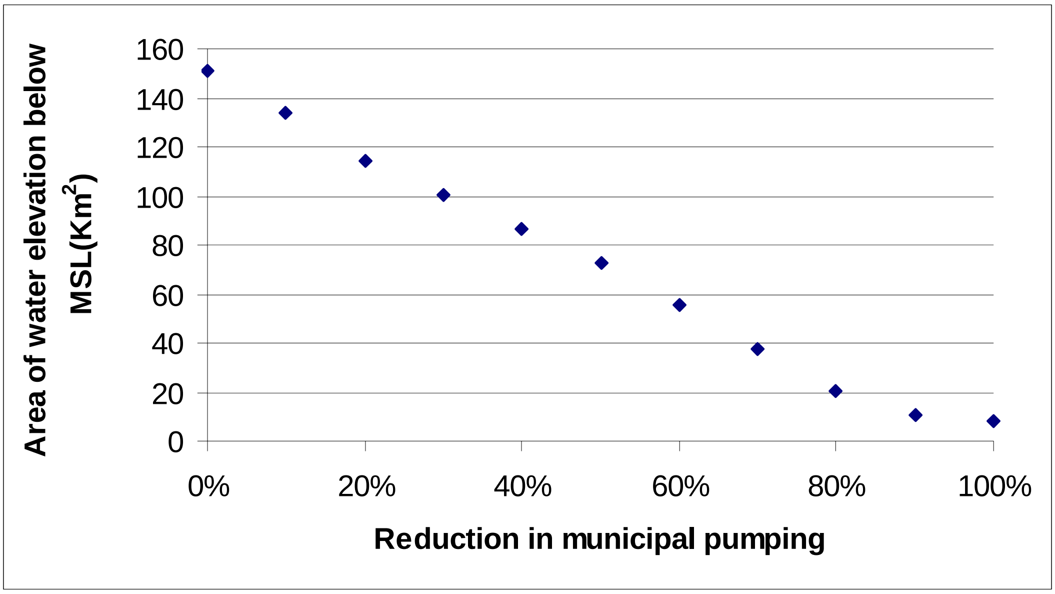
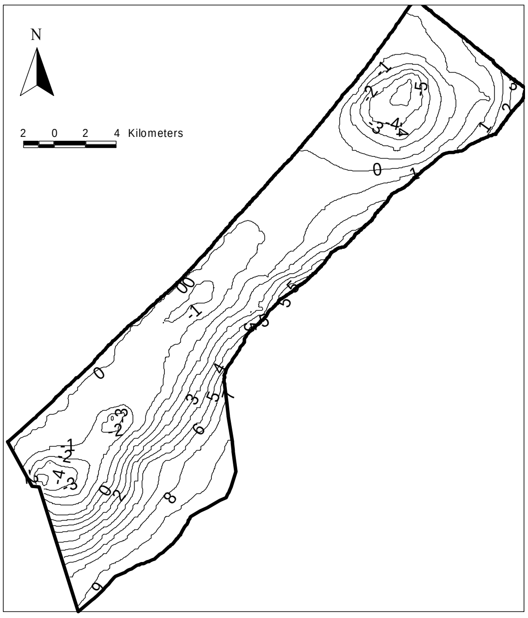
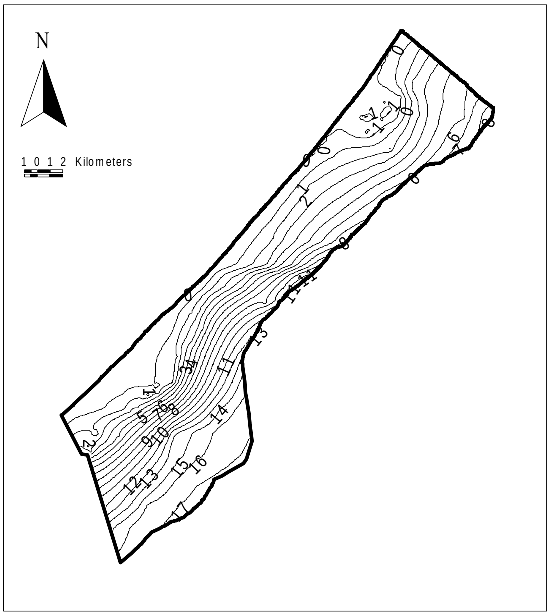


Figure 6-4: The relationship between the area that has negative head and the reduction in municipal pumping

6.3 The impact of agricultural wells

There are more than 1,848 agricultural wells in Gaza Strip. These wells abstract about 111 mcm/year (more than 49% of the total pumping). Figure 6-5 depicts the contour lines of water table elevations under two scenarios; the current situation (100% pumping) and the no-agricultural pumping situation. This figure shows that, as in the previous case, when we shut off the agricultural wells most of the areas that have negative water table elevations will be eliminated. However under this scenario, the water table elevation is closer to the no pumping scenario (section 6.1) than the previous scenario (section 6.2). This indicates that agricultural wells have more impact on groundwater elevation since the number of these wells and the total agricultural abstraction are greater than those of the municipal wells.





a b

Figure 6-5: a- Water table elevation contours under the current situation.
b- Water table elevation contours in the no-agricultural pumping scenario.

Figure 6-6 shows the relationship between the areas with negative heads and the percentage of reduction in agricultural pumping. This figure also indicates the great impact of pumping from agricultural wells on groundwater elevations.

