Hydrogeo-Eco-Systems in Aqaba/Jordan –Coasts and Region; Natural Settings, Impacts of Land Use, Spatial Vulnerability to Pollution and Sustainable Management.

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By

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from

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Dedication

To the Memory of His Majesty
King Hussein Bin Talal.

وفاءً للراحل العظيم.. الحسين

Acknowledgement From the Author

When I finished my study at the University of Jordan in 1995, which led to a B.Sc. degree in the field of Geology and Environment, it was the encouragement of **my parents**, **brothers** and **sisters** to continue my higher studies in the same field, and at the same university. Accordingly I joined the M.Sc. program at the Faculty of High Studies/University of Jordan.
Prof. Dr. Elias Salameh (Professor of water sciences) from the Department of Geology, smoothed my mission lighting the way for me and emphasizing on the way how to serve the nation, I was offered a subject for the master research, regarding studying the karst phenomena north Jordan and its role in enhancing human impacts on the groundwater resources. In 1997 the study came to an end. Prof. Salameh gave me a hand by allowing me to work on his researches and projects to gain some experience while waiting for the suitable chance for a Ph.D. study in the field of Hydrogeology and Environment.

Prof. Salameh contacted his study collage **Prof. Dr. Dr. Peter Udluft,** head of the Institute of Hydrogeology and Environment in the University of Wuerzburg/Germany, who accepted me for a Ph.D. research under his supervision.

My M.Sc. thesis was sent to his majesty **King Hussein Bin Talal** in 1998. One month later **Dr. Fayes Al Tarawneh**; the President of the Hashmite Court, informed me that his Majesty granted me a scholarship.

In the institute of Prof. Udluft and besides his fruitful discussions, hospitality and kindness, I found all the required facilities to start my mission; advanced hardware and software, information technologies, laboratories and comfortable working offices, atmosphere and groups.

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The author. 02/15/02

Abstract

The coast of Aqaba and the Aqaba region (Jordan) were investigated on their hydrogeo-ecosystem. The results of the research were translated into digits to build a geo-spatial data base. The fillings of the graben aquifer receive indirect type of recharge through the side wadis which drain the highlands. Surface water balance was modeled for a period of 20 years of daily climate records using MODBIL program which attributes direct recharge to wet years only. The hydrodynamic fresh water/seawater interface in the coastal zones was investigated by applying vertical geoelectric surveys and models of several methods to confirm its coincidence with the aquifer’s flow amounts, where human impacts in terms of over-pumping allowed more encroachment of seawater into land, and unintended recharge which led to seaward interface migration. A groundwater balance and solute transport were approached by developing a flow model from the hydrogeological and hydrochemical data. The nature of soil cover and aquifer whose physical properties enhance human impacts indicated the vulnerability of groundwater to pollution. This certainly threatens the marine ecology which forms the sink where the in-excess flow ends. The constructed digital background was exported into GIS to sub-zone the study area in terms of the aquifer’s vulnerability to pollution risks using DRASTIC index. However, it was unable to meet all geo-spatial factors that proved to have significant impacts on the vulnerability. Consequently, a comprehensive index -SALUFT- was developed. This suggests the suitable land use units for each zone in the light of vulnerability grades aiming at protecting the available groundwater resources.

Zusammenfassung

Die Küste und die Region von Aqaba (Jordanien) wurde im Hinblick auf ihre Hydrogeo-ökosysteme untersucht. Die Ergebnisse dieser Forschungsarbeiten wurden in eine digitale Form überführt, um bezüglich der Geofaktoren ein realitätsnahes Abbild der Umgebung zu erzeugen. Der Graben-Aquifer erhält seine Grundwasserneubildung meist indirekt von den Seiten, von denen Wadis ihr Wasser abführen. Die Bilanzierung des Oberflächenwassers wurde aus Tagesklimawerten der letzten 20 Jahre unter Benutzung des Programms MODBIL errechnet. Daraus ergab sich eine Neubildung des Grundwassers nur in feuchten Jahren. Die hydrodynamische Süßwasser-Salzwasser-Mischungsfront im Küstenbereich wurde durch geoelektrische Tiefensondierungen untersucht. Durch Modellierungen mit verschiedenen Methoden wurden Fließgeschwindigkeit und Wassermenge dort mit der des Aquifers in Einklang gebracht, wo durch Überpumpen das Salzwasser weiter ins Landesinnere vordringt. Durch die Entwicklung eines Fließmodells aus den hydrogeologischen und hydrochemischen Daten konnte die Grundwasserbilanzierung und der Stofftransport ermittelt werden. Die Natur des Bodens und des Aquifers, deren physikalische Eigenschaften die Einflüsse durch menschliche Aktivitäten steigern, führt zu einer Anfälligkeit gegenüber Verschmutzung, die die Qualität des Grundwassers verschlechtert. Dies beeinflusst die Ökologie des Meeres, das an den Stellen als Schadstoffsenke dient, an denen die Grundwasserströme enden. Die im Computer erstellte digitale Umgebung wurde dazu genutzt, den Aquifer im Untersuchungsgebiet mit Hilfe von GIS in Zonen unterschiedlicher Verschmutzungs-empfindlichkeit zu unterteilen. Dazu wurde der DRASTIC-Index benutzt. Im Laufe der Untersuchungen zeigte sich allerdings, dass es nicht möglich war, alle Faktoren, die einen signifikanten Einfluss auf das System haben, mit Hilfe dieses Index zu erfassen. Aus diesem Grund wurde der SALUFT-Index entwickelt. Damit wurde es möglich, bezüglich der Verschmutzungsempfindlichkeit für jede Zone die günstigste Art der Landnutzung zu ermitteln, um die verfügbaren Grundwasserressourcen zu schützen.

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CHAPTER 1

1.1 INTRODUCTION

1.1.1 General Background

Development and decision-making not planned on scientific background may impair the ecosystems encountering negative impacts by disturbing their natural sustainability. It is important to understand the impacts of any Man-made development on the natural systems and to evaluate the system itself by building background information, that may serve in predicting any future disturbances. This results in the sustainability of the renewable types of resources and the wise handling of the non-renewable types. Consequently, the rights of the generations to come are then taken into consideration.

Geo-spatial components are subdivided into vulnerable and non-vulnerable zones for pollution. Vulnerable zones should be handled under specific and special controls.
Planning of modern cities and regions requires putting all the partners in environment and natural resources into consideration, since the random use of lands makes the cities less able to face the human need, while the method of use governs to a big extent the quality of the environment.

Water is the substance on which the continuity of all life depends. Jordan is a country well known in terms of its stressed water conditions which are characterized by;

- *lack of resources*; annual precipitation, surface and groundwater resources.
- *increasing demands*; for the different sectors and purposes.
- *the existing degradation in quality*; featured as pollution and salinity.

The country is on the way of a fast development, modernization and population growth. These affect the natural resources; especially those types which suffer the scarcity such as water resources.
Aqaba city (in the southern part of Jordan) is Jordan's only access to the open sea. It is located on the northern end of Gulf of Aqaba/Red Sea and accordingly forms the only seaport serving the country. In addition to that it is one of the big residential cities in Jordan, an important industrial complex for several heavy industries, free trade zone area and tourism attraction city in terms of its unique natural property specially that of its marine life.
The region is proposed for many future investment plans, where it was declared as a free trade zone area from the beginning of the year 2001.
As in the case of all coastal cities, Aqaba should be carefully handled especially in terms of those vulnerable and scarce resources.

1.1.2 Profiles From Jordan

Following are fast information about the country;

Location: Middle East, northwest of Saudi Arabia
Geographic coordinates: 31 00 N, 36 00 E
Map references: Middle East
Population (year 2000) : 5.1 million

Density : 52.3 person / km²
Rate of growth : 3.4% / year
Economic sectors : Agriculture 10%, industry 22%, services 68%
Area:
total: 89,213 km^2
land: 88,884 km^2
water: 329 km^2
Land boundaries:
total: 1,619 km
border countries: Iraq 181 km, Israel 238 km, Saudi Arabia 728 km, Syria 375 km, West Bank 97 km.
Coastline: 26 km
Climate: mostly arid desert; rainy season in west (November to April).
Terrain: mostly desert plateau in east, highland area in west; Great Rift Valley separates East and West Banks of the Jordan River.
Elevation extremes:
lowest point: Dead Sea -413 m. (2001)
highest point*:* Jabal Ram 1,754 m
Natural resources: phosphates, potash, shale oil
Land use:
arable land: 4%
permanent crops: 1%
permanent pastures: 9%
forests and woodland: 1%
other: 85% (1993 estimations)
Irrigated land: 630 sq. km (1993 estimations)
Environment—current issues: limited natural fresh water resources; deforestation; overgrazing; soil erosion; desertification
Environment—international agreements:
party to: Biodiversity, Climate Change, Desertification, Endangered Species, Hazardous Wastes, Law of the Sea, Marine Dumping, Nuclear Test Ban, Ozone Layer Protection, Wetlands signed, but not ratified: none of the selected agreements.

1.1.3 Climate and Water Resources in Jordan

The climate of Jordan is marked by sharp seasonal variations in both temperature and precipitation. Temperatures below freezing are known in January, the coldest month, but the average winter temperature is above 7.2° C. In the Jordan Valley, summer temperatures may reach 48.9° C in August, the hottest month, but the average summer temperature in Amman is 25.6° C. Precipitation is confined largely to the winter season and ranges from about 660 mm in the northwestern corner of the highlands to less than 30 mm in the extreme south east. The average annual rainfall for the country as a whole gives a total volume of 8.43 km^3 . Figure (1) shows the annual rainfall distribution in Jordan. About 80.6% of the total area of Jordan receives in average less than 100 mm/year of precipitation. Most of the received precipitation is being lost due to the high evaporation rates (Salameh 1990).

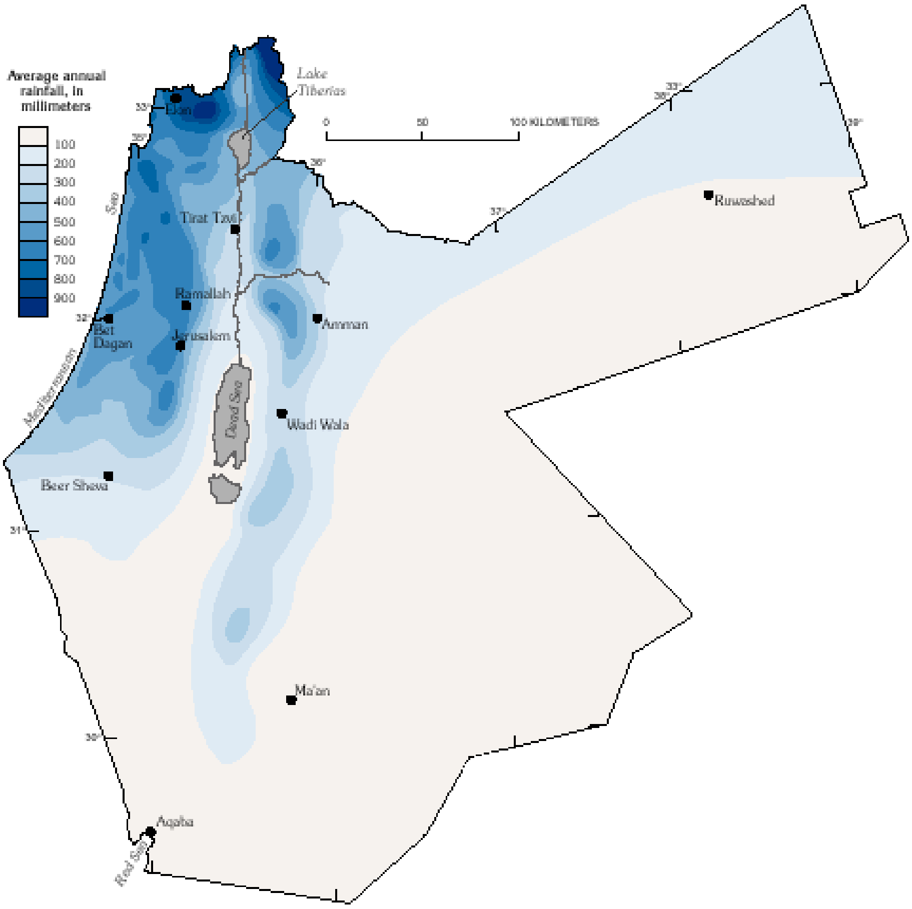


Fig. (1): The annual rainfall distribution in Jordan and the surround.

Surface water resources are unevenly distributed among 15 basins. The largest source of external surface water is the Yarmouk river, at the border with Syria. Originally, the annual flow of the Yarmouk river was estimated at about 400 million m^3 (of which about 100 million m^3 are withdrawn by Israel). Total flow is now much lower than 400 million m^3 as a result of the upstream Syrian development in the 1980's. The Yarmouk river accounts for 40% of the surface water resources of Jordan, including water contributed from the Syrian part of the Yarmouk basin. It is the main source of water for the King Abdullah canal and is thus considered to be the backbone of development in the Jordan valley area. Other major basins include Zarqa, Jordan river side wadis, Mujib, the Dead Sea, Hasa and Wadi Araba. Internally generated surface water resources are estimated at 400 million m^3 /year.

Jordan's groundwater is distributed among 12 major basins (Salameh, 1996). Total internally produced renewable groundwater resources have been estimated at 500 million m^3 /year, of which 220 million m^3 constitute the base flow of the rivers. Groundwater resources are concentrated mainly in the Yarmouk, Amman-Zarqa and Dead Sea basins.

The safe yield of renewable groundwater resources is estimated at 275 million m^3 /year. Most of it is at present exploited at maximum capacity, in some cases beyond safe yield. Of the 12 groundwater basins, 6 are being overextracted, 4 are balanced with respect to abstraction and 2 are under-exploited. Average groundwater depletion was estimated at 300 million m^3 /year in 2000. Over-extraction of groundwater resources has resulted in degraded water quality and

reduced exploitable quantities, leading in the abandonment of many municipal and irrigation water well fields, such as in the area of Dhuleil and Jafer (Salameh, 1996).
The main almost non-renewable aquifer presently exploited is the Disi aquifer (sandstone fossil), in southern Jordan with a safe yield estimated at 125 million m^3 /year for 50 years. Other non-renewable water resources are found in the Jafer basin, for which the annual safe yield is 18 million m^3. In total it is estimated by the Water Authority of Jordan (1995) that the safe yield of fossil groundwater is 143 million m^3 /year.

1.2.1 Definition of the Study Area

Aqaba locates to the most south-western part of Jordan (along 27 km of shorelines), on the Gulf of Aqaba which locates on the end of the northern extension of the Red Sea. It has two regional boarders; with Sudia Arabia from the south and with Israel (city of Eilat) from the west with 7 km of boarders.
The co-ordinates of the area of interest are [***145000-165000 E, 860000-905000 N***] on Palastine grid, and [***34°57' 0.6"-35°09'28.1"E, 29°19'35.5"-29°43'57.9"N***] on the geographic co-ordinate system. These cover about 270 km^2. Figure (2) shows the study area, and its location in Jordan. The most southern part (mouth) of Wadi Araba, the end of Wadi Al-Yutum and the northern and eastern beaches of Gulf of Aqaba meet to form the study area.
The study area consists of the following parts:

- The most northern part of Aqaba formed by the most southern part (mouth) of Wadi Araba.
- End of Wadi Al-Yutum.
- Aqaba town.
- Free area between the city and the boarders with Eilat (Israel).
- Narrow strip between the granite mountains to the east of the Aqaba’s sea port.
- Free area between the granite mountains from the eastern part and the boarders with Saudi Arabia.
- Some narrow side and coastal wadis enclosed between granite flanks.

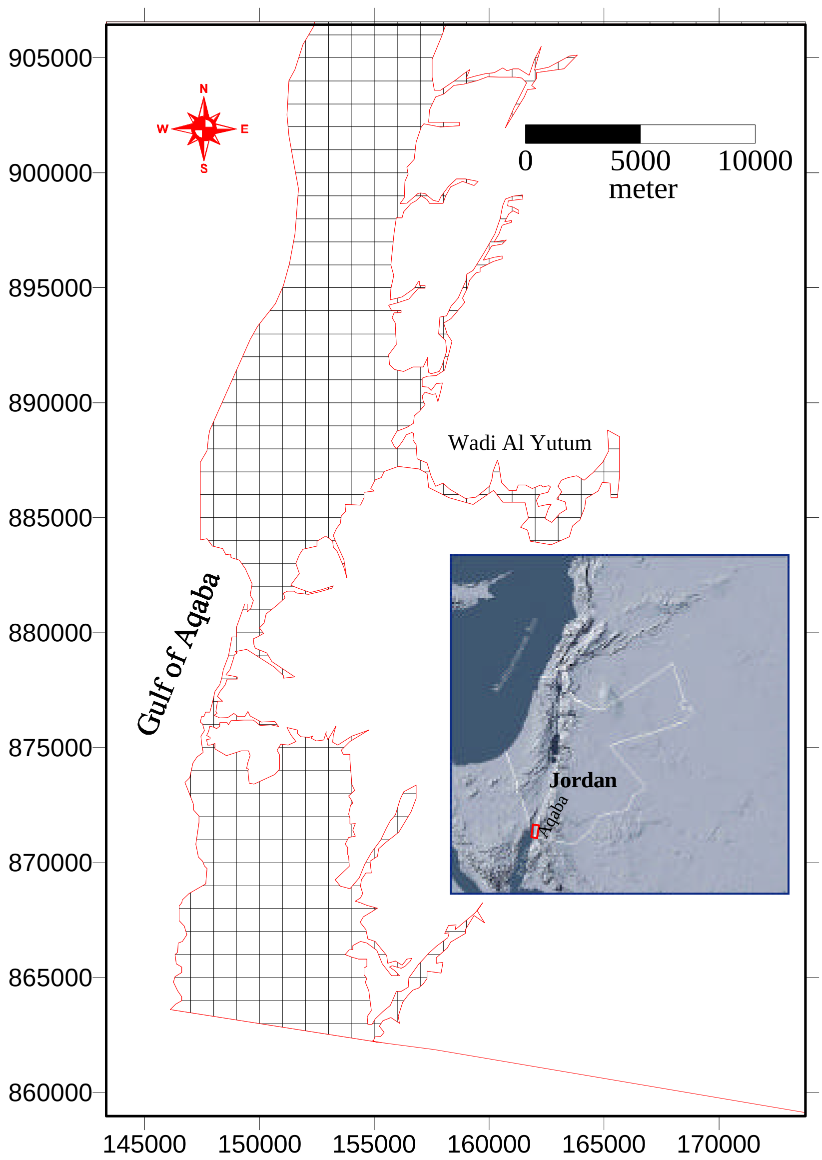


Fig. (2): The study area and its location in Jordan.

1.2.2 Problem of the Study

During the last three decades Aqaba passed through several phases of development which included industrial, economical and residential development (Aqaba Coastal resources 1993). The existing master land use plan from the year 1995 to the year 2020 has neglected the geo-spatial diversity of the hydrogeo-environmental conditions, where the hydrogeological and nature of the aquifer reflects easily the human impacts, which don't end here but in the Gulf of Aqaba that is the sink of the coastal aquifer. This is attributed to the sub-marine groundwater discharge (SGWD) which occurs primarily by advective flow. Polluted groundwater from human and industrial sources has negative effects on the marine and aquatic habitats and life when it enriches the marine water with nutrients, heavy metals and other types of pollutants. The Gulf of Aqaba and its aquatic life are vulnerable against rapid environmental changes. The water amounts discharged into the gulf are not approached or estimated. Weakness zones such as faults in the semi-lithified alluviums besides the high permeability zones enhance transportation of pollutants into the aquifer, where self purification processes are not guaranteed to clean the water, respecting their short resident time in the soil cover and unsaturation zone.