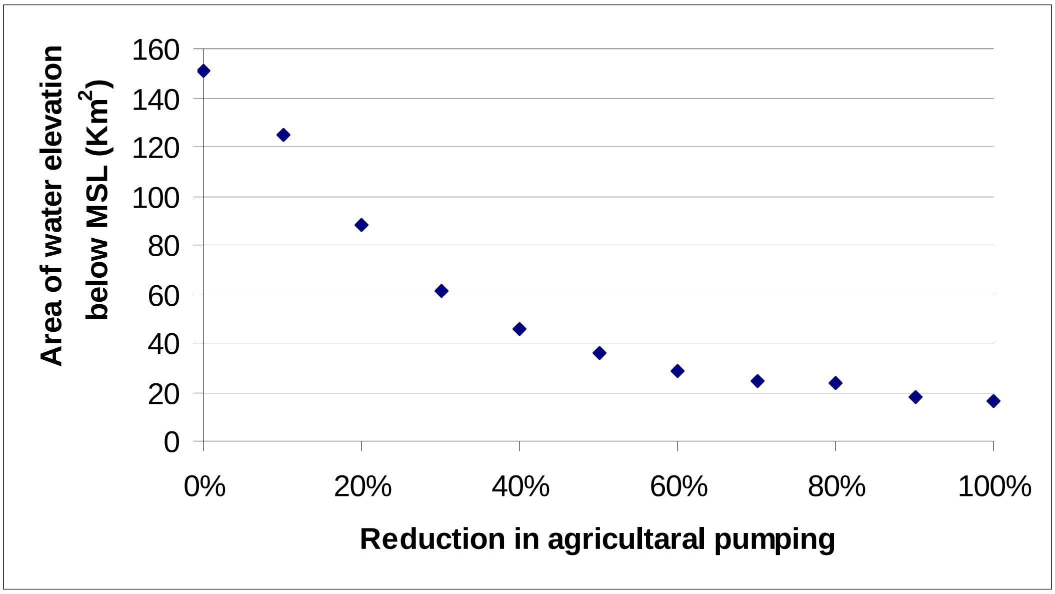
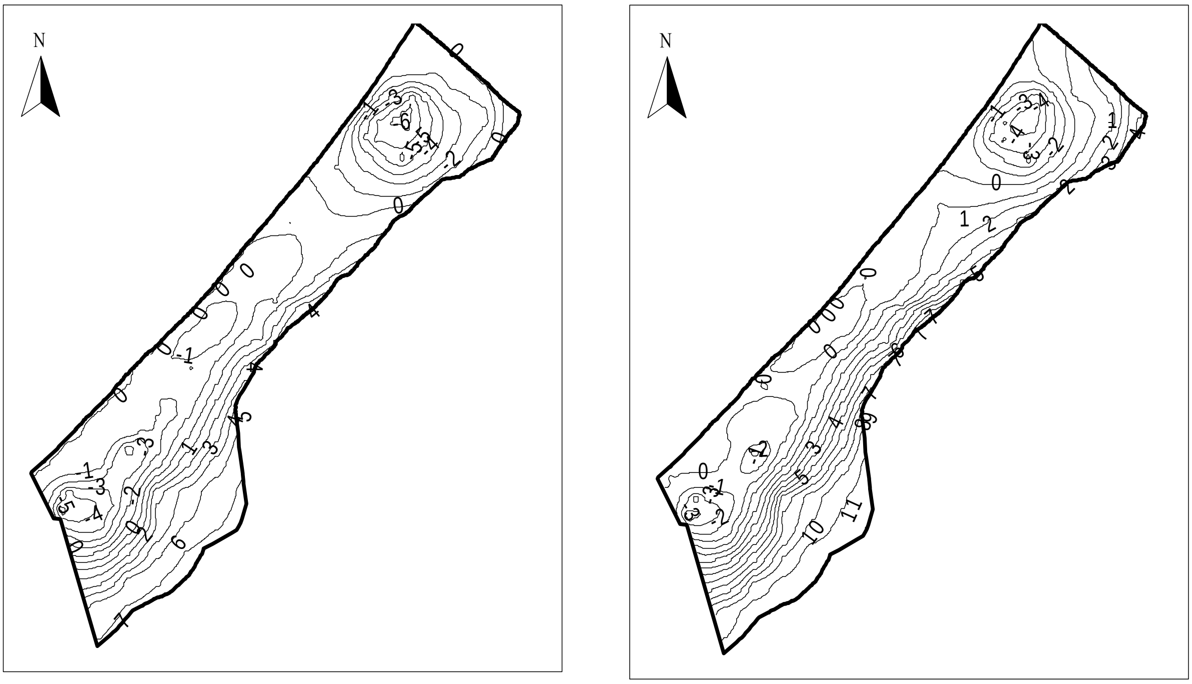


Figure 6-6: The relationship between the area that has negative head and the reduction in agricultural pumping

6.4 The impact of annual recharge

The main recharge for GCA is the infiltration of rain water. As indicated in the sensitivity analysis (section 5.8.2), recharge has a high impact on groundwater elevations, so it is important to study the effect of recharge in any management plan to take into account the climate changes and the annual variations in precipitation.

Running the model several times with 10% increase and decrease in annual recharge each time signifies a big impact of recharge on the water table elevations. The results of these runs are shown in figure 6-7. Figure 6-8 shows the impact of recharge on the relationship between the reduction in pumping and the area that has water table elevation below MSL.



a b

Figure 6-7: a- Water table elevation contours under the 10% decrease in recharge scenario. b- Water table elevation contours under the 10% increase in recharge scenario.

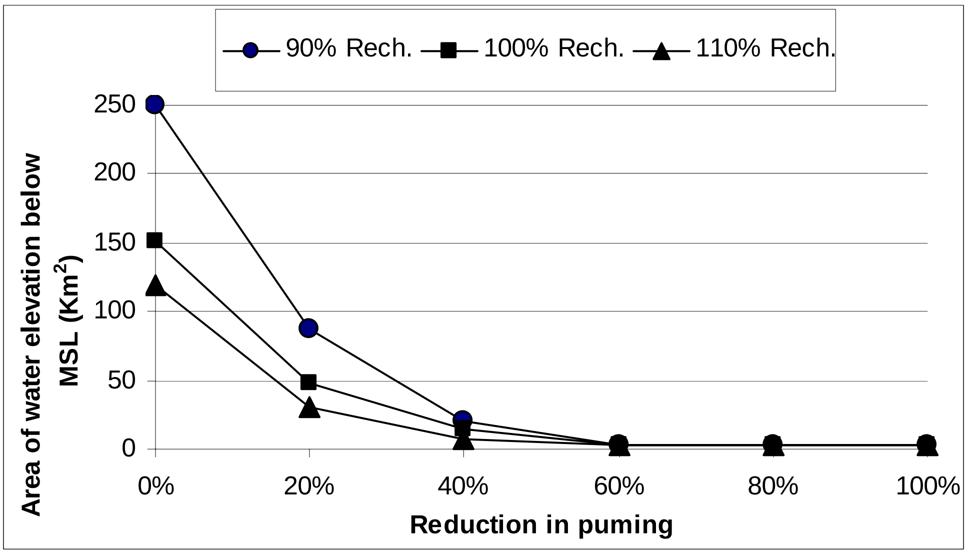


Figure 6-8: The impact of recharge on the relationship between the reduction in total pumping and the area that has water table elevation below MSL

6.5 The impact of pumping from the three zones

As mentioned before in section 6-1, there are three zones that have the largest population and the greatest pumping rates. Figure 6-9 shows the location of these zones. These zones have water table elevations below MSL, which means that saltwater intrusion may occur in such areas.