Recent indications of algae growth in the Gulf of Aqaba are alarming, the consultants attributed the phenomena to the phosphate loading process through the Aqaba port. (Aqaba Coastal Resources 1993). Possible leakage of polluted water from sewerage through the aquifer into the gulf's water were not considered in the previous projects in the Aqaba region. Eutrophication processes in the marine water body could exist with impacts on the marine life and coral reefs. After the construction of the Aqaba waste water treatment plant in 1987 (3 km north of the shoreline of the Gulf of Aqaba), Salameh (1987, 1993, 1996) pointed out to the problem of the nutrients coming from the plant through the aquifer affecting the marine environment by eutrophication.
The vulnerability grades of the aquifer's surface zones to pollution is a concept that was not considered by the decision makers during the different planning stages of the city.
The sudden development didn't allow for a wise management of the environmental resources of the city (Aqaba Coastal Resources, 1993).

Spatial background for the hydrogeological settings of Aqaba's aquifer doesn't exist to enable researchers to assess the impacts under future constructions or changes in the area. The groundwater has not been evaluated in depth from hydrogeological and hydrochemical points of view. The hydrodynamic interface between fresh water and seawater and the impacts of the seawater encroachment on the aquifer are still unknown. The city receives water to cover the different demands from Disi aquifer which is generally a non-renewable basin, and expected to additionally supply the capital Amman in the coming few years.
Aqaba was declared by the government a free trade zone area with the beginning of the year 2001. The inhabitants numbers are expected to be increased. The human and industrial impacts on the aquifers and on the marine environment are expected to deteriorate unless proper actions are implemented.

1.2.3 Objectives of the Study

This study is expected to serve four major objectives in terms of the area's hydrogeo-ecosystems:

1. To evaluate, understand, model and represent the natural systems (without human impact) and to build their background information taking in response the soil, structural, geological, hydrological, hydrogeological and water balance, hydrogeochemical, and the environmental aspects. **Building a digital spatial data base as a background** will assist in the future to control probable hydro-environmental disturbances.

2. To assess the impacts of the existing land use that stress the hydro-ecosystems not allowing for their sustainability. After assessing these impacts, modeling will be carried out aiming at predicting the possible future effects on the other natural systems such as the marine ecology.

3. Vulnerability maps for pollution for the study area in the context of the hydro-ecosystems will be constructed, where geo-spatial factors will be involved after building them in a digital form. GIS will be used to calculate all the produced maps in specific formulae and indices.

4. To use the results of this study to manage and protect the groundwater resources and the in relation ecosystems. **It is believed that the different zones of the study area do not show the same behavior against the different types and releases of pollutants.**

1.2.4 Methodology

Direct measurements and samplings in the field were the main source of data for this research. The data about the study area was very rare.

Following are the methods used in the different phases of the study, and the purpose of every method:

1. **Vertical geo-electrical soundings** were used to:
- understand the depths of the aquifer, and the water bearing layers
- locate the groundwater table of some areas
- locate the interface of fresh and saline waters
- investigate the hydrodynamic interface between the sea and fresh water
- study the pollution impacts on the groundwater of some suspected areas
- locate the depth of the granite basements

2. **Field measurements on the available wells in the study area:**
- to determine the water depths
- to locate well sites on the map using GPS
- the elevation of each well was calculated using the available topographical model of the study area (DEM).
- information about abstraction quantities and fertilizers use were obtained from owners of wells.

3. **Field measurements and laboratory analyses on soils** included :
- infiltration tests for different location.
- permeability of soil core samples taken from different locations.
- grain size analyses for about 60 samples of different locations and depths.

4. **Groundwater sampling**; from the available wells in the region, from the Aqaba waste water treatment plant and from some selected locations of seawater. Field measurements of pH, EC, Eh, and Temperature of all samples were carried out on site. Major and trace elements were analyzed in the laboratory. Also some wells were analyzed in terms of Fecal Coliform, Total Coliform, Algae content and BOD contents.

5. **Soil sampling:** to investigate the **soil chemistry** along a north-south profile in the city of Aqaba and its southern coastal area, samples from several depths were taken. They were analysed on their soil water contents, where the purpose was to detect the impacts of the different industrial and porting activities on the soil and to measure the soil ability to purify the water from specific pollutants.

6. **Aerial photography study (1:30.000 scale)** was used to:
- study the geological features of the clastic deposits' types and of the aquifer.
- define the aquifer types according to morphological shapes.
- locate the exact extension of the alluvial fans to understand their depositional nature.
- locate the possible weakness zones such as faults within the lithified clastic sediments.
- divide the study area to a set of pixels, each pixel will be given (x,y) location, and hydrogeological variables. This was used to build the vulnerability maps of the study area.

7. **Evaluation of previous pumping tests on wells in the study area** trying to estimate the aquifer's physical parameters.

8. **Using the digital elevation models of the area** to:
- estimate the slope and the aspect model of the area.
- estimate the different catchment, watershed and drainage areas of the flood water.
- overlay the different 2D maps of the area on it trying to understand their relations to each other.

9. **Calibrating the results by using real existing conditions**.

10. The obtained data from field measurements and laboratory analyses were introduced wherever possible in a **geo-spatial digital form**.

1.2.5 Previous Studies

In 1966 the government of Jordan wished to evaluate the water resources in the area of the lower reach of Wadi Al Yutum, the project was carried out by MACDONALD (1966). The main idea of the study was to assess the use of establishing a subsurface diaphragm at the mouth of the wadi, in order to capture its discharges to Wadi Araba. It was found that 3-5 million cubic meters/year is the groundwater flow amounts of the wadi. Geophysical and hydrogeological methods have been used to investigate the alluvium in the wadi.
A study was carried out in 1967 by the government to evaluate the water resources of the southern part of Aqaba, which in 1965 was exchanged against other lands with Saudi Arabia.
The Aqaba Region Authority applied a qualitative study on the coastal resources in 1993, and a study on the flood analysis in the Aqaba region in 1987.

1.2.6 Profiles and Recent Historical Development of the City of Aqaba

Aqaba city is one of the most important cities in Jordan due to many aspects; economical, industrial, tourist, and as the only city on the open sea.
Aqaba International Airport -the second airport in Jordan- connects the city with world. Future plans of the government imply to expand it to receive heavier international aviation.
Before 1960 Aqaba was not more than a small village consisting from the old town. **During the 1960's** the southern border of Aqaba was moved 17 km to the south along the coastal area in exchange with Saudi Arabia to enlarge the coast of Aqaba.
Throughout the last three decades Aqaba passed through several development phases in many aspects and sectors. **From 1979-1989** the Iraq – Iran war made the Aqaba seaport more prosperous due to heavy shipping and porting. Accordingly Aqaba attracted more inhabitants from all over the country who were looking for better employment chances. The city and gulf were developed to a tourist site in Jordan attracting Arabs and foreigners.
In the year 1992 the Jordanian-Israeli peace talks started and added the security to the Middle East, and enhanced the opportunity for more world wide tourist activity for Jordan. Aqaba was involved in this activity which reflected good on the city in the field of economy. **In the year 2001** the city was declared as a free trade zone area for Jordan. In the same year many plans were put to utilize the southern beach in the city master plan until **the year 2020**.
At the southern coast of the city many heavy industries were constructed besides the former Aqaba seaport.

1.2.7 Climate of the Study Area

In general, the climate of the study area is dry and hot. June, July and August are the hottest months of the year. During these months the average monthly temperatures range between 30.6 and 32.1 degree. December, January and February are considered as the months of winter. Mean temperatures are ranging between 14.9 and 17.6 degree. The proximity to the Gulf of Aqaba and the changes in the topography play a noticed role in the variation of the temperature in the different locations of the city. The most moderate months of the year with regards to the temperature are March-May and September- November.

1.2.8 Plant Cover and Vegetation in the Study Area

The plant cover in the area has special characteristics due to dryness, wind and salty soil dominant in the area. These factors make the soil very poor without organic matter content and rich with salts. Accordingly this is reflected on the plant cover making it sparse and of less diversity.

The plant cover of the city is composed of some desert plants, some grazing plants in wadi beds, palm trees and special gardening activities in the surrounding of residential areas. The largest plantation in Aqaba is the palm plantation project, initiated by the Aqaba Regional Authority in the northern part of the town to serve two reasons: to utilize the treated waste water of the Aqaba Waste Water Treatment Plant, and to create a barrier against the wind borne sand coming from Wadi Araba. The second large one is the private plantations called (Al Hafair) located to the north-east of the Gulf of Aqaba which are planted by the inhabitants of the city, where about 20 randomly distributed very shallow wells (1-3 meter depth) were dug to supply irrigation water. These plantations are overlooking the coastal area at about 50-100 meter away from the shore. Palm and some other seasonal plants are planted.

1.2.9 The Gulf of Aqaba and Marine Environment

The Gulf of Aqaba, the northernmost extension of the Red Sea, is a semi-closed sea 180 kilometer long, oriented north—to-south. It is bounded by four states; Egypt and Saudi Arabia border the west and east respectively, while Jordan and Israel both have small coastlines at the northern edge of the Gulf. In its physical and biological features, the Gulf of Aqaba is unique in a number of ways. It is home to the world's northernmost coral reef ecosystems, due to the exceptional tropical climate of the area. Summer temperatures in the surrounding desert areas, and the nearly constant brilliant sunshine, heat the water to 29 degree Celsius at some shallow waters, and 26 degrees on average at the surface. Although the Gulf is only 26 kilometer wide at its widest point, it is exceedingly deep, as much as 1,800 meters in some points, with an average depth of 800 meters. These unusual geographic features are due to the Gulf being situated within the Syro-African Rift Valley, which stretches from East Africa to Turkey. Very little surface water flows into the Gulf of Aqaba, and its southern mouth at the Strait of Tiran is extremely narrow. As a result of these factors, the Gulf is a highly saline, still environment, with little hydrological interface with the Red Sea or the larger Indian Ocean.

The ecosystem of the Gulf of Aqaba is a spectacular one, *but one that is highly vulnerable to rapid environmental changes*. More than 300 individual sub-species of coral, a remarkably high number in comparison to other tropical areas, are the key to the Gulf ecosystem. The reefs which fringe the Gulf of Aqaba coastlines host more than 1,000 species of fish, making the Gulf one of the world's most popular for scuba diving and snorkeling. Corals depend on two principal environmental elements: clear water free from sediments, and steady, slow currents to carry off waste and provide nutrition. In this regard, the Gulf of Aqaba is exceptionally well suited for a mature coral reef ecosystem. The deep, still waters of the gulf allow sediment to settle, and the bright sunshine penetrates the water as far as 100 meters. As a result, coral formation – both reef building and soft coral- is extensive and unusually deep in the gulf. The slow, circular currents of the Gulf of Aqaba provide abundant nourishment without endangering coral polyps, and the high levels of dissolved oxygen in the warm waters allow luxuriant coral growth. ***In the absence of high levels of human activity in the region, it could be safely said that the Gulf of Aqaba would remain one of the world's most productive and divers coral reef ecosystems***. The northern section of the gulf is far from the flushing dynamics of open ocean circulation patterns, which means that pollutants and sediments accumulate rapidly and have nowhere to go. (Marine Science Station Aqaba, 2000).

1.2.10 Present Land Use Schemes and Urbanization Units in the Study Area

Several activities occur in Aqaba; residential, governmental/institutional, tourism, gardens and open spaces, industrial and economical. Future plans for land use under the master plan of Aqaba were produced for the period until the year 2020. The Aqaba Region Authority is responsible for the planning of the city according to all aspects and uses. Figure (3) shows the land use units in Aqaba.

1.2.11 Industrial Activities in the City and Aqaba Sea Port

Aqaba Port, operated by the Ports Corporation, is Jordan's only seaport. The activities of the port have been growing sharply during the last decade. A peak was registered in 1988 when imports reached about 9.1 million tons and exports about 11 million tons. The Gulf Crisis, which resulted in the embargo on Iraq and the blockade of Aqaba Port, severely affected the activities of the Port.

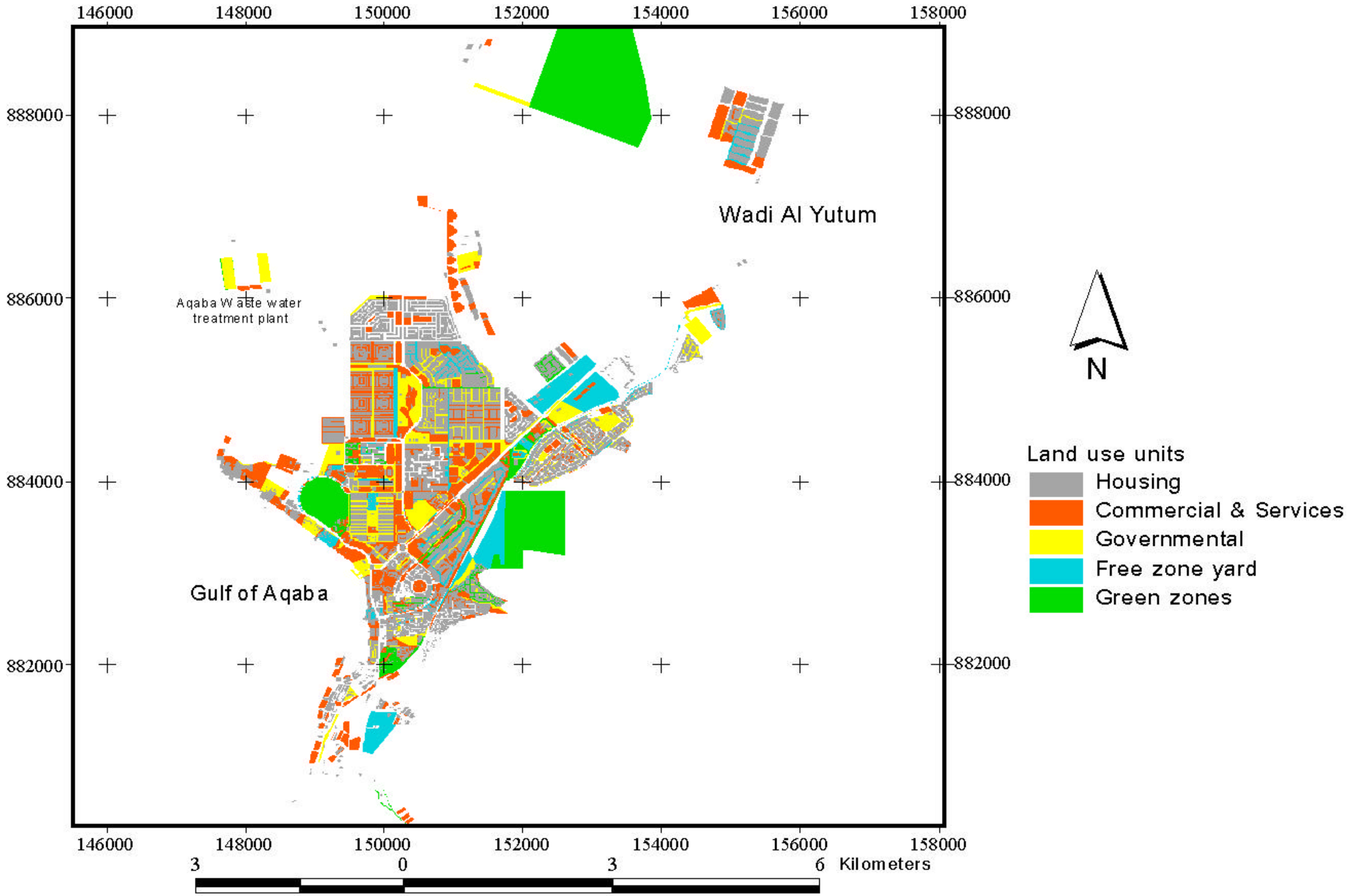


Fig. (3): Land use units in Aqaba (modified after Water Authority of Jordan, 2000) .

However, it is expected that the cargo handling volume of the port of Aqaba will increase once the embargo on Iraq is lifted; and as the activity from and to the Indian and Far East regions, where economic growth is very high, increases in the near future due to the port's advantageous location.
The port handled about 11 million tons of cargo in 1995. This included bulk phosphate, potash, fertilizer and other bulk exports, trans-shipment goods, and the major portion of domestic imports. At present there is a need to develop some of the ports facilities to handle future demands resulting from the Peace Process and the expected increase in industrial development in the country. Now there are several ports locate on the Jordanian part of the Gulf of Aqaba, they include the main port at the north eastern part, the containers port to the south of the former one, the passengers port also to the south of the former. Oil , cement and potash and fertilizer ports are located in the southern part of the Gulf.
Some heavy industries and constructions exist in the study area, all of them are concentrated in the southern part of the coastal area.
The most southern part of the Aqaba Gulf is proposed to be used as an industrial zone, besides what exists now there of recent industrial activities such as the potash and fertilizers with their high productivity’s.

1.2.12 Population and Activities

The population in the city come from the different parts of Jordan besides about 3-5% from other nationalities. The employment is the main financial income source for the population, trade is the second activity mainly in the field of food staff and clothes. Table (1) shows the recent and future population projections in Aqaba; with and without the impact of the free zone area.

1.2.13 Water Resources and Demands of Aqaba City; Previous, Recent and Future

The water supply of the city of Aqaba was developed at three stages;

(Before 1960)

The local water supply was covered from the local shallow aquifer in the town, where some distributed shallow dug wells existed. Some of them are close to the shorelines, in Al Hafair (small fields overlook the northern sea beach and used for some light planting activities), and others were dug in the surrounding of some houses and were manually pumped, they were used to cover the need of the local population, and to irrigate the light plants.

(1960-1980)

Besides the local water supply, some wells were drilled in Wadi Al Yutum aquifer to meet the increase in water demands of the city.

(After 1980)

The city was supplied from Al Disi aquifer (80 km north east of Aqaba). It presently supplies Aqaba and the industries on the south coast and some agricultural projects in the Disi area itself with their needs of fresh water. Worth mentioning is that the aquifer is not a 100%

renewable one, and according to the future plans this aquifer will be used to support Amman with drinking water.

Table (1): The recent and future population projections in Aqaba; with and without the impact of the free zone area.

YEAR	AQABA WITHOUT THE FREE ZONE AREA. (LOW PROJECTION)	ADDITIONAL POPULATION WITH THE FREE ZONE AREA.	TOTAL AQABA POPULATION. (HIGH PROJECTION)
1999	71,553	1,580	73,133
2000	74,200	5,131	79,331
2001	76,946	8,584	85,530
2002	79,793	11,936	91,729
2003	82,745	16,422	99,167
2004	85,807	21,580	107,387
2005	88,982	26,626	115,608
2006	92,274	31,554	123,828
2007	95,688	36,360	132,048
2008	99,229	41,039	140,268
2009	102,900	49,996	152,896
2010	106,707	58,817	165,524
2011	110,655	68,900	179,555
2012	114,750	78,836	193,586
2013	118,995	88,622	207,617
2014	123,398	98,250	221,648
2015	127,964	107,715	235,679
2016	132,699	117,011	249,710
2017	137,609	126,132	263,741
2018	142,700	135,072	277,772
2019	147,980	142,224	290,204
2020	153,455	147,946	301,401
2021	159,133	152,523	311,656
2022	165,021	156,185	321,206
2023	171,127	159,114	330,241
2024	177,458	161,458	338,916
2025	184,024	163,333	347,357

There are some indications in recent years that the groundwater is being salinised and the water table is dropping (Salameh 1996). Depending on data obtained from Aqaba Water Authority (open files, 1999), the following facts about Al Disi aquifer can be said:

- The safe pumping –due to the Authority's water strategies- is about 125 million m^3/year.
- The amount pumped now is about 70 million m^3/year from the Jordanian side.
- 51 wells were drilled in the aquifer including:

· 13 wells feeding Aqaba city of a total productivity of 2320 m^3/hr.
· Five wells feeding the Disi region (population and irrigation) of summed productivity 438 m^3/hr.
· 33 private wells managed and owned by the private sector.

Recent water demand of the city of Aqaba is summarized in Table (2). It represents the consumption distribution of the city water according to the type of consumption for the year (1997).

According to the Aqaba Region Authority future plans, the expected figure of population in the year 2020 will reach about 301,000. Also according to these plans, many additional projects and industries are going to be established. ***Depending on the Disi aquifer as the only***

source to support this development, and on the previous mentioned facts about the aquifer, the long term sustainability is suspected.

Table (2): Distribution of present annual water demands of Aqaba.

TYPE OF CONSUMPTION	QUANTITY ($1000 m^3$)	%
Domestic	3779.56	41.92
Industrial	4604.5	51.07
Commercial + service	106.74	1.18
Tourism	343.1	3.80
Agriculture	183.5	2.03
Total	9017.4	100.00

After Aqaba water Authority.

1.2.14 Aqaba Waste Water Treatment Plant and Sewerage System

Before the year 1987 the city was not connected to any type of waste water treatment plants. Cesspools or direct discharges into the Gulf were used before 1987.
In 1987, a waste stabilization treatment plant was constructed north of Aqaba on an area of about 0.21 km^2 at the end of Southern Wadi Araba, about 2 km from the bay, to treat a flow of 9000 m^3/day. It works according to the natural purification method where the settlement of the suspended particles and natural decomposition of the organic matter are the processes of treatment. The produced treated water is allowed then to join the groundwater by infiltration. Elaboration's on that are to be discussed in the following chapters. Recent researches indicate that the plant is overloaded. (Salameh, 1996).
In Summer the daily inflow to the plant is about 9000 m^3 and about 5000 m^3 as outflow per day, and in Winter the daily inflow is about 10,000 m^3, and the outflow is about 7000 m^3 per day. These values were estimated from the staff of the plant (personal contacts during the field work 1999). The outflow was estimated after subtracting the evaporation from the different stages of treatment, and also the amounts of treated water directed for irrigation purposes. The rest is led to an open non-sealed wide areas and allowed to infiltrate to the ground.
After the year 1987 most houses of the city were connected to the WWTP. Some areas in Aqaba are still not connected to the WWTP and use the method of cesspools.

CHAPTER 2

NATURAL SETTINGS OF THE STUDY AREA

Introduction

In this chapter the study area will be defined in terms of its natural settings from hydrogeo-ecosystems point of view.
Land forms, geology of the area and structures, soil cover, hydrology, hydrogeology and hydro-geochemistry are considered here as the main components of the hydro-ecosystems. They were investigated in the course of this research applying different methods and techniques.

2.1 Aerial Photography Study and G.I.S Surface Analysis

2.1.1 Introduction

Aerial photographs are among the most important, widely available and commonly utilized kinds of remote sensed images. They are used for all types of land resources, cartographic and appraisal surveys in the public and private sectors. They are often employed as "base maps" upon which thematic data are portrayed. Locating appropriate aerial photographs is a fundamental first step for many land mapping and evaluation projects, and air photos often form the basis for interpretation of other kinds of remote sensing.
The techniques used to predict specific kinds of surface features, landforms, attributes of soils and soil boundaries from photographs are continually being refined. Relief can be perceived by stereoscopic study. Shadows and differences in tone between slopes that faced the sun and those that did not at the time of photography also help show relief. Relief features help locate many soil boundaries on the map. Relief also identifies many kinds of landforms which are commonly related to kinds of soil. (Lueder 1959).

The Digital Elevation Model (DEM) which covers the study area allows reflecting all the surface features. G.I.S modeling on the elevation data is of a paramount importance in mapping any region for many purposes, such as calculation of runoff, slope, surface watersheds and topographical shapes. The higher the resolution of the DEM, the more accurate are the results.

2.1.2 The purposes of studying the area using aerial photos

The purposes of studying the area using the aerial photos are:

-to divide the study area in terms of the morphological features into:
1. Granite zones
2. Side wadis and wadis’ deposits
3. Alluvial fans
4. Flood plains
5. Coastal wadis
6. Coastal zones

- to define the aquifer types according to land forms.
- to locate the exact extension of alluvial fans, to divide them according to grain size, and to divide the one alluvial fan into active and inactive flooding zones.
- to locate possible weakness zones such as faults or lineaments within the semi- lithified overburdens.
- to produce final maps of these studies including the previous items.
- to define the base map to be used in the course of this research for the spatial results. And to fix the net of the spatial distribution of the different parameters; the measured, calculated and interpolated.
- to assist estimating some spatial parameters in the areas where no good data cover exists.
- to confirm on the concept of this research, which considers the study area not of a unique spatial physical and dimensional properties. This confirms in turn that the vulnerability degrees of the aquifer for pollution is different from one place to another.

2.1.3 Applying the Aerial Photography Study in Aqaba

Modern 1:30,000 scale black-white aerial photos of the study area –September/1992- were used in this research. They cover almost all the study area from the southern to the northern part, Fig. (4).
The photos were scanned into the computer and joined with each other using (Surfer 7). The resulted map was georeferenced according to the Palestine Grid coordinate system.
The tones and shapes in the produced aerial map are clear. They led to distinguishing the extension of the different land forms.

- The granite series in the study area are distinguished by their complexity of relief configuration. A regular pattern regarding its weathering shape is dominant and characterized to show the shadows of the opposite side where they intersect the sun rays due to the contrast in elevations.

- Side wadis and their deposits are clear in terms of tone and shape. The tone is characterized to be more bright and white indicating that they are still active and not much affected by the impacts of chemical weathering as oxidization. The shape is more easily recognized than the former tone. The wadis intersect the granite series from east to west and follow as a major E-W faults.

- Alluvial fans were the most easy land forms to be distinguished. They are of two tones, one indicates those parts which were still active afar from weathering impacts. They possess white color which is less brightening than side wadis, this is attributed to the activity of flooding, which is higher in side wadis than in alluvial fans. The other tone in color is desert varnish which is distinguishable on aerial photographs, it is the product of the chemical weathering due to the long exposure time. The shape is a semi fan possessing a rounded end. The contrast between the active and the inactive zones allows to delineate the alluvial fans.

- Flood plains extend to the ends of the alluvial fans.

- Coastal wadis are those which flood discharge directly into the sea.

- Coastal zones are the land zones directly surrounding the sea, their elevation is supposed to be the lowest one in the study area, and approaches zero i.e. the sea level.

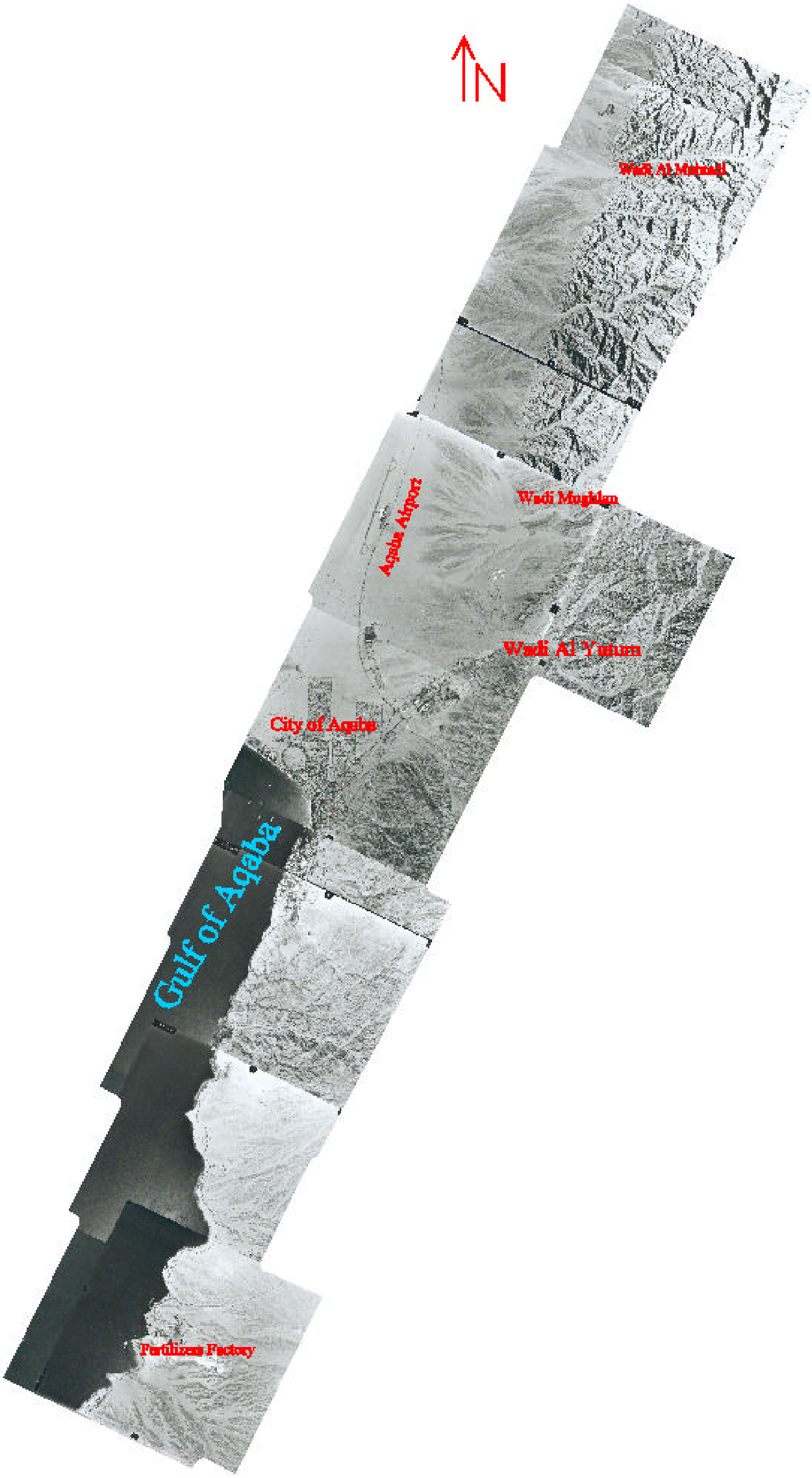


Fig. (4): Aerial photo of the Aqaba region.

- Aquifer types are deduced after deducing the different previously mentioned land forms.

- Weakness zones such as faults or lineaments within the semi- lithified overburden can be best deduced using a high resolution Digital Elevation Models (DEM), after noticing them from the aerial photos.

- The vegetation zones could be delineated using the available colored Landsat images of the study area.

- General primary indications on the vulnerable areas to the groundwater pollution can be noticed regarding the relative grains size of the different parts of land forms and weakness zones distribution.

- Producing the final map by overlapping the layers of the different previous items with each other.

2.1.3.1 Stereoscopic Study

Stereoscopic study –3D visibility- of the aerial photos was carried out to confirm some results. It was used to confirm the presence of small scale active faults in the alluvia, and to measure their fault throws if possible. Also it was used to check where these faults are best seen, i.e. in which type of land forms. It allowed detecting the fault extensions in the inactive parts of the alluvial fans, which keep their imprints afar of floods' impacts, since these inactive parts are not involved in the surface run off net.

2.1.3.2 Granite Series Zones

In the study area, granite series prevail with the major direction of their contact with the overburden trending at about 40° from the north. To the east of Aqaba's sea port, the contact approach the periphery of the sea. In the southern part in the area between 146000-154000 E and 862000-874500 N they disappear to allow the overburden to exist. Worth mentioning here is that this area is nearly free of urbanization except some industries.
According to their natural relief configuration, they divide the rain products in two parts; one to the eastern side of them mainly to the early start of Wadi Al Yutum, and the second is towards the eastern part of the study area.

2.1.3.3 Side and Coastal Wadis' and Wadis' Sediments

From north to the south along the eastern part of study area the following wadis exist within the granite series and their overburden;

1. Wadi Al Muhtadi
2. Wadi Umm Ratam
3. Wadi As Sammaniyya
4. Wadi Zibliyya
5. Wadi Mulghan
6. Wadi Al Yutum
7. Wadi Al Akhadar

8. Wadi As Shahbi

These wadis deposit their flood sediments on land.
The followings wadis end into the sea, and are classified as coastal wadis;

1. Wadi Ash Shallala
2. Wadi Jeishieh
3. Wadi Mabruk
4. Several Wadis cutting the existed Pleistocene gravels in the southern part of the study area. (See the geology of the study area).

They deposit their sediment loads as alluvial fans. The major direction of their mouths is towards the west.
Aerial photographic interpretation indicates that these wadis seem to be active as the tone of the most bright color on the photos shows. All the wadis except Wadi Al Yutum are of a length ranges between 8000-3000 meters, and width of 500-250 meters.

Wadi Al Yutum is the biggest one in terms of its length and catchment area, and accordingly its capacity to transport clastics deposits. It extends from the north eastern parts of the study area through the Rum Basin towards the Southern Wadi Araba Basin. In the study area it is of a width ranges from 500-300 meters.

Wadi Al Muhtadi at its middle part cuts another wadi that trends north-south. Wadi Mulghan is an extended one, it starts from the position 162000E-900000N. It is about 8 km in length. This wadi and its alluvial fan were investigated by geoelectrical method in terms of its groundwater availability and quality (see the hydrogeology of the study area).

Wadi Umm Ratam seems to be straight one and possesses no curvatures, indicating that it is an extension of a faulting process.

Wadi Mabruk forms a small delta in the sea.

Wadi Ash Shallala is the only wadi on which land use exists. Coastal wadis are vulnerable zones (Al-Rifaiy, 1988).

The nature of the deposits in the wadis are of two types in terms of the deposition environment; in the normal situations they receive the mountain’s weathering products with the action of gravity as mountain debris. From the aerial photos these debris could be noticed clearly as small hills nearer to many mouth forms in the granite series. Floods produced from heavy rainfall drive these debris away. The second possibility occurs with rain effect; local extended depositional layers of different grain sizes in the wadis within the last criteria may exist. Figure (5).

Fig. (5): Bedding forms in the alluviums in Wadi Al Yutum.

2.1.3.4 Alluvial Fans Zones

Alluvial fans are most abundant feature in the study area. The lack of vegetative protection allows infrequent, heavy rains some times, to flush large amounts of rock debris down slopes. The transported alluviums made up the alluvial fans.

Abundant groundwater is usually present at the base of alluvial fans along the bedrock contact, making them favoured locations for settlement and agriculture.
The deposition of sediment on alluvial fans is an interesting process because the pattern of sediment deposition results in a natural sorting of materials by size. Coarser rocks and gravel are deposited near the mouth of the canyon, near the apex of the fan. Coarser material is also found in and along the main channel beds further down the fan from the apex as is seen in the figure below. These materials can be carried further down the channel because the carrying capacity of the stream flow does not decrease as rapidly in the channel as it would elsewhere on the fan. As the distance from the head of the fan increases, the size of the materials continues to decrease, from rocks and gravel, to small gravel and sand, and finally to fine sands and silts.

Alluvial fans are distinguished in terms of the active wadi sediments by retaining an incipient desert varnish which is distinguishable on aerial photographs. The active wadi deposits are found in the lowest part of the wadi profiles and grade laterally in depth into the feeding fans. They occur directly at the sharp contact between the granite mountains and the overburden, necessarily indicating a dominant fault occurs along this contact. They slope to the west with an angle at the apexes of about 3.82°, 1.85° at the middle parts and the slope is still decreasing until it approach zero at the end of every fan.
The alluvial fans in the northern part of the study area (in the southern Wadi Araba) follow the mouths of side wadis that have been formed due to the E-W faulting process in the granite complex.

18 alluvial fans exist clearly in the study area. The extent of the alluvial fans range from 30 sq. km to less than 1 sq. Km. The length of the vertical axes range from 0.6 to 5 km, while the widths range from less than 1 km to 7 km.
They start in the northern part of the study area between the coordinates 156000-158000 E, and their exact extension don’t exceed the coordinate 151000 E. In this part they are mostly rounded to semi-rounded shape. Their sediments are mainly derived from the granite weathering products.
In the southern part of the study area where Pleistocene gravels prevail, they extend from 146000 to 1542500 E. In this part they are mostly elongated alluvial fans. Their deposits are a mixture of granite weathering products, and Pleistocene gravel weathering products.
Due to the selective pattern action of the flood water, which follows the most easy ways, alluvial fans in the study area especially in the northern part are divided into two parts; active and inactive parts. The active parts are connected with each other, and of more bright tone of color than those inactive parts which tend to be not connected and of dark tone of color on the aerial photos. (See Figure (4))
Field observations indicate that the active zones are those where recent floods flow. They are less elevated than the inactive zones, which are about one meter higher in elevation.
From the aerial photos and field work observations it seems that the active zones possess some sporadic distributed desert plants, where as the inactive zones are free of any vegetation, indicating that active zones are more saturated with water than the inactive zones.

Coastal wadis deposit a part of their loads on land forming alluvial fans, the rest flows to the sea to form small deltas. Wadi Mabruk is an example on that.

2.1.3.5 Flood Plains and/or Palays

The flood water that flows and seeps along the alluvial fans become slower in the flat lands where the slope decreases. This allows the rest flood water to collect in areas called flood plains and palays. The resulted deposits are mainly the smallest sizes such as clay and silt. A mud flat zone exists in the study area between the coordinates 151000-153000 E and 893500-901000 N and is the result of flood water in such areas.

2.1.3.6 Coastal Zones

The width of the coastal zone in the study area was governed by the city urbanization and hotels. It is wide in the northern part of the study area (3-4 km) narrowing in the middle part to a few tens of meters and broadening in the south to 4-5 km.
The area between coordinates 874500-880000N has a very narrow coastal zone, where the granite mountains approach the periphery of the shoreline.

2.1.3.7 Land Use

Land use in the study area is divided into two parts; the area between co-ordinates 882000-888000N is occupied by civil housing and activities, where as the area between 863000-882000N is occupied by recreational, industrial and porting activities.
The extent north of coordinate 888000N is considered as an area free of any activities except the Aqaba International Airport.

The study area could be divided into the following;
- urbain zones
- suburbain zones
- agricultural zones
- industrial zones
- free zones

2.1.3.8 Locating Zones of Expected Weakness In the Alluviums

The granite basements in the study area is active tectonically. Recent movements in the basement will be reflected on the overburden above them.
The study area is tectonically active as indicated by its seismicity nature related to the Dead Sea Transform Faulting-displacement (Abed, 1982). Due to the fact that the alluviums in the area are relatively lithified with respect to their compaction, some small faults and/or lineaments in them. These types of faults and/or lineaments create good chances for the percolation of rain water and floods, but on the other hand they are of negative impacts on the groundwater quality, when they are located in or near pollutants releasing sites such as solid waste disposal sites.
From the stereoscopic study of the aerial photos it was possible to locate some active faults within the alluvial deposits. Many of them are clear and easy to be distinguished with the naked eye. They take a major direction of north-south, and locate close to the granite mountains. It seems that they are relatively recent and active. Indications on that are their clear extensions in spite of flood events. Some of these faults have distinguished fault throws as indicated by the stereoscopic study.
Faults extensions in the inactive parts of the alluvial fans are more clear than in other parts because they are not exposed to strong erosion.

2.1.3.9 Vegetation Zones

The natural relative abundance and distribution of desert plants on alluvial fan is a good on its relative grain size distribution. It seems that these plants are more distributed going downstream the alluvial fan. Since small grain size of the deposits possess higher soil field capacity. This allows soils to trap more water.
Man-made gardens and plantations in the city zone can be distinguished on recent colored landSat images.

2.1.3.10 Natural Boundaries of the Aquifer and its Types in Terms of Land Forms

Granite forms the eastern and the western inactive types of boundaries and the groundwater divide for the groundwater basins in the study area. At the same time it separates the study area regarding its hydro-geological continuity into two main parts; the northern part which extends from co-ordinate 874000 N to the northern end of the study area, and the southern part which extends from coordinate 874000 N to the south, where seawater is considered as a general stable head type of boundary.

The interpretation of the nature of land forms in the area reveals several types of aquifer systems:

- ***Side wadi aquifers***
- ***Alluvial fan aquifers***
- ***Flood plain aquifers***
- ***Coastal aquifers***

2.1.3.11 General Vulnerable Zones relative to Groundwater and Sea Water Pollution

It was possible to declare from the aerial photographs study the following zones as vulnerable for pollution with respect to groundwater:

- The heads of alluvial fans.
- The areas where the granite mountains build the shoreline.
- The belts surround the sea water were considered as vulnerable areas. They possess normally shallow groundwater table, and they are close to the vulnerable marine ecology.
- Side wadis were also considered as vulnerable. They have normally little small size deposits to buffer the percolated water. They are also considered as a good sources to support the aquifer with good water quantities and qualities.
- Faulted areas within the semi-consolidated sediments.
- Coastal wadis.