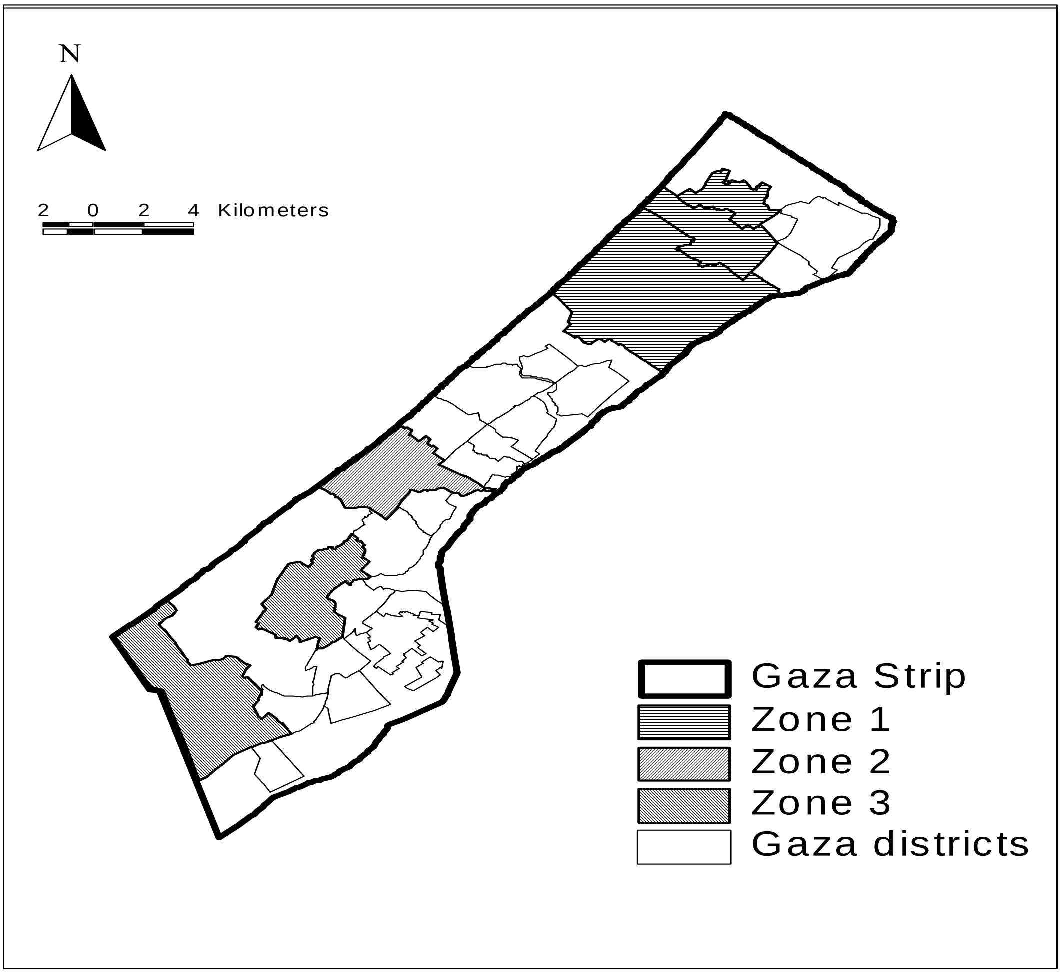
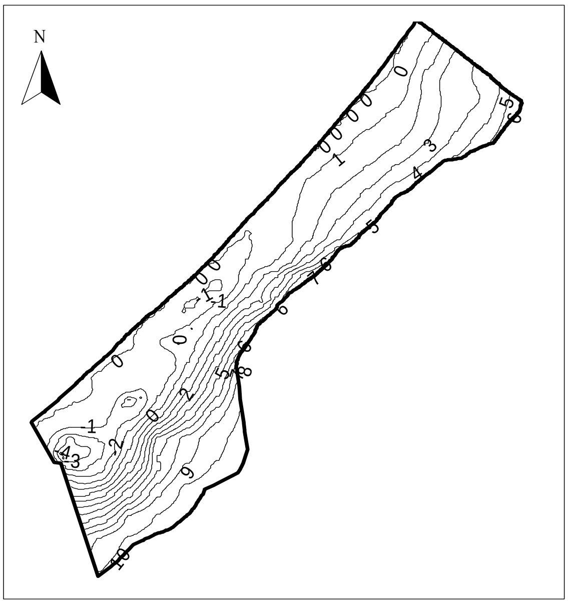


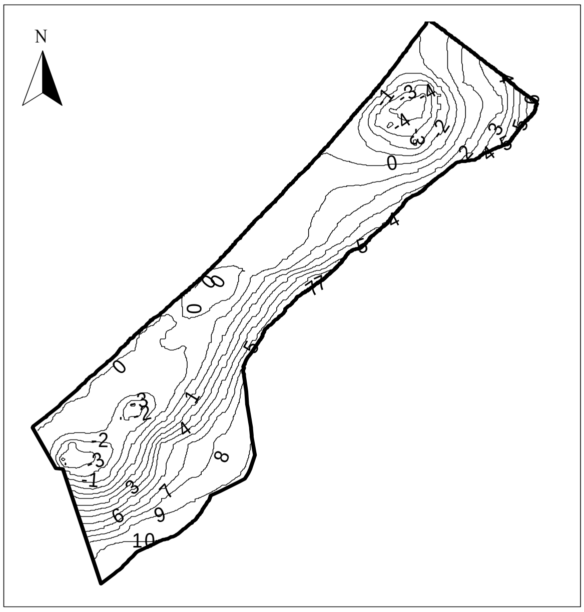
Figure 6-9: Locations of zones 1, 2 and 3

Figure 6-10 shows the contour lines of water table elevations in the two cases; the current situation (100% pumping) and the no-municipal pumping from each zone. This figure shows that municipal pumping from these governorates has great influence on the water table elevations.