2.1.3.12 Final Maps and Base Map of the Study Area

Analyses on the aerial photos led to produce a final map Fig. (6). It includes the majority of the layers of the studied items. Plots were used to delineate the extension of the different zones, where symbols were used to divide the zones into sub-zones.
The structural evolution of the Dead Sea Transform Fault led to the present land forms of Aqaba. The elevations of the area range between zero and about 1600 meters a.s.l. The granite mountains form the highest elevations with slopes more than 45°.
The dominant visual impression of the area is a series of parallel ridges and wadis running east-west from the backdrop of high granite mountains to the gently sloping coastal strip. The width of the coastal strip varies considerably in the different parts of the south coast. North of the marine station the mountains are high and rugged, close to the coast the wadis are narrow and steep sided. Further south, and especially east of the bay, the land form is more open, with wider and less defined wadis but some dramatic outlying hills.
In the northern part of the study area the alluvial fans are forming the distinguishable features, their depositional nature as indicated from the aerial photos indicate active uplifting processes of the nearby granite mountains where the deposition is still take place.
Wadi Al-Yutum to the north east of the Aqaba city meets the end of southern Wadi Araba in the northern parts of the study area, their sediments form the flood plains where the city locates. The major slope direction of these flood plains is towards the Gulf of Aqaba.

The low lying Gulf of Aqaba –Wadi Araba alluviate depressions in the west is bordered by an abrupt straight granitic fault scarp, along the foot of which alluvial fans have developed.

Mountain peaks east of the escarpment retain an even altitude not rising markedly above a median altitude of about 1300 meters, and falling gradually eastwards.
Fault lines have been exploited by erosions to form linear wadis, all drain ultimately south and west. Wadis are narrow and deeply incised near the western mountain front but widen

towards the east and north away from Wadi Araba and the marine base level as the drainage incision becomes less and the relief diminishes.
Most of the modern drainage lines are causative of fault lines, but one wadi, the lower E-W course of the Wadi Yutum and its southeastern branch, is interpreted as being pre-block faulting in origin and as having been superimposed from the original sedimentary cover. This river course cuts across a number of fault blocks in incised meanders.
Fans descending from the mountain front into the Wadi Araba have been faulted by the main Wadi Araba left-lateral strike –slip fault. The fan complex from Wadi Yutum has displaced the main axial drainage of the Wadi Araba to the west, caused bonding and mud flat development, and has contributed to the gentle shelving of the submarine slope at the head of the Aqaba Gulf and the Gulf's termination at this point.
Alluvial fans and alluvium slope seawards compose the foundations of the city of Aqaba.

2.1.4 Modeling on Land Forms Using GIS

Digital Elevation Models (DEM) is a term used to refer to an image which stores data that can be envisioned as heights on a surface. Although the grid structure breaks up the surface into cells of uniform character, the data are considered to come from an underlying continuous surface. A special case is the DTM (Digital Terrain Model), where the heights are above mean sea level on the land surface.

The study area was modeled on its elevations. Two models were used; one covers the study area and its surrounding. This model is of 1000-950 meters resolution, and put according to the degrees co-ordinate system. The second one is of 100 meters resolution and covers the study area from the northern part to the most northern part of the Aqaba's Gulf regional sea water. It is co-ordinated in Palastine grid.

2.1.4.1 Digital Elevation Model (DEM) of the Study Area

The general regional topographical trend of the study area is a north-south directed graben, bounded by two major flanks of higher elevations and cut with east-west directed wadis. The study area doesn't possess extreme elevations in the floor of the graben. The elevations start from values approaching zero nearby the sea zone, and start to increase gently to reach in the upper part of Wadi Al Yutum within the study area more than 350 meters above sea level and at the southern Wadi Araba more than 80 meters. In the southern part of the study area the elevations start from values of zero, and rise very gently east wards until the highway. From the highway to the east they start to strongly rise to reach more than 500 meters nearby the granite zone.

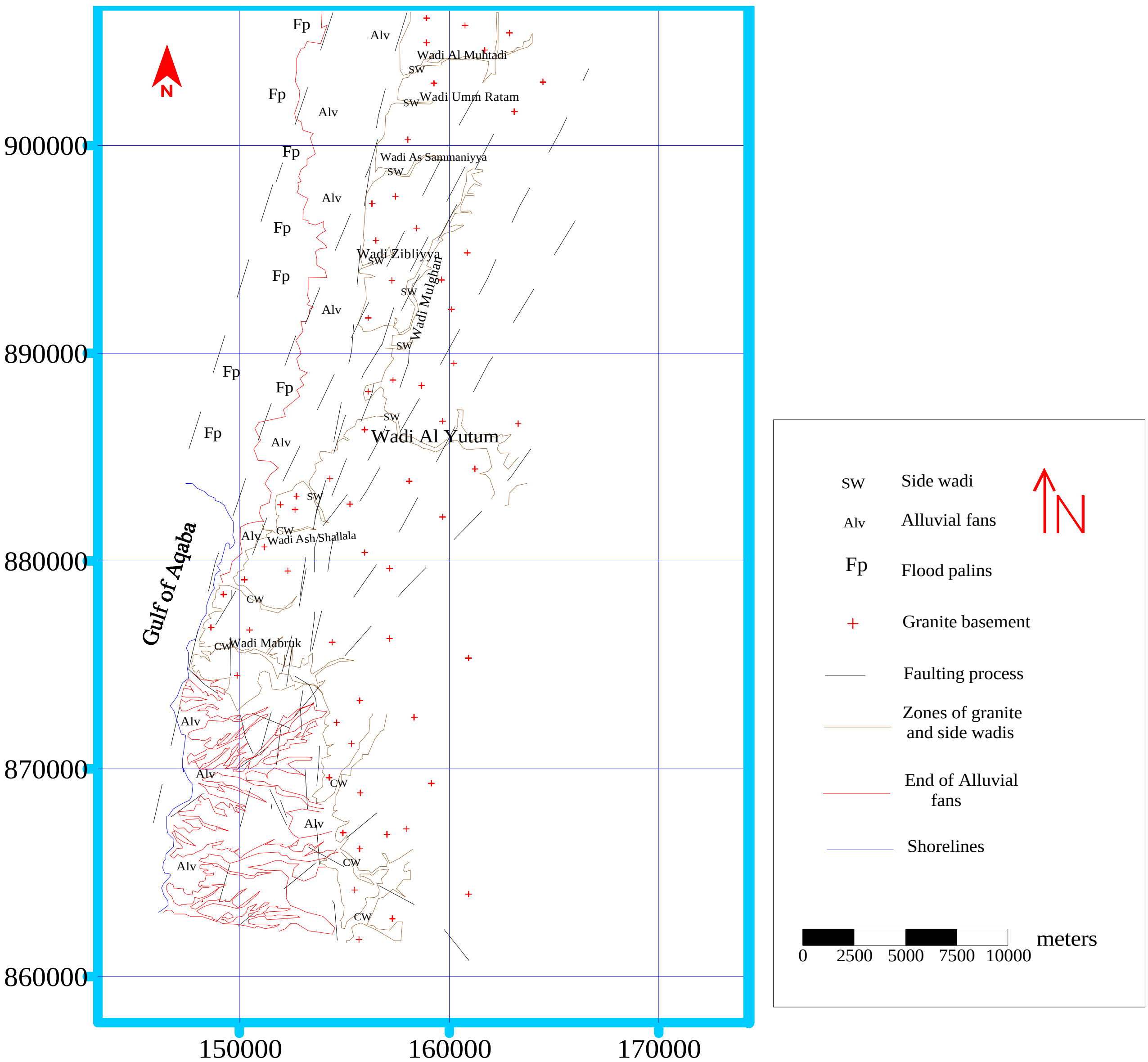


Fig. (6): End type of map of the aerial photographical analyses in Aqaba.

The granite series have tops reaching about more than 1000 meters above sea level. Figure (7) shows the regional (DEM) of the study area and the areas in the surrounding. Figure (8) shows the local model of the study area.

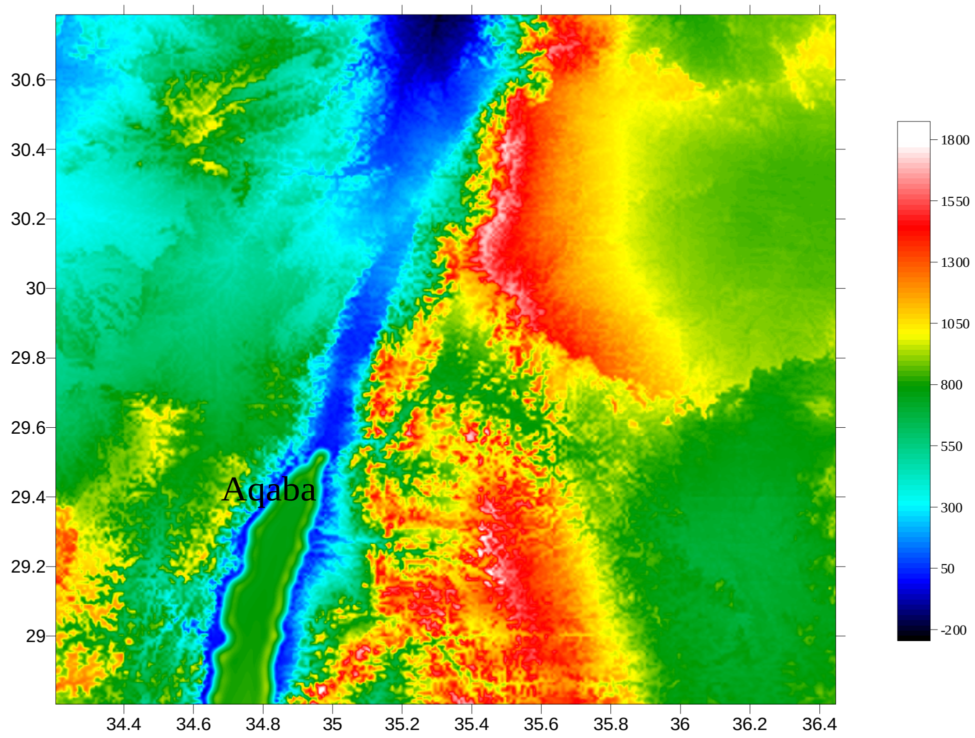


Figure (7): Regional DEM model of the study area and its surroundings.

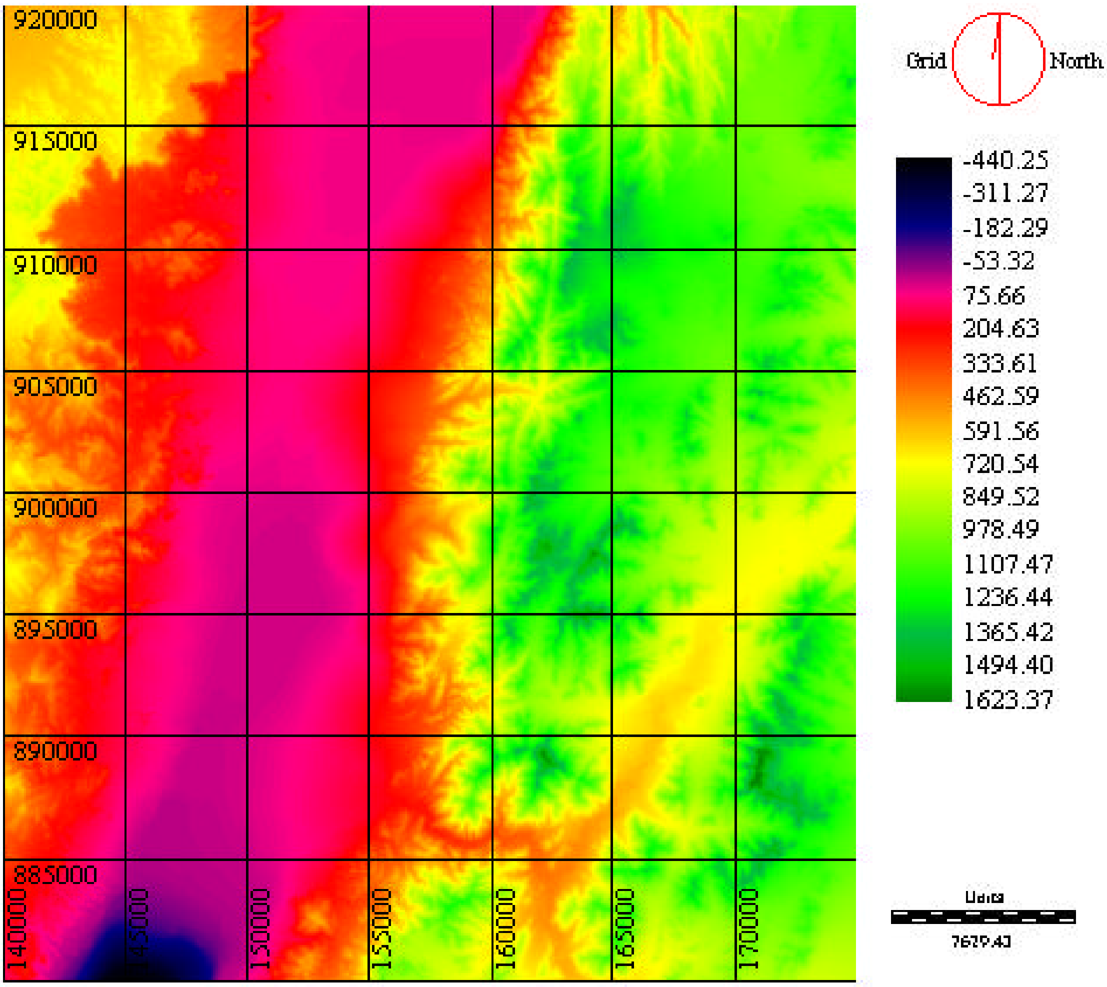


Figure (8): Local DEM model of the study area.

2.1.4.2 Slope Model of the Study Area

The slopes in the study area (Fig. 9) are inherited from the nature of its topographical distribution. The topographical data were used to model the study area with respect to its slopes. The floor of the graben attains slopes ranging from less than 1° to less than 4°. While the alluvial fans zones have averaged values of about 4°. The granite mountain series has a slope ranges of about 20° to 60°. Slope has a major role in governing the run off, infiltration and recharge of groundwater (Udluft, 2000)

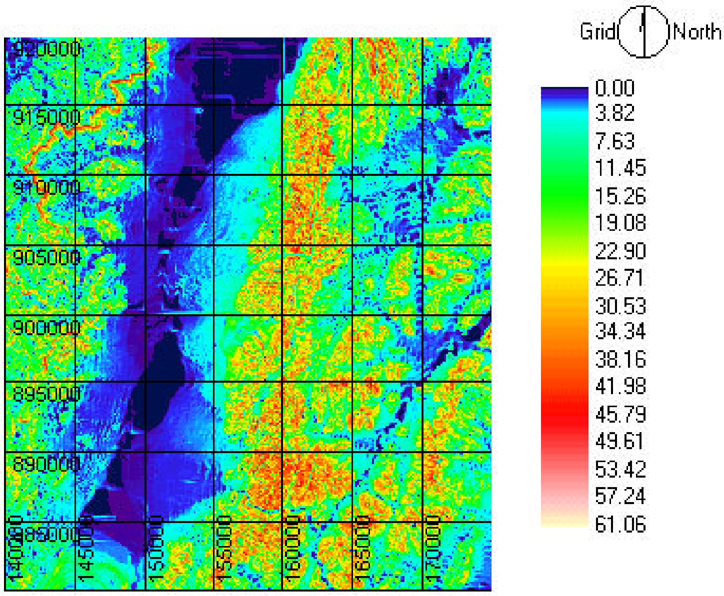


Fig. (9): Slope model of the study area in degrees.

2.1.4.3 Aspect Model of the Study Area

This is determined as the direction that would be faced when looking downhill at the line of steepest descent, it is the direction of the major slope of the area.
Aspect model Figure (10) shows the major directions of the land forms in the plain (0-360°) for the Aqaba area.

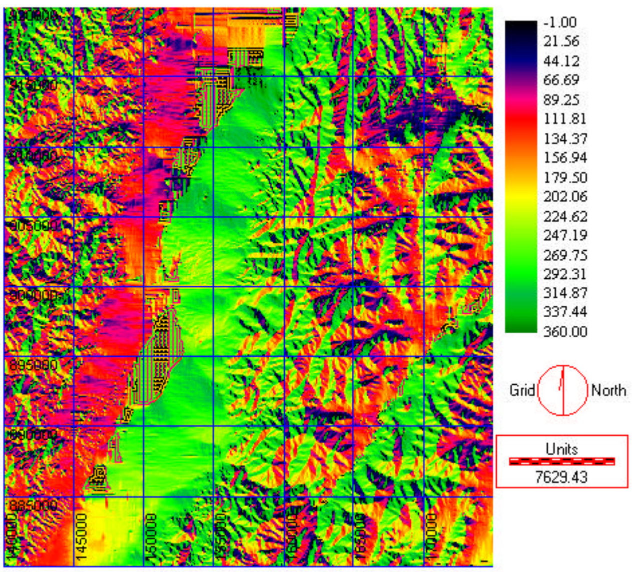


Figure (10): Major directions of the land forms in the plain (0-360°).

The major directions of alluvial fans are towards the west, while the major trend of the whole region is towards the gulf. Adding the architectural touches on the land use plans are carried out using such models.

2.1.4.4 Shaded Relief Model of the Study Area

Shaded relief maps are raster maps based on grid files. These maps use colors to indicate the local orientation of the surface relative to a user-defined light source direction. Surfer 7 determines the orientation of each grid cell and calculates reflectance of a point light source on the grid surface. The light source can be thought as the sun shining on a topographic surface. Portions of the surface that face away from the light source reflect less light toward the viewer, and thus appear darker.
A shaded relief modeling of the study area was carried out and correlated with the visibility with a space photo of the study area. The use of this model here is to see the major and the minor relief's dominant in the area, and to see them without colors, but in terms of their behavior in a 3-D view. Figure (11) shows view correlation between the shaded relief of the units of the study area together with a space photo of the same location.

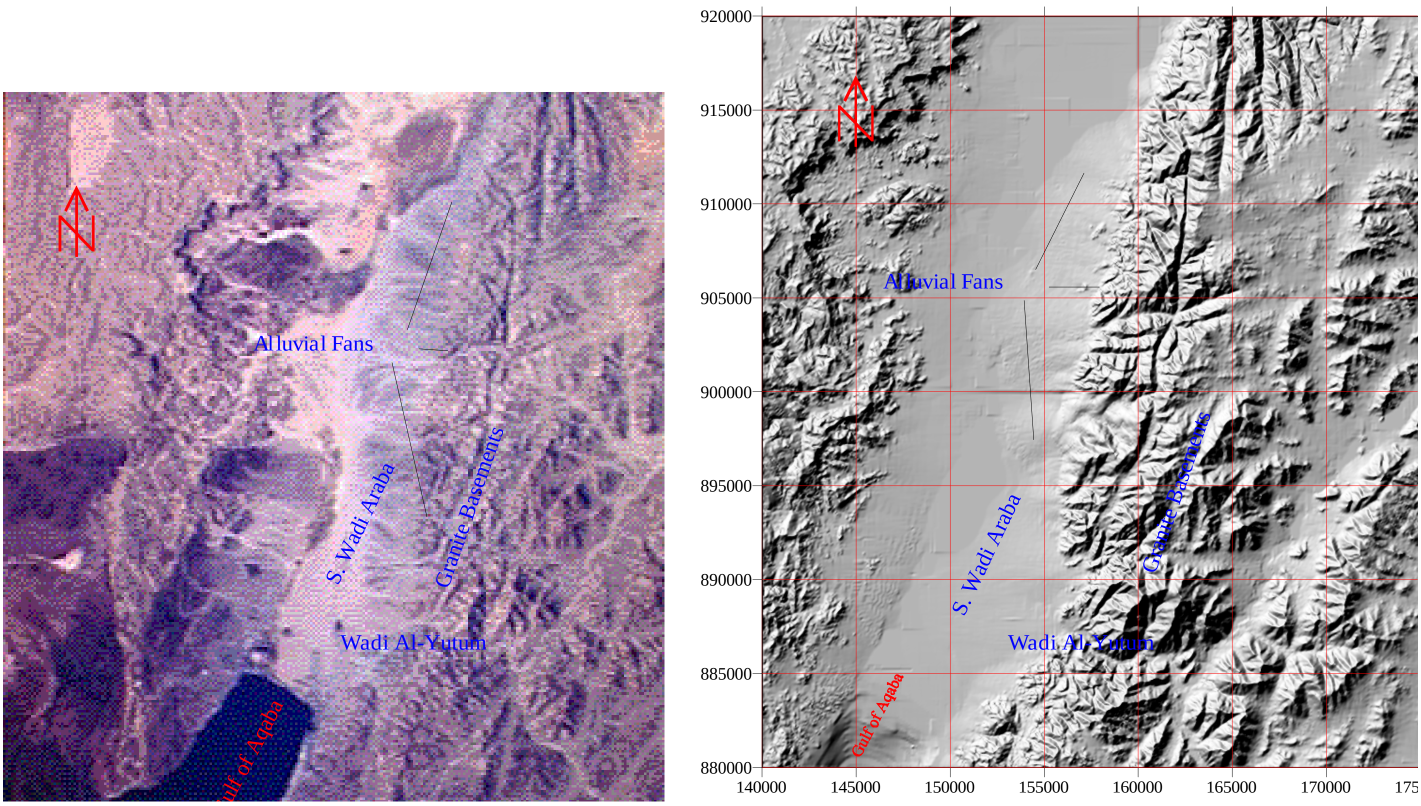


Figure (11): View correlation between the shaded relief of the units of the study area together with a space photo of the same location.

The produced shaded relief map indicates also the possibility of the presence of a step faulting process in the southern part of the study area in a north-south direction. The faults in the clastic aquifers may retard the groundwater flow when they lift up or lift down impermeable layers in contact with a permeable ones.

2.1.4.5 Topographical Shape Model of the Study Area

The output of TOPOSHAPE is a surface shape classification consisting of 11 possible topographic features; peak, ridge, saddle, flat, ravine, pit, convex hillside, saddle hillside, slope hillside, concave hillside and inflection hillside. Any pixels not assigned to these classes are assigned to the “unclassified” class. The procedure is performed on a DEM.

Many shapes may exist in a 3-D distribution of the topographical units. The study area was modeled with respect to its topographical shapes using IDRISI (GIS software).
The model resulted in several different toposhapes; flat areas, ridges –elevated peripheries-, ravine – extremely dipped areas-, convex hillside, saddle hillside, concave hillside, inflection hillside and little area unknown due to their dominant toposhape. The flat areas were the most markedly zones and exhibit extended areas. Figure (12) summarizes the produced toposhapes of the study area.

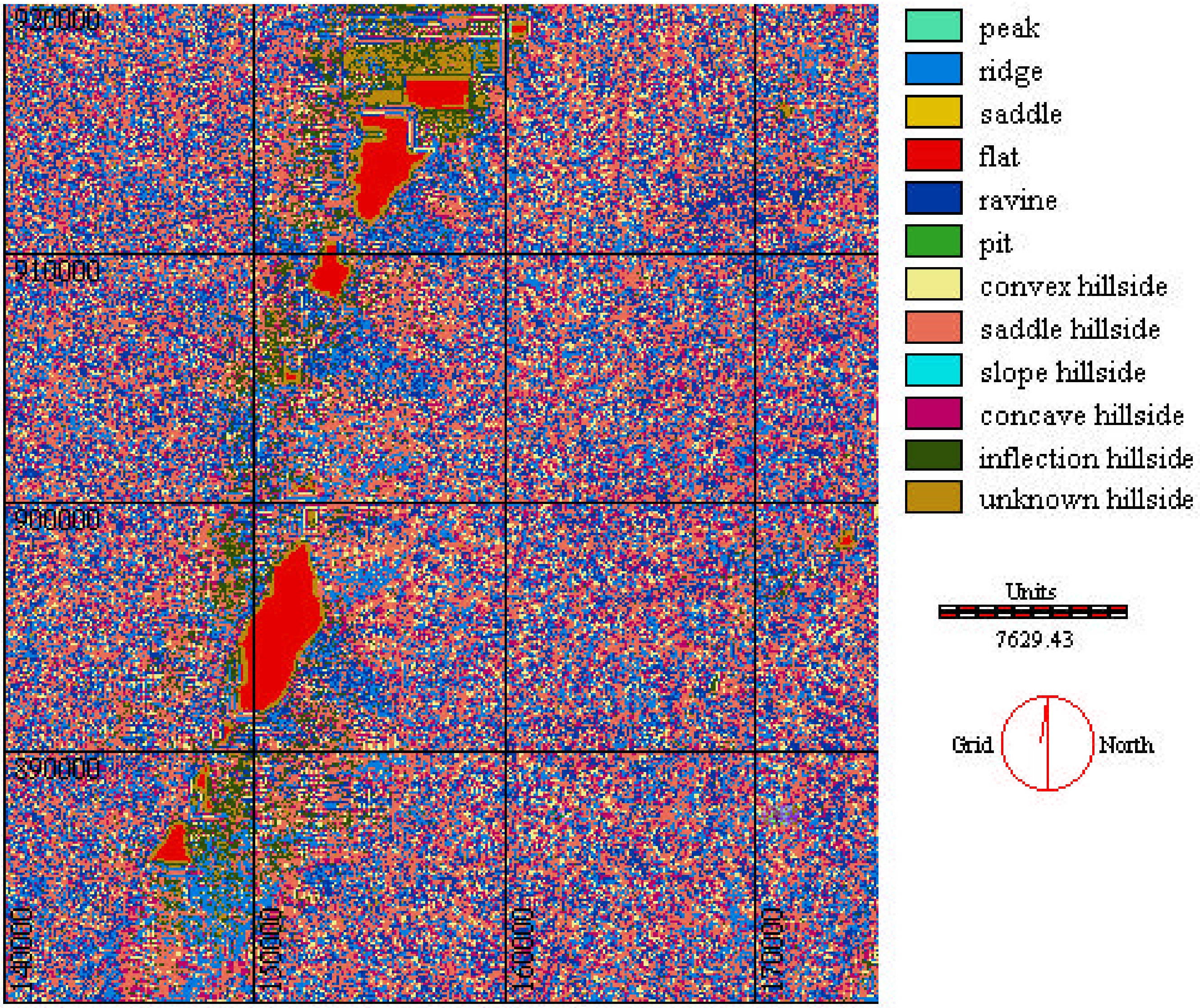


Figure (12): Produced toposhapes of the study area.

2.2 Geology of the Study Area

2.2.1 Introduction

The interactions between the natural resources and the population of Aqaba -recent and future- require good understanding of the body on which these reactions and activities take place.

Jordan from a geological point of view is located at the eastern edge of the Dead Sea rift which represents a part of the Great East African Rift System. The frequent regression and transgression of the Tethys sea in addition to the periodical left-lateral stresses all along the rift that formed as a result of the opening of the Red Sea played the major role in forming the geology and the structure of Jordan indicated by repeated unconformities and related structures.

The geologic stratification exposed in Jordan represents most of the geological time, ranging from Precambrian to Recent deposits.

The Precambrian igneous rock complex associated with the metamorphic rocks occupy about 896 km². This is unconformably overlain by the Late Proterozoic sediments (Bender, 1974). The Precambrian rocks are also unconformably overlain by the Lower Paleozoic marine to continental sediments dipping to the north and north-east. The Upper Paleozoic sediments do not crop out anywhere in Jordan except for some Permo-Triassic rocks which were recognized in a trial well of Ramtha. The carbonate and clastic rocks of the Jurassic conformably overlay the Triassic sediments. The Upper Cretaceous in Jordan is characterised by the wide transgression of the Tethys sea and consists mainly of marl, dolomite, limestone, chert and phosphate. The Upper most Cretaceous rocks thin gradually in S-SE direction. In the Tertiary a considerable thickness of marine sediments in addition to some fluviatile and lacustrine sediments were deposited. *The Quaternary rocks are mostly of continental origin as a result of the uplifting*.

The volcanic activities were very limited in the Paleozoic and Mesozoic ages, while these activities increased with the rifting processes after wards.

2.2.2 Depth To the Basement and Thickness of Overburden

Before speaking about the geology of the study area it is of great importance to define the depth to the basement, and to give an idea about the expected thickness of the alluviums.

The study area is a part of the graben formed in the Miocene (25 million years ago), where as before that time, the rocks at the east and west flanks of the graben were connected with each other, but now as a result of the rifting process they are not more connected and the older rocks are exposed along the rifts shoulders. (Abed 1982).

The basement under the alluviums is still sinking down, *confirming that is the recent active faults surround the separated granite fragments in the northern part of the study area.*

2.2.3 Boreholes Data

In the columnar sections taken in Wadi Al Yutum Figure 13, all the boreholes penetrated the alluviums and reached the granite basement beneath them. The depth to the basement ranges from 24-50 meters below ground level. The depth to the basement in Wadi Al Yutum seems to be very shallow compared with that under the city of Aqaba. This refers to the fact that the wadi is not affected by faulting processes like those existing in the Aqaba area which threw the basement down to more than 2000 meters.

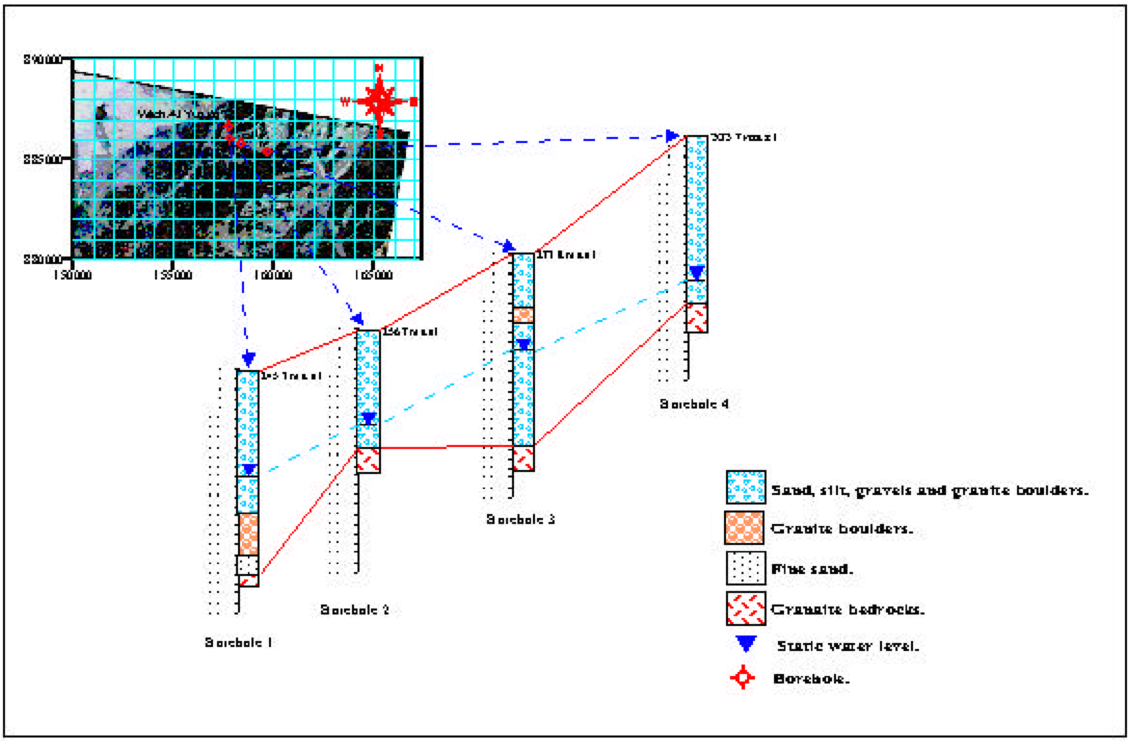


Fig.(13): Columnar sections taken in Wadi Al Yutum.

2.2.4 Geoelectrical Method to Estimate the Depth to the Basement

One of the vertical geo-electrical sounding profiles that were carried out through the phases of this study is 400 meters west of the borehole 1 -see the columnar sections and their location map in Wadi Al Yutum- it resulted in a depth to the basement of 49 meters under ground level with a resistivity of 2711 Ohm*m. In addition to that a study by Macdonald (1966) shows that the basement beneath the sediments of Wadi Al Yutum in its end part is as estimated by geoelectrical and shallow seismic refraction measurements within the same mentioned ranges.

El Kaisi (1976) using geoelectric investigated the water availability in the area between Wadi Mughlan and Aqaba airport in the southern part of Wadi Araba. He approached penetration depths of more than 285 meters in the alluviums and didn’t receive any signal that indicate the basement. (The results of this study are shown in the section of the hydrogeology). Geoelectric studies carried out in the course of this study didn’t give any signals which can indicate the granite basement, which is of resistivity about 5000 Ohm*m (Sharma 1986). The spacing of the longest profile wasn’t more than 1200 meters (Schlumberger vertical sounding method). Accordingly the penetrating depths don’t qualify them to approach these rocks.

2.2.5 Gravity Method to Estimate the Depth to the Basement and the Overburden Thickness

The margins of the Wadi Araba Rift extending from the Dead Sea to the Gulf of Aqaba, have been investigated by the geophysical Institutes of Israel (Terra Nostra 1997). The study area was also included. The study modeled the thickness of alluviums directly to the north of the Gulf of Aqaba to a distance of about 25 km to the north and a total width of about 7 km to be

more than 2000 meters. This was considered the depth of the crystalline basements. Gravity survey has been used in this concern to estimate the depth to the crystalline basement in the rift valley.
The Natural Resources Authority of Jordan combined its gravitational measurements carried out in Aqaba with the Israelian measurements of Eilat. All the corrected measurements were brought to a grid in terms of Bouger anomalies. It resulted in the map of Figure 14.

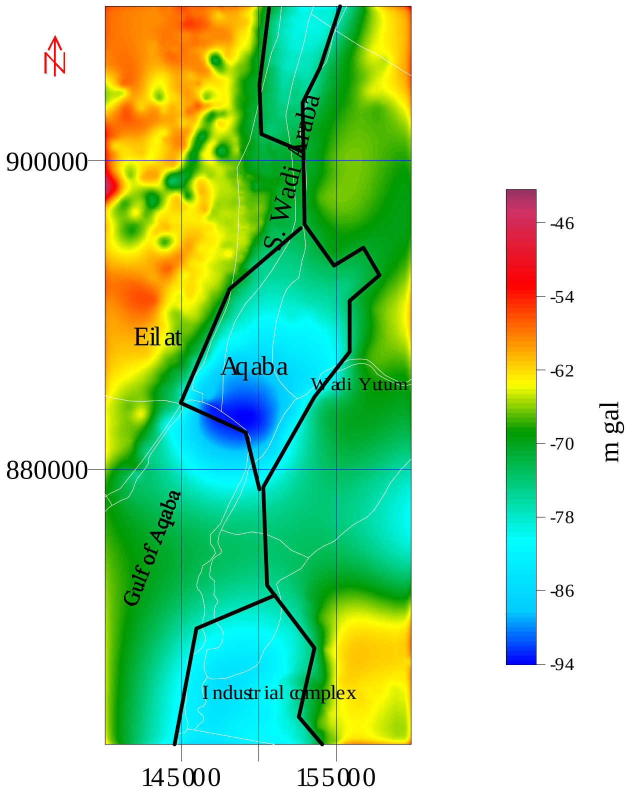


Fig. (14): Groundwater basins (black lines) modeled in the study area according to the gravity, Bouger anomaly.

The nature of geology in the area, which is normally composed of alluviums overlying the basement resulted in a specific surface morphology of the basement, and accordingly the sub-basins of groundwater.
The map indicates three sedimentological basins in the study area; the first starts in the south at 900,000 N 150,000 E and go north ward, the second is directly under the city of Aqaba and seems to be the deepest one where the Bouger anomaly is the lowest (–94 m gal). The area of the industrial complex posses a basin which is shallower than the former one.

2.2.6 Geology and Stratigraphy of the Study Area

The most southern part of Wadi Araba starts to slope towards Aqaba city from the area of Al Risha – about 75 km – north of Aqaba. It forms the wadi plain about 16 km wide at the end of Wadi Al Yutum. The Gulf of Aqaba occupies these plains and receives its products of floods.
The area is generally covered by Quaternary sediments consisting of a stream type of alluviums with a valley fill type of sediments in the lower part of the basin.
It is worth mentioning here that the study area is devoid of any deep wells, so the deep geology of the study area was not touched at any report or study, except as a result of indirect methods such as geophysical ones.

2.2.6.1 Surface Geology

Figure 15 shows the different rock units in the study area.
The rocks of the area range in age from Pre-Cambrian to Recent. The main rock types are:

Igneous Rocks

Aqaba Granite (Basement Complex)

Stratified Rocks

1. Paleozoic Sandstone
2. Cenozoic (Quaternary)

Pleistocene Gravels (Pl)

Alluvial Terraces and Wadi Bed Sediments (Al, Alf, Alm, Als)

Mud Flats

Coral Reefs

Aqaba Granite Complex

These are igneous rocks of Precambrian age. Their chemical and mineralogical analysis determined their classification as follows:

Grey Granite – Granodiorite

This rock has fine to medium grains of quartz, orthoclase, oligoclase which is altered to chlorite. It is deeply weathered and friable.

Red Granite

This rock is younger than the grey granite. It contains much microcline and porthite and lesser amounts of oligoclase. It is generally fresh and not deeply weathered.

Basic Intrusives

These occur as dolorite dykes which contain granular augite, crystals of labradorite in a base of feldspar.

Acid Intrusives

These are porphyry dykes and strike due north. They contain orthoclase, plagioclase and hornblend, some of which is altered to hematite.

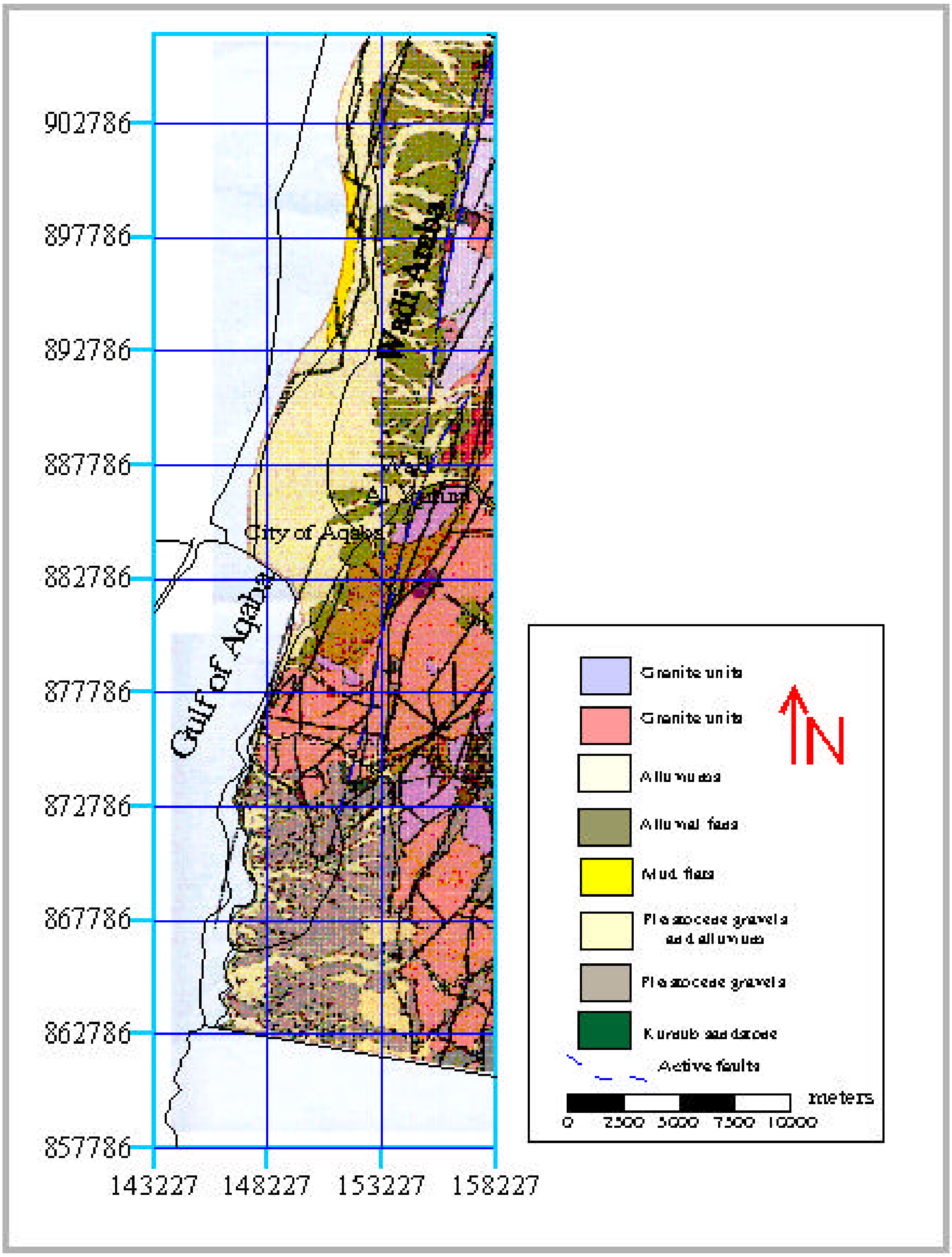


Fig. (15): Rock units in the study area.