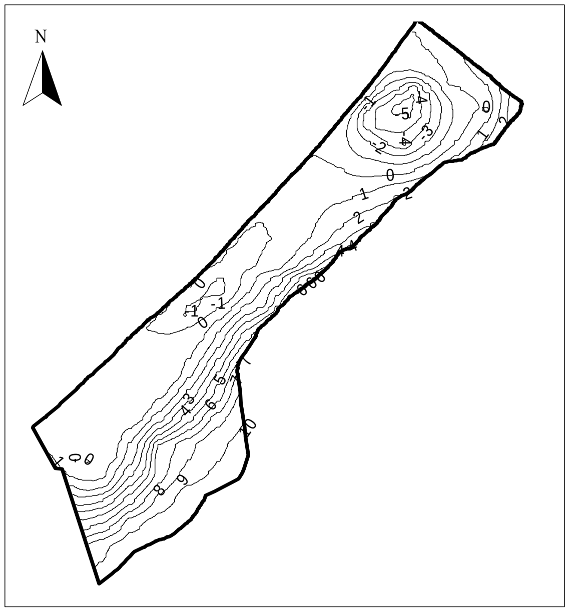
a



b



c



d

Figure 6-10: a- Water table elevation contours under the current situation. b- Water table elevation contours under the no-municipal pumping scenario from zone 1.c- Water table elevation contours under the no-municipal pumping scenario from zone 2. d- Water table elevation contours under the no-municipal pumping scenario from zone 3

In addition, the agricultural pumping from these zones has a high effect on water table elevation as shown in Figure 6-11.

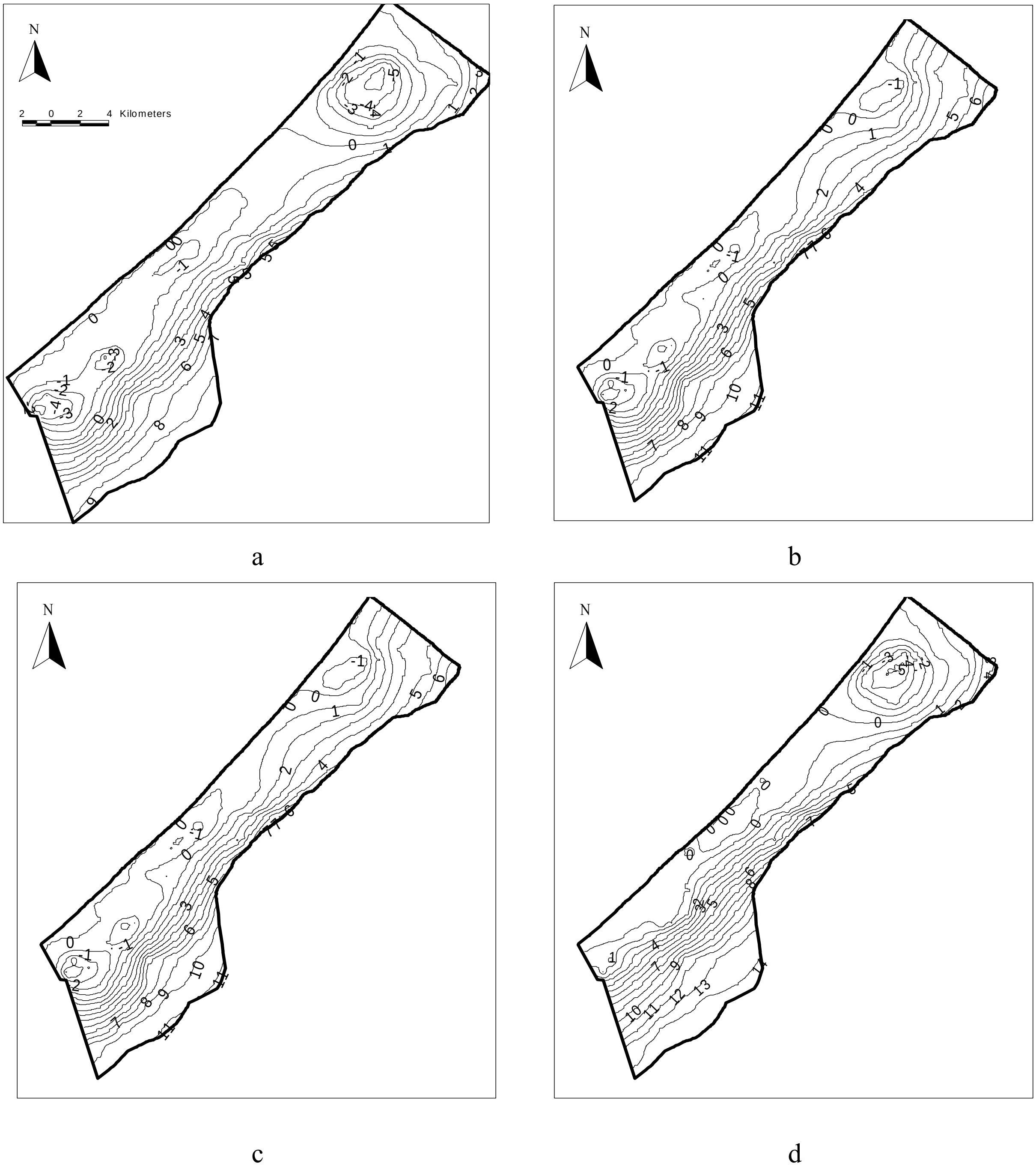


Figure 6-11: a- Water table elevation contours under the current situation. b- Water table elevation contours under the no-agricultural pumping scenario from zone 1.c- Water table elevation contours under the no-agricultural pumping scenario from zone 2.d- Water table elevation contours under the no- agricultural pumping scenario from zone 3

Figure 6-12 is a presentation of the effect of pumping from each of the three zones on the area that has water table elevation below MSL for the entire Gaza Strip. This figure indicates that the municipal pumping from zone 1 and the agricultural pumping from zone 3 have the great effect on groundwater elevations. These results can be used in future management plans.