Paleozoic Sandstone

These are found in small areas unconformably overlying faulted blocks of granite at the head of Wadi Mabruk –152000 E & 875000 N.

They are composed of medium to coarse grained sandstone of variable colours of reds and browns. The thickness of these sandstones at Wadi Mabruk reach about 40 meters. They are found also in the area to the north of Wadi Al Muhtadi.

Pleistocene Gravel (Pl)

Terrace gravel of presumed Pleistocene age occur in two small outcrops in the study area along the same fault zone. The gravel has been preserved from erosion by being down-faulted into small grabens and were presumably originally much more widespread.
They consist of granitic cobbles and pebbles set in a non-cemented matrix of finer unsorted materials. Many of the larger clasts have been noticeably weathered since deposition. The weathering and the unique perched position are the principal characteristics to distinguish these deposits from recent alluvial fan materials which is much more abundant.

Alluvial Terrace and Wadi Bed Sediments (Al, Alf, Alm, Als)

The quaternary alluvial fans existing in the northern part of the study area –east and north east of Aqaba airport- occur as dissected piedmont fans, descending from the peripheral wadis and exists as a terrace level one meter or so above the modern southern part of Wadi Araba course. The alluvial fans are distinguishable from the active wadi sediments by retaining an incipient desert varnish which is distinguishable on aerial photographs. The active wadi sediments are found in the lowest part of the wadi profiles and grade laterally in depth into the feeding fans. (Natural Resources Authority of Jordan, 1988).
In the southern part of the study area these are unconsolidated, bedded, nearly flat lying quaternary sediments. They are composed of gravel, sands and silts which were derived from the igneous rocks and Paleozoic sandstones. Rejuvenation –relative uplift with respect to sea level- of the drainage system has formed at least two terraces in the southern part of the study area, where along the lower granite mountain slopes 5 to 10 meters of debris are present.
The alluvial terraces form outcrops in the southern part of the study area -in the area of the industrial complex- and can give some information on those present in the other parts of the study area due to their similar sedimentological coditions.
The terrace sediments form the major outcrops in the west and south of this area. The full thickness of the older terraces is not known. Exposed section of 5 to 50 meters were observed in various places.
The younger terrace sediments occur on the sides of modern wadis and reach a thickness of one to two meters above wadi levels. They consist mainly of granite, granodiorite, quartz diorite and sandstone debris. The grain size of the younger terrace sediments is usually finer than that of the older terrace sediments. The older terrace sediments are bedded and their grain size ranges from very fine to boulder. The Pliocene – Pleistocene is suggested as the age of these sediments (Natural Resources Authority of Jordan, 1988).

To the east of the industrial complex area, an exposed section was described as following;

20-25 meters, coarse grained reddish to yellowish sandstone inter-bedded with gravel zones.
1-2 meters, very fine grained, yellowish, sandy silt.
5-7 meters, reddish, ferrogenous, coarse to medium grained, unconsolidated sandstone.
1-2 meters, very fine grained, reddish and yellowish sandy silt.
5-6 meters, reddish, coarse to medium grained unconsolidated sandstone.
1-2 meters, flat lying younger terrace material of fine to coarse grained sand with some gravel.

Mud Flats

Fine pelitic – argillaceous- sediments in Wadi Araba overlay the normal wadi sediments. This area of ephemeral standing water has formed a mud flat (see the geological map) through

which has threadened the modern, usually dry, water course down to the coast where there is a narrow selvedge of beach sand. The beach and stream deposits represent the most superficial phase in the alluvial hierarchy.
Extended outcropping sediment lenses were noticed during the field work. One of them have been investigated according to its dimensions and bedding form, it was of 23 meters diameter and 1.5 meters thickness. From the upper to the lower limits the grain sizes increase to end with at the lower part mostly with gravel to boulder sizes, where as the upper parts clay and silt sizes are dominant. The expected depositional environment of such lenses is the captured water after flood events in some concave shaped areas.

Coral Reefs

Fossil coral reefs occur at some localities along the shore. Al-Rifaiy, (1988) stated that three major cycles of fossil coral reef development have been recognized on the Jordanian coast of the Gulf of Aqaba. It seems that the eustatic sea level changes governed the development of these reefs correspond to glacial and interglacial episodes of the late Pleistocene.

2.2.6.2 Subsurface Geological Setting

Columnar Sections from the Overburden of the Study Area

Some shallow columnar sections were reconstructed. They mainly represent the unsaturated zone of the alluviums building up the aquifer. Some of them penetrate also the water table. These sections give information on the thickness and the lithology of these alluviums.
Three locations have been defined here they included; Wadi Al Yutum; (Macdonald, 1966), the area underlying the waste water treatment plant (data from Lafi, 1987) and a third one at the southern end of the study area; (Jordan Office for Geological and Engineering Services, 1967).
A major trend in the study area is that the grain size of the alluviums tends to be smaller westward of the eastern granite mountains, and vice versa.

Wadi Al Yutum

The nature of the alluviums indicate low maturity and near source rock where the majority of these deposits originated as mountain washing products and wadi fillings. Four columnar sections were reconstructed from borehole data (Fig. 13).

Borehole No. 1

Elevation 245.34m a.s.l. (top of casing)
Lithology 0-29m Sand, silt and gravel
29-33m Granite boulder
33-41.5m Fine sand
41.5-44m Granite bedrock
Static water level 18.58m below the top of casing.

Borehole No. 2

Elevation 256.7m a.s.l. (top of casing).

Lithology 0-24m Sand, silt and gravel
24-29m Granite bedrock
Static water level 21.33m below the top of casing

Borehole No. 3

Elevation 273.79m a.s.l. (top of casing)
Lithology 0-13m Sand, silt and gravel
13-14m Granite boulder
14-39m Sand, silt and gravel
39-44m Granite bedrock
Static water level 19.53m below the top of casing

Borehole No. 4

Elevation 303.70m a.s.l. (top of casing)
Lithology 0-34m Sand, silt, gravels and granite boulder
34-40m Granite bedrock
Static water level 29.42m below the top of casing

Columnar Sections in the Area Underlying the Waste Water Treatment Plant

Figure (16) shows the different alluvium sequences beneath the Aqaba waste water treatment plant. Some layers extend to a certain distance and then disappear afterward, indicating the presence of lens form of deposition and/or local faulting processes. The last possibility confirms the tectonic impacts on the semi lithified alluviums.

The boreholes included the following type of lithologies:

Ghabat Al Nakheel No. 2 (Gh.2)

0-3m...........Clay, silty clay and few gravel of quartz and granodiorite
3-30m..........Silty clay, fine sand with some grains of granite
30-38m.........Mostly fragments of granite productions with silty clay materials
38-39m.........Silty clay, fine sand with some products of granite
39-42m.........Mostly small size products of granite with clay fine sand and gravel
42-44m.........Clay, silt, fine sands and fragments of granite
44-49m.........Sand, mostly coarse to gravel size with fragments of granite and granodiorite
49-51m.........Clayey silt, fine sand with gabbro, granodiorite and quartz
51-53m.........Crushed gabbro, granodiorite and sugar sized quartz particles

Waste Water Plant 1 (WWTP.1)

0-16m.........Sand, cream like, fine to silty clay
16-25m.........Sand, coarse mixed with cuttings of igneous rocks(60%)
25-30m.........Sand, coarse to fine mixed with cuttings of igneous rocks (20%)
30-31m.........Sand, cream like mixed with silty clay

Waste Water Plant 2 (WWTP.2)

0-11m...........Silty –fine sand

11-16m............Silty sand
16-24m............Gravel consisting of granite and granodiorite

Waste Water Plant 4 (WWTP.4)

00-02m............Sand, fine to coarse and silty
02-10m............Sand, fine to medium, cream-like, and contains some cuttings of igneous rocks.
10-21m............Fine sand creamy-like, and silty
21-32m............Sand containing gravel of granodiorite

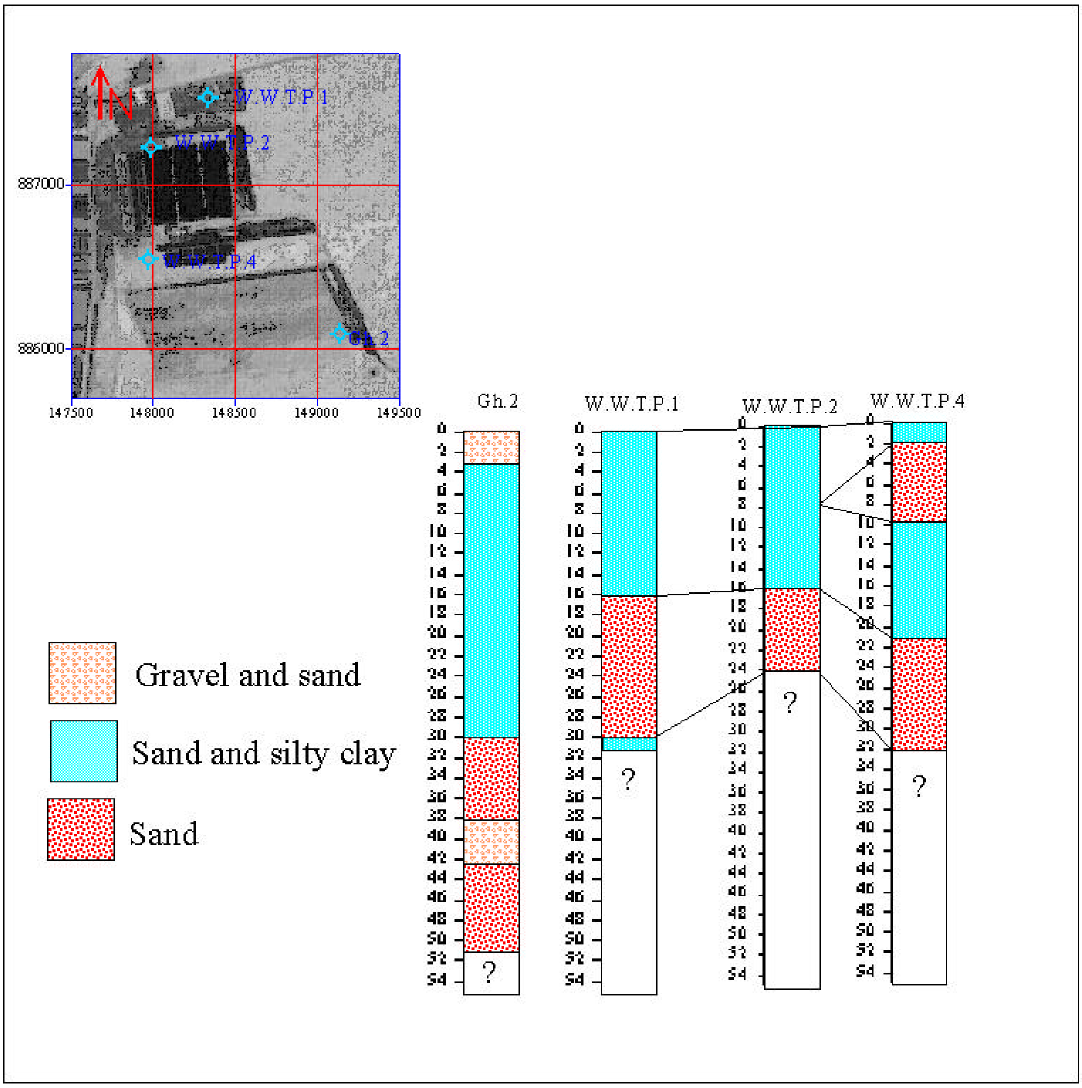


Fig.(16): Alluvium sequences beneath the Aqaba waste water treatment plant.

Section from the Most Southern Part of the Study Area

0-25m.....Coarse grained reddish to yellowish sandstone inter-bedded with gravel zones
25-27m.....Very fine grained, yellowish, sandy silt
27-34m.....Reddish, ferrogenous, coarse to medium grained, unconsolidated sandstone
34-36m.....Very fine grained, reddish and yellowish sandy silt
36-42m.....Reddish, coarse to medium grained unconsolidated sandstone
42-44m.....Flat lying younger terrace material of fine to coarse grained sand with some gravel

This section was taken from an outcrop of an alluvial fan area. The section with prevailing fine grain sizes is located at the western end of the alluvial fan.

Alternating Marine-Alluvial Sediments

Fluctuating sea levels have resulted in alternating continental and marine deposits. The presence of fossil coral reefs on the southern part of the study area near shore, confirms the alternating marine-alluvial sediments.

Al-Rifaiy (1988) modeled a block extending 1 km east-west along co-ordinate 864000-N in the most southern part of the study area. The results indicate about 270 meters lateral extension of the alternating marine-alluvial sediments eastwards from the sea periphery, east of which only continental sediments occur.
The recognised different alternating marine rock types within the block were limestone (boundstone) with corals in life position, and calcarenite (packstone & wackestone) with and without coral fragments. While the continental inter-bedded alluvial stratas were as conglomerate and recent beach sand and alluvial fan deposits. These several sedimentological cycles are separated from each other by normal faults and erosion surfaces representing the old shores.

2.2.7 Structural Geology of the Study Area:

The study area is located at the northern end of the Gulf of Aqaba, the north-east extension of the Red Sea, which separates south-east Sinai from south-west Jordan and north-west Saudi Arabia. The Gulf of Aqaba is part of Wadi Araba – Dead Sea Rift Zone which in turn is a segment of the major geo-suture extending from East Africa to South Turkey with 6000 km length. Accordingly, tectonics and evolution of this rift graben system have had an important bearing on the regional structure of the rocks exposed in the study area.
The grabin formed in the Miocene (25 million years ago). Before that time, the beds and rocks of the east and west flanks of the graben were connected with each other, but now and as a result of the rifting process they are no more connected and the older rocks are exposed along the rift shoulders.
The Dead Sea transform fault is the most important tectonic feature in Jordan. Many theories have been suggested to explain the formation of this rift.
Faults and tectonic features seem to be restricted to the basement complex. These faults vary in length but most of them strike to north-east, north and east-west. These last sets are the main cause for the presence of the majority of wadis trending east-west, crossing the granite basement and forming a part from the drainage system and alluvial fans.
Sharp contacts between the high contrasts in the gravity map indicate the step faults of the graben.
The wadis and water passages that cross the granite mountains at mainly E-W direction are structural wadis formed due to faulting processes where the weathering added some enhancements on them.
Active faults which cut the granite series and the alluvium and take NNE-SSW direction, where delineated on aerial photography.
Sinking down of the granite basement beneath the graben is still active. Live evidence on that are the small granite blocks separated from the mountains in the northern part of the study area.

2.2.8 3-D Geoelectrical Stratigraphy Modeling On the Study Area

One of the main functions of geoelectrical sounding is to study the stratigraphical sequences of a specific region. Calibrating the results of the vertical electrical sounding near a known well of known lithology, groundwater depth and quality is of great importance to approach the real conditions.

In the case of the study area the resulting layers of geoelectric sounding are electrical ones, their resistivities are a function of the liquid content of the layer and its porosity, because the alluviums here are of the same origin regarding their mineralogical composition. So the modeling of the depths of the study area is liquid-salinity dependent.

Figure (17) shows the resulting 3-D model of the geo-electrical survey in the study area.

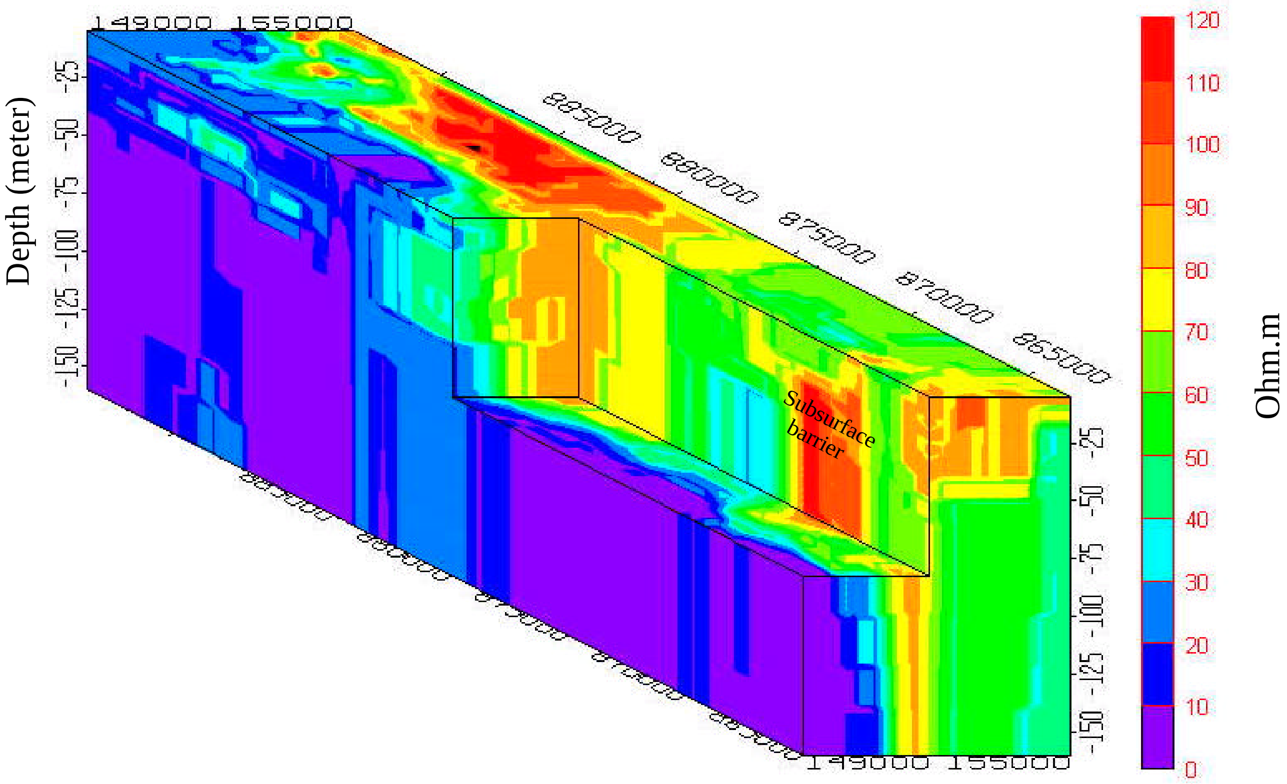


Figure (17): 3-D resistivity model in (Ohm*m) of the geo-electrical survey in the study area.

This model reflects the water salinity which increases westwards. Also it reflects the impacts of the Aqaba waste water treatment plant on the groundwater which supplies the aquifer with less salinity water than that underlying it.

2.3 Soils; The First Reception and Defense Zone of The Aquifer

2.3.1 Introduction

Soil is the first zone of groundwater basins. Sometimes and according to erosion processes it can be absence. It is important in groundwater recharge studies, land use planning, vulnerability and contamination risk analysis of groundwater. Spatial soil mapping relevant to its characters and classes is one of the main items of the modern cities planning.

2.3.2 Soil of the Study Area

It is important for this study to understand the behavior of the areas soil cover for water infiltration, permeability and soil field capacity. These physical parameters are of a paramount importance for calculating and/or estimating the surface water balance (budget), groundwater recharge for the aquifer and the spatial vulnerability of the aquifer.
The soil in the study area is mainly a product of mechanical weathering. This type of the prevailing climate and natural vegetation in the study area have no major role in developing the soil.
Although no considerable natural vegetation cover has developed in Aqaba because the total annual precipitation does not exceed 37 mm, the high annual average temperature encourages the chemical weathering process.
Despite that the specific definition of the soil does not match the upper cover of the study area, the most upper part of the alluvia will be treated as a soil cover.
The granite bedrock (the parent rock) reflects its mineralogical composition on that of soils. The parent rock is an igneous basement complex intruded by basic and acidic dykes, and the transported weathered parts of the Paleozoic sandstone to the northern east of the study area. The major mineralogical composition of the resulted soil refers to the low temperature minerals in the Bowen's reaction series including quartz (SiO_2), biotite ($2KMg_2FeAlSi_3O_{10}(OH)_2$), sodium feldspar ($2NaAlSi_3O_8$) and plagioclase (sodium rich).
When the climate conditions allow the presence of water, kaolinite ($Al_2Si_2O_5(OH)_4$) can be produced by chemical weathering reactions. The marine carbonate rocks exposures in the southern part of the study area reflect the mineralogical composition on the soil including besides the previously mentioned composition some calcite ($CaCO_3$).
The depositional pattern of the area's floods inherited the soil layers and the subsurface stratas some clay-silt sizes taking lens shapes.

Although the soil in the study area is resistant to the chemical weathering reactions, the chemical reactions between the solid and liquid phases with the action of high evaporation lead to the precipitation of some salts within the soil matrices. This leads to the soil salanization.
Organic matter residuals in soil matrices exist in the cultivated part due to the urbanization processes. The spatial distribution of the soil in the study area is to a high degree affected by the land forms; they are reflected on its texture and maturity. The beach soil is more mature, well sorted and of more rounded grains than that of other places. The canyons and the mouths of the alluvial fans are characterized by coarse sizes and less maturity, where their ends and the flood plains are distinguished by small grain sizes and the presence of mud flats.

Land use affected the soil cover in several ways; by adding some fertilizers rests from the different present gardening and planting activities, some unwanted organic materials such as mineral oil wastes, besides the dust particles from Aqaba sea port and from trucking process of some raw materials.

2.3.3 Soil Texture by Grain Size Analysis

Soil texture refers to the percentage of sand, silt, and clay particles in a soil. Sand, silt, and clay particles were defined by their sizes according to the U.S.D.A (*United States Department of Agriculture)* classification system, which was used in the research, (Table 3).

Table (3): Classification categories of soil, after U.S.D.A.

TEXTURE	SIZE
Very coarse sand	2.0-1.0 mm
Coarse sand	1.0-0.5 mm
Medium sand	0.5-0.25 mm
Fine sand	0.25-0.10 mm
Very fine sand	0.10-0.05 mm
Silt	0.05-0.002 mm
Clay	<0.002 mm

Fifty two soil samples from different locations were collected in May/2000; from the surface and from a depth 25 cm. They were exposed to wet mechanical sieve analyses in the soil laboratory of the Department of Geology/University of Jordan.
The locations of the samples were selected to cover all the land forms in the study area; from the heads, middles and ends of alluvial fans, beaches, flood plains, wadis sediments and from the mountain debris. They were analyzed using sieve sizes: 6.7mm, 4.0mm, 2.0mm, 0.5mm, 0.3mm, 0.125mm, 0.063mm, 0.053mm and 0.035mm. These indicate medium gravel, fine gravel, very coarse sand, coarse sand, medium sand, fine sand, very fine sand and the rest was considered as silt and clay sizes.

The percentage distribution of the sizes of surface samples were exposed to a clustral statistical analysis for better handling using the software SPSS for Windows (1999). Accordingly it was possible to classify them into 6 clusters as shown in Table (4).

Table (4): Spatial clustering of the soil in the study area.

CLASS	CLUSTER					
	1	2	3	4	5	6
Medium Gravel	46.57%	0.17%	6.70%	2.14%	13.23%	0.42%
Fine Gravel	10.21%	0.43%	7.69%	1.50%	8.42%	0.98%
Very C. Sand	11.53%	1.17%	24.01%	4.45%	14.44%	0.90%
Coarse Sand	14.03%	23.89%	45.01%	31.95%	29.67%	66.14%
Medium Sand	4.08%	17.35%	7.11%	23.10%	11.31%	20.14%
Fine Sand	5.58%	47.97%	6.10%	23.72%	14.50%	5.78%
Very F. Sand	5.68%	7.96%	2.63%	11.59%	6.75%	5.32%
Silt and Clay	2.32%	1.05%	0.76%	1.55%	1.68%	0.32%
Samples per cluster	2	2	4	7	9	1

From the spatial distribution of the clusters a spatial trend was found; **cluster 1 belongs to heads of the alluvial fans**, where gravel and sand sizes are 56.78 % and 40.85 %

respectively, while silt and clay sizes are 2.32 %. Dominant here is the gravel size which the case of the deposits in such land forms.

Two samples were grouped in **cluster 2. It represents mostly the soil within the beach zones, and the ends of the flood plains**. Here the gravel, sand and silt and clay sizes are respectively 0.6%, 98.34 and 1.05. Highly dominant here is the sand size; the case of the beach soils.

Cluster 3 includes four samples and **it represents generally the heads and middles of the small alluvial fans, and the middles of the big fans**. The gravel constitutes 14.39% by weight, the sand size 84.86%, while the rest refers to the silt and clay sizes that equal 0.76%.

In **cluster 4** seven samples were found to represent **the most lower end of the flood plains**, and somehow the beach soils. The sand size here is the most dominant one; 94.81%, the gravel size occupies 3.64% and silt and clay sizes 1.55%.

Nine samples were found in **cluster 5** representing the **ends of alluvial fans**. The gravel size is relatively high and equals 21.65%, the sand size 76.67%, and the clay and silt sizes 1.68%.

In **cluster 6** only one sample was found, it includes high amounts of sand and represents the **beach soils**.

The general trend here is that in the study area, down the ephemeral streams the fine grains increase, while the gravel grains decrease, and vice versa. The sand size tends to increase downstream. From the simple field observations, down the ephemeral stream the roundness and sphericalness of the grains increase.
The normal percentage distributions of the sizes was cumulated for every sample, the results were plotted in a semi-log diagram to show the behaviour of every cluster relevant to its group. Fig. (18) shows the plots.

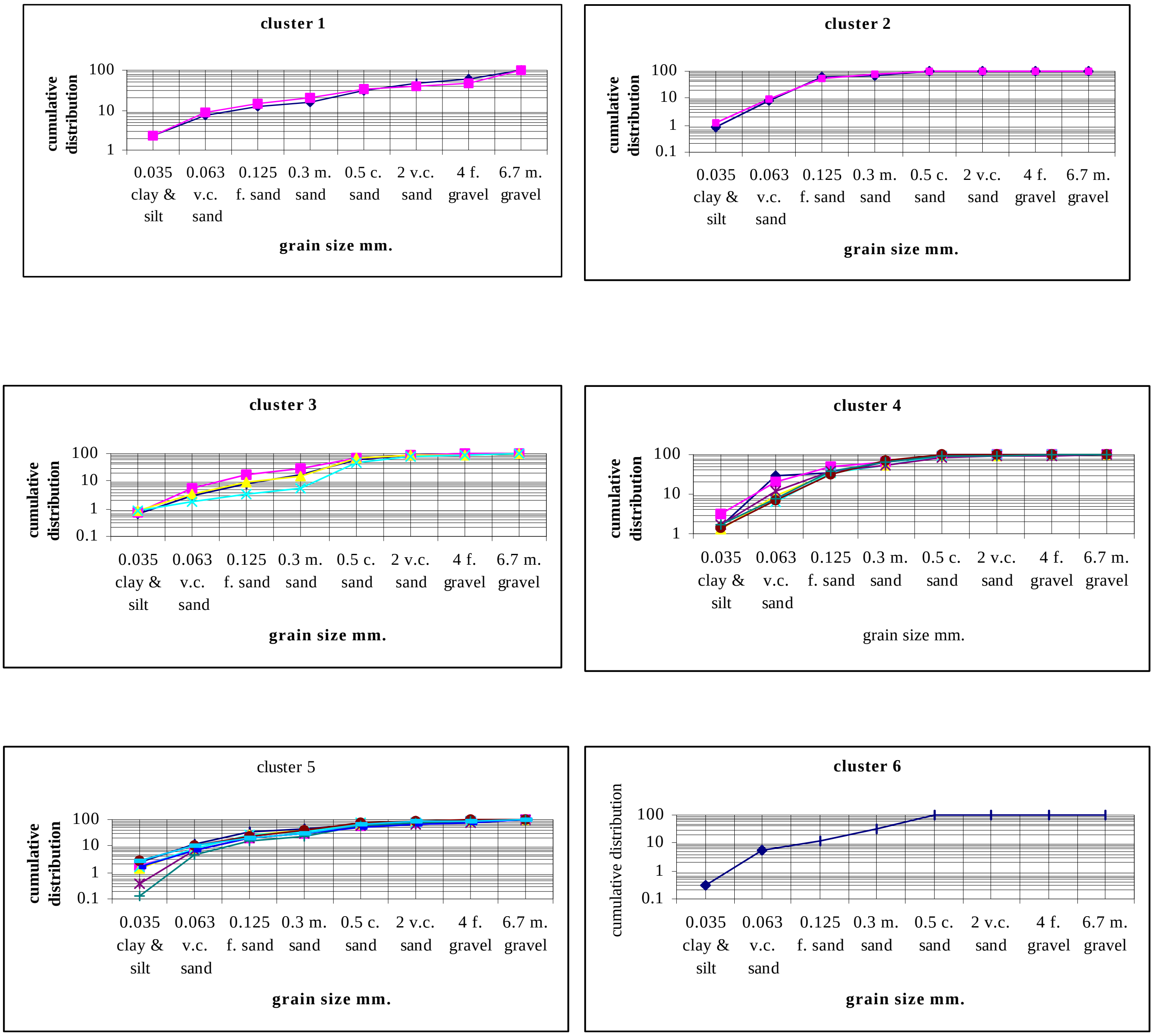


Figure (18): Soil clusters and soil sizes.

23 samples of the depth 25 cm were clustered within similar groups, and had nearly similar behaviors (Table 5).

Table (5): Cluster of soil sizes in the study area at a depth 25 cm.

CLASS	CLUSTER					
	1	2	3	4	5	6
Medium Gravel	5.64%	11.51%	13.69%	0.18%	2.35%	1.14%
Fine Gravel	2.92%	9.60%	8.42%	0.22%	2.39%	0.47%
Very C. Sand	4.70%	20.17%	11.98%	0.12%	4.73%	3.08%
Coarse Sand	15.99%	39.50%	28.70%	48.24%	34.82%	13.69%
Medium Sand	15.04%	8.05%	16.90%	32.79%	23.07%	29.59%
Fine Sand	43.92%	6.66%	14.46%	7.49%	24.99%	45.25%
Very F. Sand	10.24%	3.34%	4.51%	8.91%	6.16%	5.19%
Silt and Clay	1.56%	1.17%	1.34%	2.04%	1.49%	1.59%
Samples per cluster	2	8	4	2	6	1

2.3.4 Textural Classification of Soils

The classification of samples in terms of their textural classes (Table 6) fits only within sand category, ***accordingly the soil in the study area is best described as sandy soil.***

Table (6): Classification of the samples according to their textural classes.

TEXTURAL CLASS	SOIL SEPARATE RANGES IN PERCENT		
	Sand	Silt	Clay
Sand	85-100	0-15	0-10
Loamy sand	70-90	0-30	0-15
Sandy loam	40-80	0-50	0-20
Loam	23-52	28-50	7-27
Silt loam	0-50	50-88	0-27
Silt	0-20	80-100	0-12
Sandy clay loam	45-80	0-28	20-35
Clay loam	20-45	15-53	27-40
Silty clay loam	0-20	40-73	27-40
Sandy clay	45-65	0-20	35-45
Silty clay	0-20	40-60	40-60
Clay	0-45	0-40	40-100

*. Soil Physics.

2.3.5 Modeling Soil-Water Parameters

This item is very important for calculating the surface and groundwater balance and it will be used in studying the vulnerability of the groundwater for pollution. Ghildyal & Tripathi (1987) stated that four forces act on the water in the soil;

1. *Gravity, inertial or body force;* Ô.
2. *Hydrostatic or forces associated with pressure gradients;* ψ.
3. *Osmotic forces related with solutes concentrations;* ù.
4. *Adsorptive forces-long range electrical forces and the short range London van der Waal's forces;* $\propto$.

These forces give the water in the soil the potential to move. If the total soil water potential (Φ*)* is constant throughout the soil mass, the soil water system is said to be in static equilibrium. The following formula governs that behavior;

$$F = \hat{o} + y + \mu + \grave{u} + \ldots,$$

The resultant force (Φ) of the soil water is the summation of these four forces, in addition to any force which can act here. The thermal contrast also has a role in this process.
Movement of the soil water, and the pollutants movement within the soil depend mainly on these forces.
Soil texture has important effects on soil properties. Water-holding capacity, drainage class, consistence and chemical properties are just a few examples of properties that are affected by soil texture. In general coarse-textured soils (lots of sand-sized particles) hold relatively little amounts of water, drain rapidly and are low in fertility. Fine-textured soils (lots of clay-sized particles) hold relatively large amounts of water may be poorly-drained or well-drained depending on their structure, and can be high or low in fertility depending on the types of clay particles present. http://www.agronomy.psu.edu/Courses/SOILS101/Labs/texture.html

The natural relative abundance and distribution of the desert plants in the one alluvial fan in the study area was a good index at the relative grain size distribution, which controls the field capacity of soils and the trapped water amounts.

Field capacity is the water that is left after gravity drainage takes place. More exactly, it's the field at saturation minus the gravitational water. What all this means is the amount of water that the soil will hold, resisting what drains away through gravitational pull (**and what doesn't soak in and runs off**).
Theoretical values can be assigned to each soil type based on the amount and type of clay content of the soil, but there are many more factors involved. The major ones are:

- *Tillage depth*- determines how far the water will soak in at a rapid rate. A "tillage pan" develops in soils with clay content at the tillage depth. This is a result of water moving rapidly through the tilled area and carrying clay particles. When it hits the bottom of the tillage zone, the water slows down and the clay is deposited at this depth forming an impenetrable layer. (Just like putting clay in a pond to seal the bottom.) Then the water moves horizontally, resulting in erosion.

- *Organic matter content*- the higher the organic matter percent, the greater the water holding capacity of a soil. Organic matter can hold up to 8 times it's weight in water. It will help a sandy soil retain water (slow down the drainage) and help a clay soil drain (accomplished by the open structure built by life in the soil).

The problem with a high clay soil is that the water holding capacity excludes high oxygen content atmospheric air resulting in aerobic soil life plant death. Plants need oxygen at the root hair for nutrient absorption and root extension.
The problem with sandy soils is they don't hold water well (though water is easier for plants to absorb) and the *high pore space means faster evaporation, as well as higher gravitational water.*
Though clay soils hold more water (higher field capacity) than sandy soils, the water is not as available to plants. That is, plants cannot pull the water as easily away from clay particles. So, there is no advantage to any soil type, there are just plus and minuses for each. The advantage is in knowing the particular soil texture and knowing how to manage it for the best soil and plant life response. The whole thing is theoretical and instantaneous. Field capacity is diminished right away by evaporation and plant absorption. But it gives an idea about the amount of water a particular soil type will hold. This is valuable for determining when and how much irrigation will be needed by a particular crop.
(http://www.sare.org/htdocs/hypermail/html-home/45-html/0235.html)

Typical values of soil-water parameters in relation to the texture are shown in Table (7).

Table (7): Typical values of soil-water parameters in relation to the texture.

SOIL TEXTURE	FIELD CAPACITY MM WATER PER CM DEPTH OF SOIL	WILTING POINT MM WATER PER CM DEPTH OF SOIL	AVAILABLE WATER MM WATER PER DEPTH OF SOIL
Sand	0.9	0.2	0.7
Loamy sand	1.4	0.4	1.0
Sandy loam	2.3	0.9	1.4
Sandy loam + organic matter	2.9	1.0	1.9
Loam	3.4	1.2	2.2
Clay loam	3.0	1.6	1.4
Clay	3.8	2.4	1.4
Well structured clay	5.0	3.0	2.0

Saxton, (2001) developed a soil water calculator for estimating generalized soil-water characteristics from texture. The input parameters for the software are restricted to the percentage contents of the gravel size, sand size and clay size in the soils sample. While the output are the **Permanent Wilting Point, Field Capacity, Water Saturation, Available Water (AW), Hydraulic Conductivity** and **Bulk density (BD)** of the soil cover. This method depends on formulae derived from the statistical regression output of studies done on many soil samples, which were measured and analyzed on their water parameters and soil textures. (http://www.bsyse.wsu.edu/~saxton/soilwatr/article/article.htm)

Permanent Wilting Point

is the water content at a matric potential of -1,500 *kPa* (-15 *bars*). It roughly corresponds to the lower limit of the Available Water. This value is expressed in *(units³ water/units³ soil)%*.

Field Capacity

is the water content at the upper limit of the Available Water or drained upper limit. It roughly corresponds to a matric potential of -30 *kPa* (-0.3 *bars*) in most soils and to -10 *kPa* (-0.1 *bars*) in sandy soils. This value is expressed in *(mm³ water /mm³ soil)%*. It is dependant only on the soil texture and unaffected by salinity or gravel.

Water Saturation

The saturation moisture content of the soil matrix such that the entire soil porosity is water filled, *(%Volume)*, and dependent only on the soil texture, and unaffected by salinity or gravel.

Available Water (AW)

AW = (FC - PWP) This value is expressed in *(mm³ water / mm³ soil)%*, or rather, percent water. It corresponds to the difference between field capacity and permanent wilting point.

Hydraulic Conductivity:

The capability of water to move within the soil matrix driven by matrix and gravitational potentials, *(cm/s; in/hr)* dependent on soil texture and moisture content.

Bulk density (BD)

BD = (1 - saturation) * 2.65 Bulk density is used in determining soil porosity. The value is expressed in grams of soil mass per cubic centimeter of soil volume.

The software was used in estimating the previous mentioned parameters depending on the soil texture, measured natural moisture content and soil water electrical conductivity of the surface samples in the study area from different locations. The surface and 25 cm depth samples of the soil found to have the same behavior relevant to their texture. Accordingly only the surface samples were used in estimating the previous mentioned soil water parameters. The clay ratios within the samples were derived theoretically from the silt contents, where the smallest sieve size in the study was 0.035 mm, which represents the total silt and clay in the one sample. The location of the sample in the study area and its spatial cluster trend in relation to the distribution of the sizes were used to determine these ratios. Table (8).

Depending on the chemistry of the soil water, spatial distribution of the electrical conductivity (EC in μ S/cm) was used to estimate the salinity of the samples with respect to their location.

Table (9) shows the output of the modeled soil textures with respect to their soil-water parameters.

The field capacity was found to range around 0.9 mm/cm. The lowest value was registered as 0.74 mm/cm, while the highest value was 0.97 mm/cm. The sandy nature of the soil in the study area made the values not to exceed more than that.

The Wilting point ranged between 0.35 mm/cm to 0.23 mm/cm, which is the normal range for sandy soils. The soil showed relatively high saturation hydraulic conductivity, the average was 19 cm/hour.