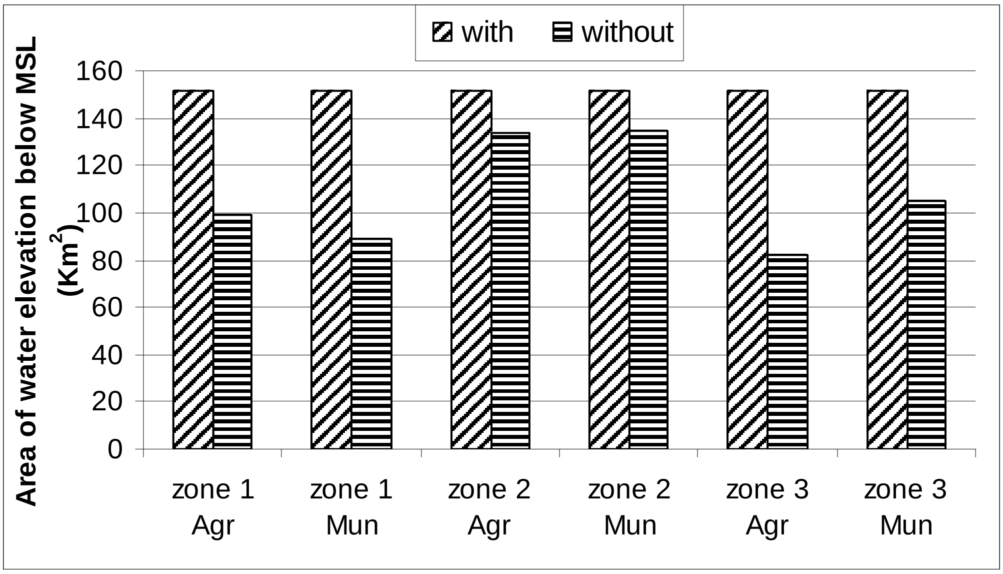
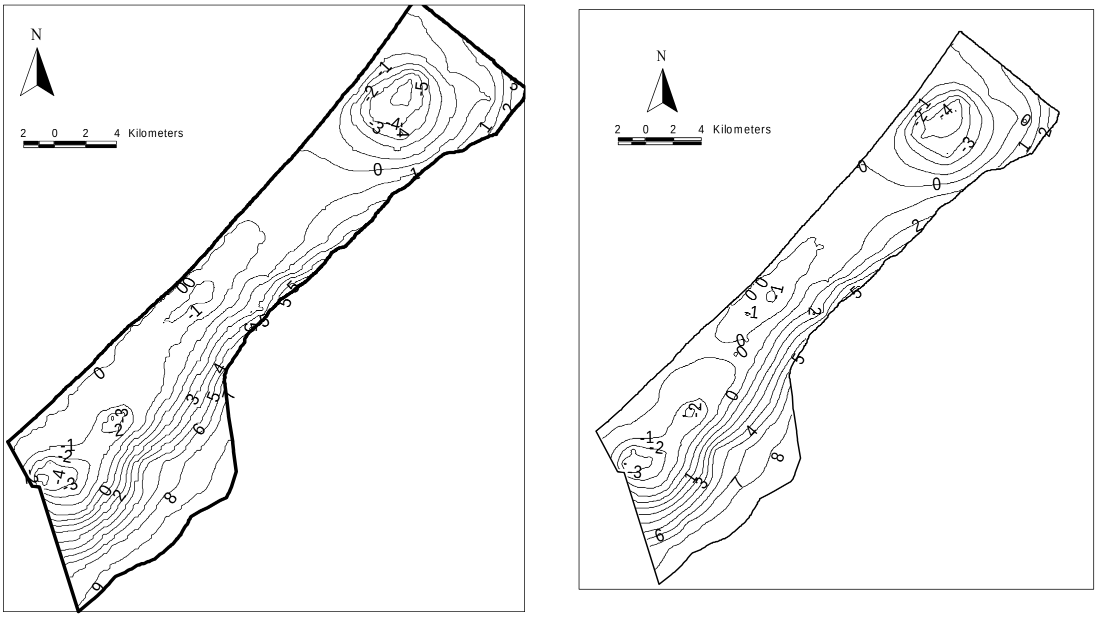


Figure 6-12: The impact of pumping from each of the three zones on the area that has water table elevation below MSL ("with" means with pumping from the specified zone)

6.6 The impact of pumping from wells adjacent to the shoreline

One important factor that should be taken into consideration when studying the impact of pumping is the distance of pumping wells from shoreline. Figure 5-2 shows that many of the wells located adjacent to the shoreline. For example, 265 wells are located within 1 Km from the coast. Although these wells abstracts only about 17 mcm (7.5% of the total pumping), they have a big impact on the water table elevation. Figure 6-13 shows the contour map of water table elevation with no pumping from these wells scenario, and figure 6-14 shows the reduction in the area that have water elevations below MSL under this scenario.



a b

Figure 6-13: a- Water table elevation contours under the current situation. b- Water table elevation contours in the no-pumping from wells located 1Km from the shoreline scenario.

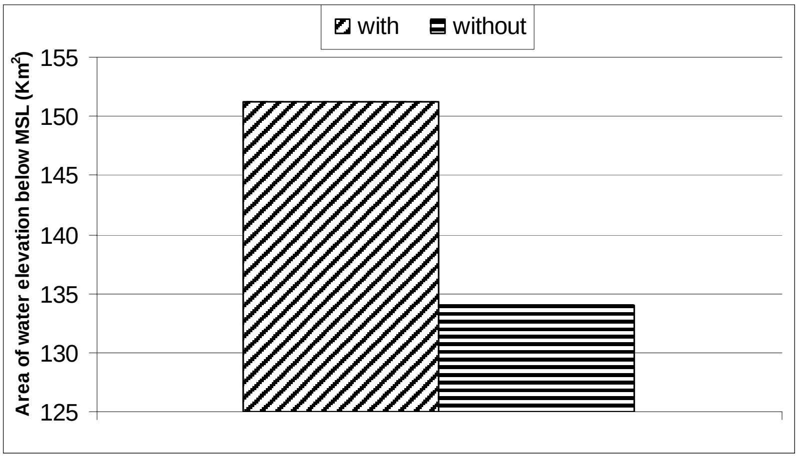


Figure 6-14: The impact of pumping from wells located 1Km from the shoreline on the area that has water table elevation below MSL ("with" means with pumping from the wells)

To show the impact of the above mentioned wells locations, a run was conducted with these wells were moved 200 m away from the shoreline.

The results show that this movement reduces the area that has water table elevations below MSL by about 16.5 km^2 (see Figure 6-15).

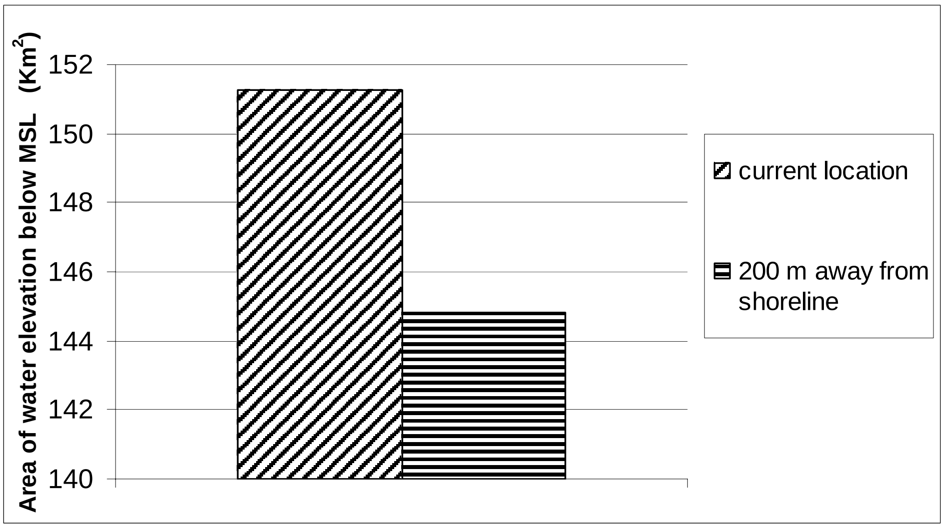


Figure 6-15: The impact of wells locations

6.7 The impact of injection wells

An alternative to solve the problem of salt water intrusion is by injecting freshwater through injection wells. The following set of injection wells were proposed as shown in figure 6-16. This set consists of 50 wells distributed adjacent to the seashore near the zones that were highlighted in Figure 6-9.

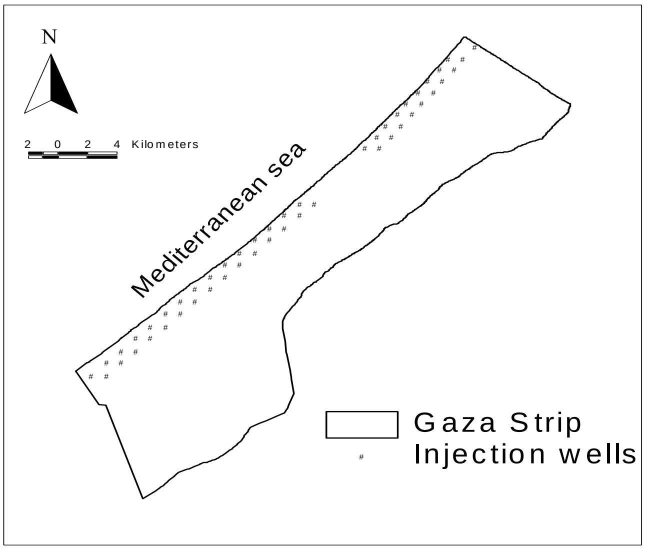


Figure 6-16: Location of the injection wells

The model was executed several times with these injection wells by increasing the injection rate each time. The results show that the area of negative head declined to about 20 Km^2 when the total injection rate was about 226.6 mcm (the total abstraction rate) as shown in Figure 6-17.

The injection wells were modeled in MODFLOW-2000 using the WEL package. This was done by creating a new parameter and assigning the injection wells under this parameter by specifying well layer, row, and column, and a positive value of Q (injection rate).

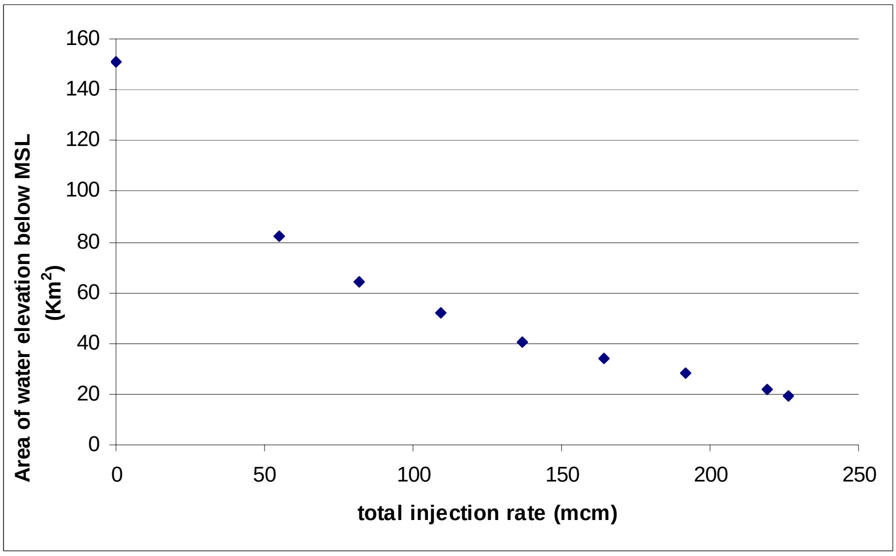


Figure 6-17: The effect of injection rate

6.8 Summary

This chapter (chapter 6) analyzed the impacts of pumping on the water table elevations in GCA. The results show that the different types of pumping have high impact on the areas that have water table elevation below MSL as shown in Figure 6-18. As stated before these areas have high possibility of saltwater intrusion because the reversal of the gradient between sea and inland.

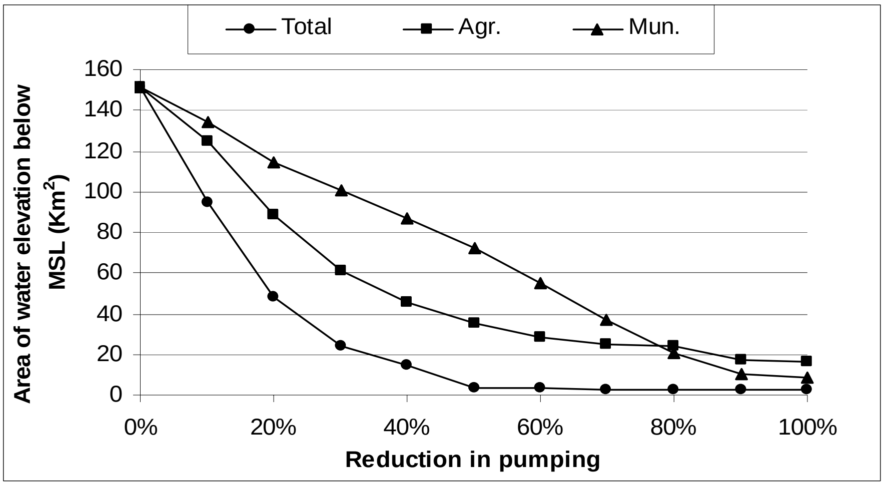
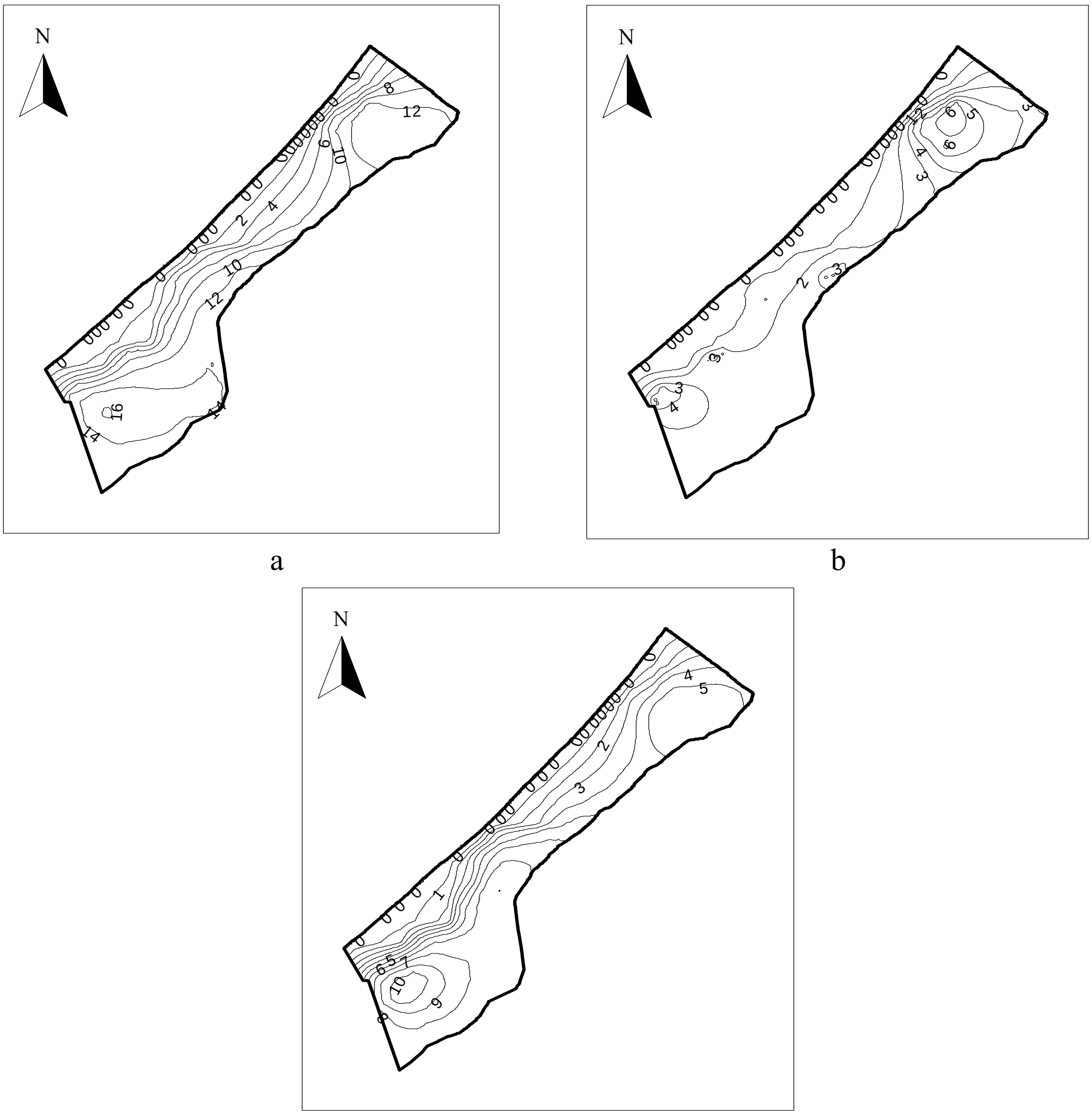


Figure 6-18: The impacts of different types of pumping on the areas that have water table elevations below MSL.

Figure 6-19 depicts the deviation contour maps between the calibrated current situation and the three scenarios; no pumping scenario, no pumping from agricultural wells scenario and no pumping from municipal wells scenario. These maps indicate the impact of pumping on water table elevations spatially, they show how pumping decrease the water table in the whole Gaza Strip.



a b

c

Figure 6-19: Deviation Contour map of water table elevation between the current situation and: a) No pumping. b) No municipal pumping. c) No agricultural pumping.

Two potential management scenarios where discussed in this chapter; reducing the pumping from and injecting water into GCA. While these two scenarios are hydraulically successful in solving the problem of saltwater intrusion, they need to be studied economically. Both of the two scenarios need quantities of water to satisfy the demand in the first scenario, and to be injected in the second scenario. There are three possible sources of this water:

1. Desalinated sea water;
2. Treated waste water; and
3. Imported water from outside Gaza Strip.

Chapter seven

Conclusions and recommendations

7 Conclusions and recommendations

7.1 Conclusions

The following are the research conclusions:

- Recent studies and reports indicate that there is an ongoing problem of saltwater intrusion in GCA. The high salinity and the continuous decline in groundwater elevations below MSL are the main indicators of this problem.

- The excessive pumping to meet the increasing water demand for Gaza Strip is the main reason of saltwater intrusion in GCA. This necessitates the reduction in pumping to eliminate the ongoing problem of saltwater intrusion.

- For any management plan to be successful for GCA, pumping from both municipal wells and agricultural well must be addressed. This is due to the fact that they both have high impacts on water table elevation especially in the three zones that have negative heads.

- One of the potential management scenarios is to set up a realistic pumping strategy. The results show that the total pumping should be reduced by 50% to eliminate the problem of saltwater intrusion.

- Another potential successful management scenario is to inject water into the aquifer through injection wells along the coast.

7.2 Recommendations

The following are the key research recommendations:

- In the groundwater flow model of this research, water quality did not taken into consideration because MODFLOW-2000 is quantity based software. Some times it is needed to study the extent of the saltwater intrusion interface using models that can simulate quality. So it is recommended to cover this point for future research work using SEAWAT (Guo and Langevin, 2002), which is a combined version of MODFLOW-2000 (Harbaugh and others, 2000) and MT3DMS (Zheng and Wang, 1999). This computer program can simulate variable density groundwater flow and solute transport in three dimensions.

- It is recommended to use GWM (Ahlfeld et al, 2005) for the optimization of pumping.

- A benefit-coast analysis should be conducted to figure out the feasibility of the management options arrived at in this research. This analysis should considered as well as the social and political implications.

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Appendix:

The input files for the groundwater flow model

This appendix contains the input files for the groundwater flow model. The input file of the well package was not are not completely shown in this appendix because it is too long to be displayed. Additional files were not shown such as the initial head, hydraulic conductivity, and recharge distributions because they are in raster format and each consists of 94,080 cells which makes it impossible to include them in this appendix.

The name file: GCA_NAM.nam

```
#
# This is the name file for MODFLOW
#
GLOBAL 1 GCA_GLO.glo
LIST    2 GCA_LST.lst
BAS6    3 GCA_BA6.ba6
BCF6   30 GCA_BCF6.bcf6
WEL    12 GCA_WEL.wel
RCH    18 GCA_RCH.rch
PCG    19 GCA_PCG.pcg
OC     22 GCA_OC.oc
DIS    10 GCA_DIS.dis
ZONE   29 GCA.zon
DATA   31 GCA_HEAD.out
DATA(BINARY)  42   budget.bud
```

The Basic Package: GCA_BA6.ba6

```
#
# this is the basic package
#
FREE
OPEN/CLOSE mask.asc 1 (FREE) -8 IBOUND LAYER 1
-9999 HNOFLO
OPEN/CLOSE ini_head.asc 1 (FREE) -12 IBOUND LAYER 1
```

Block Centered Flow Package: GCA_BCF6.bcf6

```
42 -9999 0 0.25 1 1 IBCFBD, HDRY, IWDFLG, WETFCT, IWETIT, IHDWET
1 0 0 0 0 0 0 0 Ltype
CONSTANT  1. TRPY
OPEN/CLOSE hk.asc 1.1 (FREE) -8 Hydraulic conductivity Layer 1
```

Well Package: GCA_WEL.wel

```
#
# This is the well package file
 PARAMETER              5        2647    PARAMETER LINE: NPWEL  MXPWEL
           2647        42                 MXACTW  IWELCB
 Ag          Q       1.150       1848    PARNAM  PARTYP  Parval  NLST
1        66       153      0
1        66       154      0
1        67       154      -110.14
1        67       155      -110.14
1        67       156      -110.14
1        68       150      0
1        68       153      -110.14
1        68       153      -110.14
1        68       155      -110.14
1        68       155      -110.14
1        69       149      0
1        69       149      0
1        69       150      0
1        69       150      0
1        69       151      0
1        69       151      0
1        69       154      -110.14
1        69       158      -110.14
1        70       150      0
1        70       150      0
1        70       153      -110.14
1        70       158      -110.14
1        71       150      0
1        71       151      -110.14
1        71       153      -110.14
1        71       156      -110.14
1        71       157      -110.14
1        72       149      0
1        72       150      -110.14
1        72       150      -110.14
```

Recharge Package: GCA_RCH.rch

```
1 42 NRCHOP,IRCHBD
1 INRECH
OPEN/CLOSE recharge.asc 1.0 (FREE) -12 RECH LAYER 1
```

Preconditioned Conjugate Gradient Package: GCA_PCG.pcg

```
       55        200         1   MXITER  ITER1  NPCOND
   0.0001     0.001      1.00         2        1        0        0  HCLOSE
RCLOSE RELAX NPBOL IPRPCG MUTPCG IPCGCD
```

Output Control Package: GCA_OC.oc

```
# This is the output control package
# |
HEAD PRINT FORMAT 2
HEAD SAVE FORMAT (20F12.4) LABEL
HEAD SAVE UNIT 31
PERIOD 1 STEP 1
SAVE BUDGET
SAVE HEAD
```

Discritization File: GCA_DIS.dis

```
# |
# The discretization file
1 336 280 1 4 2 NLAY, NROW, NCOL, NPER, ITMUNI, LENUNI
0 0 0 0 0 0 0 0 LAYCBD
CONSTANT   200  DELR
CONSTANT   200  DELC
CONSTANT   200  This is the top elevation for layer 1
OPEN/CLOSE bottom.asc 1 (FREE) -8  This is the bottom elevation for layer 1
365    1     1.0  SS     PERLEN,NSTP,TSMULT,Ss/tr
```

جامعة النجاح الوطنية
كلية الدراسات العليا

تأثير الضخ على تملح الحوض الجوفي الساحلي في قطاع غزة، فلسطين

إعداد
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إشراف
د. محمد نهاد المصري

قدمت هذه الاطروحة استكمالا لمتطلبات الحصول على درجة الماجستير في هندسة المياه و البيئة، بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس، فلسطين.
2007

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الملخص

الحوض الجوفي الساحلي هو المصدر الأساسي للمياه في قطاع غزة. تشير الدراسات الحديثة أن هناك تدن ملحوظ في نوعية المياه في هذا الحوض، حيث أن تراكيز الكلوريد و النترات و السلفات و الفلورايد لمعظم آبار الضخ في قطاع غزة تفوق بكثير التراكيز المسموحة لهذه الملوثات. العديد من الآبار الزراعية لم تعد صالحة للاستعمال بسبب الملوحة العالية. هذه الملوحة العالية هي مؤشر على ظاهرة التملح و التي تظهر بشكل أساسي في الأحواض الجوفية الساحلية نتيجة للضخ الجائر.

تشكل هذه الدراسة محاولة لمعرفة تأثير الضخ على منسوب المياه الجوفية في الحوض الساحلي. من أجل ذلك تمت نمذجة المياه الجوفية لهذا الحوض باستخدام برنامج MODFLOW-2000 بالاعتماد على المعلومات المتوفرة من سلطة المياه الفلسطينية. تمت معايرة هذا النموذج اعتمادا على منسوب المياه في آبار مراقبة محددة مسبقا و على خرائط كنتورية لمنسوب المياه في الحوض الجوفي الساحلي. تم استخدام النموذج لمعرفة آثار الضخ و التغذية السنوية و آبار الحقن المقترحة على منسوب المياه الجوفية. لقد أظهرت النتائج أن الحوض الجوفي الساحلي لقطاع غزة يتأثركثيرا بهذه العوامل.

أظهرت النتائج أن آبار الضخ لها أثر كبير على مستوى المياه الجوفية، فقد تبين أن تقليل كمية الضخ الكلي (من جميع الآبار) بشكل بسيط يقلل بشكل ملحوظ مساحة المنطقة التي يكون منسوب المياه فيها أقل من مستوى سطح البحر، و هي المنطقة المرشحة أكثر من غيرها لحدوث ظاهرة التملح. و قد ظهرت نتائج مماثلة عند تقليل كمية الضخ من الآبار الزراعية و البلدية كل على حدة.

تقترح الدراسة حلين محتملين لظاهرة التملح: تخفيف الضخ من الحوض أو حقن المياه إلى داخل الحوض من خلال آبار الحقن. بعد دراسة كلا الخيارين، تبين أنهما صالحين لحل المشكلة من الناحية الهيدرولوجية، و لكنهما بحاجة لدراسة معمقة من حيث الجدوى الاقتصادية.