Positive correlation exists in the study area between the natural moisture content of the soil and the amounts of clay, while a negative relation proceeds between the moisture content and the gravel amounts, Fig. (19). This is a normal trend, where the clay keeps normally the water against gravity and evaporation, while it is more easy to get water from gravely soils. Strong positive correlation was found to proceed between the soil field capacity in the study area and the contents of clay and silt. Figures 20 and 21 show the major behavior of the soil samples in the study area in terms of moisture curves.

Table (8): Estimating the clay ratios, depending on the silt content.

CLUSTER	SILT%	CLAY %
1	80%	20%
2	20%	80%
3	50%	50%
4	60%	40%
5	50%	50%
6	40%	60%

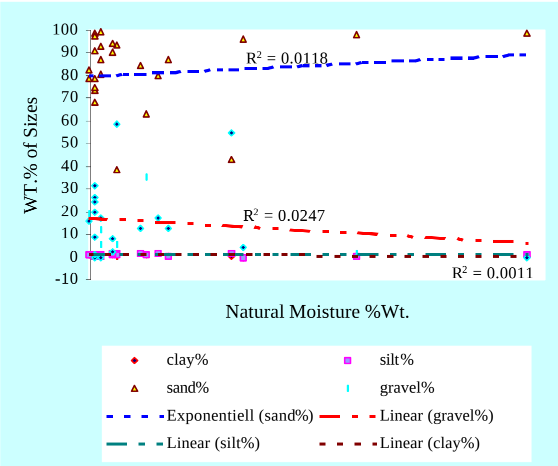


Figure (19): Correlation between moisture content, and grain sizes of soils in the study area.

Table (9): Output of modeled soil textures with respect to their soil-water parameters.

Sample No.	Cluster	Salinity ds/m	Moisture Content % WT.	Soil texture				Soil-Water Output Parameters							
				Clay %	Silt %	Sand %	Gravel %	Wilting Point mm/cm	Field Capacity mm/cm	Water Saturation mm/cm	Available Water mm/cm	Bulk Density g/cm^3	Matric Potential kPa	Matric + Osmotic kPa	Saturation Hydraulic conductivity Cm/hour
1	**1**	3.0	0.25	0.47	1.89	38.83	58.81	0.35	0.970	2.9	0.65	2.16	512	1056	16.55
2	**1**	2.7	1.25	0.46	1.82	42.97	54.75	0.34	0.975	2.8	0.64	2.13	512	1056	17.31
3	**3**	3.0	0.70	0.40	0.40	86.79	12.40	0.24	0.780	1.7	0.54	1.79	489	1033	17.90
4	**5**	3.5	0.05	0.18	0.18	68.15	31.48	0.25	0.805	2.2	0.55	1.93	489	1214	22.30
5	**5**	3.0	0.05	0.86	0.86	78.67	19.60	0.30	0.890	2.6	0.59	1.83	489	1033	20.87
6	**5**	3.0	0.60	1.38	1.38	79.78	17.46	0.34	0.960	2.9	0.60	1.89	489	1214	18.03
7	**5**	4.0	0.05	0.07	0.07	73.58	26.29	0.23	0.750	1.3	0.50	-	-	-	13.60
8	**5**	4.0	0.45	1.36	1.36	84.65	12.63	0.33	0.950	2.9	0.61	-	-	-	18.62
9	**4**	4.0	0.20	0.69	1.03	90.36	07.91	0.28	0.850	2.5	0.57	-	-	-	21.59
10	**3**	3.5	0.05	0.37	0.37	90.68	08.58	0.25	0.800	2.1	0.55	-	-	-	22.28
11	**4**	3.5	0.10	0.67	1.00	92.80	05.53	0.27	0.850	2.4	0.57	-	-	-	21.70
12	**4**	3.5	1.35	0.00	0.00	95.81	04.19	0.22	0.740	0	0.52	-	-	-	85.12
13	**2**	3.5	0.10	0.71	0.18	99.11	00.00	0.27	0.830	2.4	0.56	-	-	-	23.16
14	**3**	3.5	0.10	0.34	0.34	87.25	12.06	0.25	0.790	2.1	0.55	-	-	-	22.18
15	**3**	40.0	0.05	0.41	0.41	74.66	24.52	0.26	0.810	2.3	0.55	-	-	-	22.54
16	**5**	40.0	0.50	0.86	0.86	62.87	35.41	0.32	0.920	2.8	0.60	-	-	-	19.63
17	**6**	8.0	2.35	0.19	0.13	98.28	01.40	0.23	0.760	1.7	0.53	-	-	-	19.21
18	**4**	8.0	0.05	0.64	0.96	98.40	00.00	0.27	0.840	2.4	0.57	-	-	-	21.90
19	**4**	15.0	3.85	0.57	0.85	98.58	00.00	0.26	0.820	2.3	0.56	-	-	-	22.03
20	**5**	5.0	0.10	1.18	1.18	80.79	16.85	0.32	0.930	2.8	0.61	-	-	-	19.25
21	**4**	4.5	0.25	0.53	0.80	93.39	05.28	0.26	0.820	2.3	0.56	-	-	-	22.03
22	**2**	15.0	0.05	0.97	0.24	97.58	01.20	0.29	0.860	2.6	0.57	-	-	-	22.26
23	**5**	25.0	0.00	0.75	0.75	82.60	15.90	0.28	0.860	2.6	0.58	-	-	-	21.66
24	**5**	3.0	0.00	0.94	0.94	78.92	19.21	0.30	0.900	2.7	0.59	-	-	-	20.47
25	**4**	4.5	0.20	1.24	1.86	94.28	02.62	0.32	0.920	2.8	0.61	-	-	-	19.28

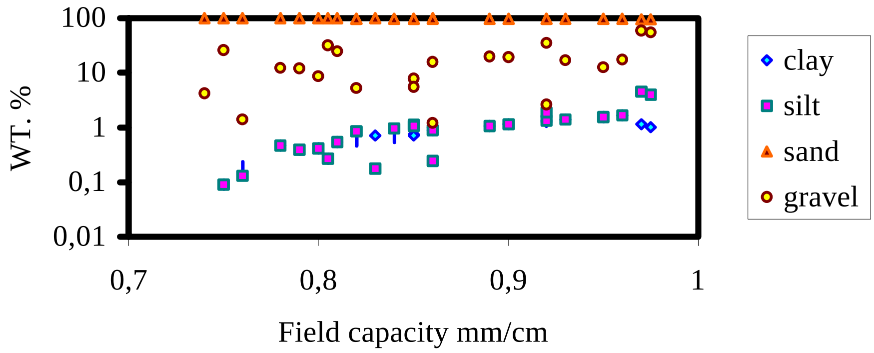


Figure (20): Correlation between soil sizes and soil field capacity in the study area.

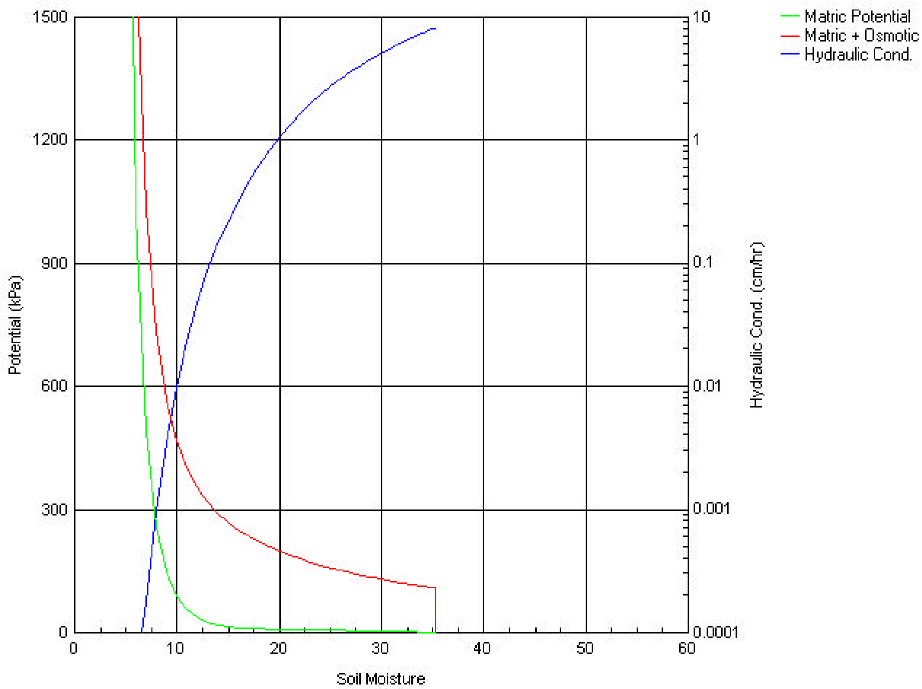


Figure (21): The major behaviour of the soil samples in terms of moisture curves. (Using Saxton Program).

2.3.6 Infiltration Study

Infiltration measurements characterize soil ability to absorb water through the ground surface. They provide data for models predicting infiltration and surface runoff behavior following rainstorms allowing estimates of soil-water and groundwater storage. Measurements of infiltration from surface ponds contained within rings pressed into the soil to prevent flooding outside the ring area are most commonly used in field investigations of infiltration behavior. (Youngs,1991).

Nassif and Wilson carried out extensive studies on infiltration using a weighable laboratory catchment 25 square meters. They concluded that for any soil under constant rainfall, infiltration rate decreases in accordance with an equation of the first form, used by Horton (Wilson,1990).

$$f = f_c + m e^{-kt}$$

where f = infiltration rate at any time t (mm/h).

f_c*= infiltration capacity at large values of t (mm/h).*

$m = f_0 - f_c$

f_0 *= initial infiltration capacity at t = 0 (mm/h).*

t = time from beginning of rainfall (min).

k = constant for a particular soil and surface (min. $^{-1}$*)*

k is a function of surface texture; if vegetation is present k is small, while a smoother surface texture such as bare soil will yield larger values.

f_0 *and* f_c *are functions of both soil type and cover.*

f_c is a function of slope *(negative relation),* initial moisture content *(negative relation),* and rainfall intensity *(positive relation). The cause that the rain intensity has a strong positive relationship with the infiltration capacity is that the heavy rain can sustain the formed vertical water heads on the present connected pores and burrows, which put the water under pressure and forces it to soak down strongly.*

For a one storm event taking place on a specific catchment area with a start time 0 and end time t, the total infiltration loss F_p can be calculated by integrating the Horton's equation for the duration of the storm;

$$F_p = \int_0^t f.dt = \int_0^t [f_c + (f_0 - f_c)e^{-kt}]dt$$

Runoff can be calculated by subtracting the value F_p and the actual evaporation from the total rainfall in the area of interest. Typical minimum infiltration rates of different soil types are shown in Table (10).

Table (10): Typical minimum infiltration rates of different soil types.

SOIL	MINIMUM INFILTRATION RATE *(mm/hour)*
Deep sands, aggregated silts	More than 20
Deep sandy loams	10-20
Clays loams, shallow sandy loams, soils low in organic matter	5-10
Clay	1-5

Direct field experiments in different locations in the study area were carried out to estimate the infiltration rates of the soil. The measured locations were selected in a specific pattern in

order to approach all the land forms of the study area in terms of their infiltration rates. They were applied using a simple iron infiltrometers rings of 12 cm height and 9.5 cm diameter, that were carefully inserted for about 5 cm in the soil, lest to disturb its fabrics. A ruler was fixed along the internal surface of the ring, where a stop watch was used to plot the infiltration rates against time immediately after pouring the water into the ring.
15 experiments were carried out, the total time for each one was 16 minutes; which is the normal period of precipitation events in the study area.

Figure (22) shows the results for the different places in the study area. The results for a time of 16 minutes ranged between 35 cm/hour and 6 cm/hour. It seems that the curves tend to decrease to less than that if experiments continue. But with that it is possible here to take some indications about the behavior of the soil in the study area. The rates are relatively high since the standard infiltration rates for the sandy soils are normally between 2 cm/hour and 10 cm/hour. Table (11) shows the rates of infiltration plotted against the time for every investigated location.

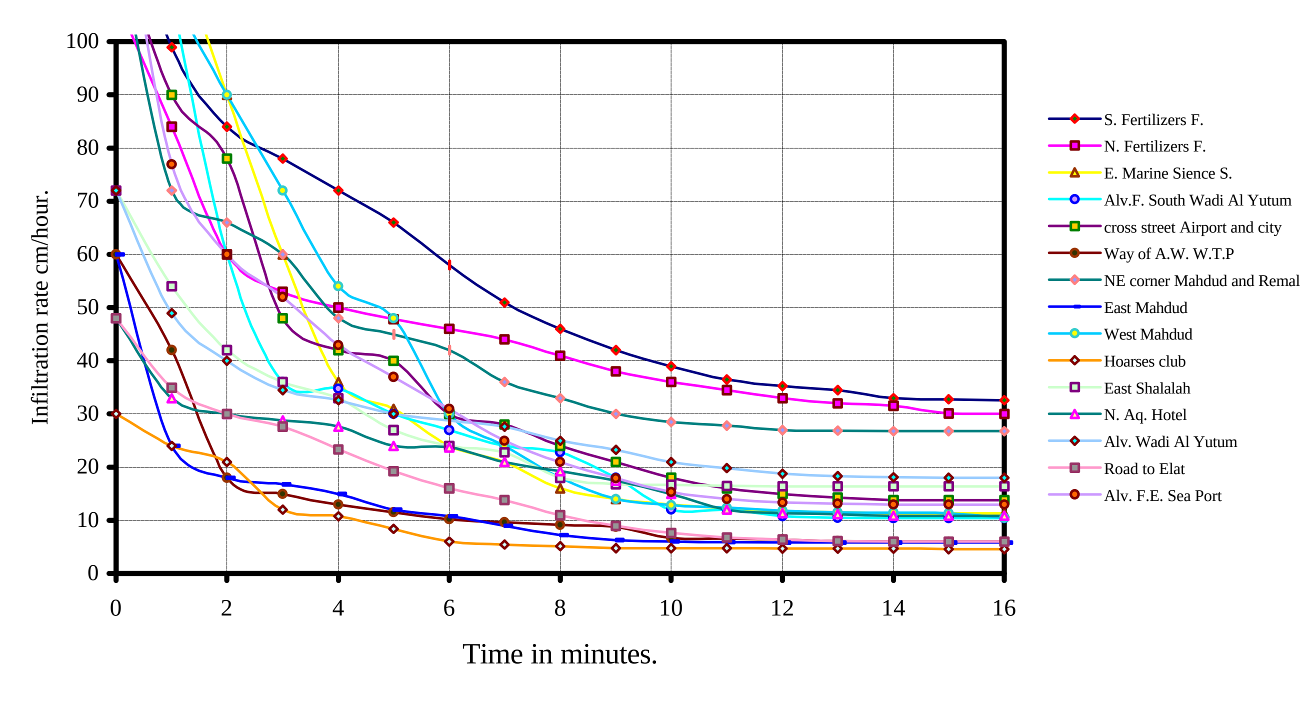


Figure (22): Resulted infiltration rates in the different parts in the study area.

<u>Spatial trends of infiltration values can be noticed. The general trend is that infiltration capacities decrease downward the stream deposits. The cause is attributed to the relative abundance of the coarse deposits in the upstream areas which enhances the process of water infiltration.</u>

The dust particles that come from the southern part of the study area; industrial zone and sea port support the surface of alluviums with small particles which may clog the existing voids and burrowing which ease the infiltration process. The impact is increases in the runoff amounts in this zone, which with it’s contains from washing materials and heavy metals may be driven into the Gulf water.

Table (11): Infiltration rates against time in the study area.

TIME MIN.	S. FERTILIZERS	N. FERTILIZERS	E. MARINE SIENCES.	ALV.F. SOUTH WADI AL YUTUM	CROSS STREET AIRPORT AND CITY	WAY OF A.W.W.T.P	NE CORNER MAHDUD AND REMAL	E. MAHDUD	W. MAHDUD	HOARSES CLUB	EAST SHALALAH	N. AQ. HOTEL	ALV. WADI AL YUTUM	ROAD TO EILAT	ALV.F. EAST SEA PORT
		Rate of Infiltration in cm/ hour													
0	132	108	150	156	120	60	120	60	120	30	72	48	72	48	135
1	99	84	120	108	90	42	72	24	108	24	54	33	49	35	77
2	84	60	90	60	78	18	66	18	90	21	42	30	40	30	60
3	78	53	60	36	48	15	60	16.8	72	12	36	28.8	34.5	27.6	52
4	72	50	36	34.8	42	13	48	15	54	10.8	33	27.6	32.6	23.3	43
5	66	47.8	31	30	40	11.5	45	12	48	8.4	27	24	30	19.2	37
6	58	46	24	27	30	10.2	42	10.8	30	6	24	23.7	28.8	16	31
7	51	44	21	24	28	9.6	36	9	24	5.4	22.8	21	27.6	13.8	25
8	46	41	16	22.8	24	9.1	33	7.2	18	5.1	18	19.2	25	11	21
9	42	38	14	18	21	8.8	30	6.3	14	4.8	16.8	17.4	23.2	9	17.9
10	39	36	13	12	18	6.7	28.5	6	12.9	4.73	16.65	15	21	7.6	15.3
11	36.5	34.5	12.2	12	16	6.55	27.8	5.9	12.4	4.725	16.5	12	19.8	6.8	14
12	35.2	33	11.7	10.8	15	6.4	27	5.85	11.8	4.7	16.42	11.3	18.8	6.35	13.36
13	34.5	32	11.5	10.5	14.3	6.1	26.9	5.8	11.55	4.68	16.39	11.1	18.3	6.1	13.15
14	33	31.5	11.38	10.4	13.85	6	26.8	5.8	11.45	4.62	16.38	10.89	18.1	6	13
15	32.8	30.1	11.37	10.39	13.8	6	26.75	5.8	11.3	4.6	16.37	10.86	18	6	13
16	32.6	30	11.35	10.38	13.78	6	26.73	5.8	10.5	4.6	16.365	10.84	18	6	13

2.3.7 Permeability Study

Permeability refers to the rate at which water moves through soil. Permeability is controlled by the size and continuity of the soil pores. The factors that influence soil permeability include;

- *Texture*
- *Organic matter*
- *Structure*
- *Roots and animal activity*
- *Density*

Soil texture refers to the proportions of sand, silt, and clay in a soil. Coarse-textured sandy and gravelly soils have the largest pores and the most rapid permeabilities. Fine-textured clayey soils have very tiny pores and very slow permeability rates. Medium-textured loams, silt loams, and clay loams have intermediate rates of soil permeability.

Organic matter helps create and stabilize aggregates of the grains of sand, silt and clay. These aggregates or units of soil structure have relatively large interstice them permitting rapid water movement.

Roots and burrowing insects and animals create large voids or "macropores," that can transmit water very rapidly under saturated conditions. Macropores are also common in very coarse-textured soils and in soils that crack extensively upon drying.

Macropores are especially important where they are connected to the soil surface. Heavy rainfall or irrigation events may create temporarily saturated surface soil, which can lead to rapid flow through macropores. If soluble pollutants also are present, they can be carried deep into the soil in a short time. If pollutants are bound tightly to soil particles, however, macropore flow may reduce groundwater vulnerability because water moving through macropores does not have a chance to react as an example with pesticides and remove them from the soil. Tillage generally reduces the number of macropores that are open to the soil surface.

Dense, compact, or cemented soil layers have very slow rates of permeability. Permeability of soil in its natural setting is highly variable and extremely difficult to measure.

Permeability rates are given in inches per hour. Typical rates are 0.01 inches per hour for compact clay, 0.5 inches per hour for a loam with good structure, and 15 inches per hour for a loamy sand.

Soil permeability rates are published in each county soil survey report. These rates are mostly estimates based on soil properties, rather than the results of actual measurements, but they are useful for evaluating leaching potentials of different soils.

Soil permeability can be determined in a laboratory by measuring the rate of flow through a column of soil under a constant head of water.

(http://physics.uwstout.edu/geo/perm_dewat.htm)

2.3.8 Modeling on Permeability

Calculated and measured saturation hydraulic conductivity of surface soil samples are given in Table (12). Positive correlation of 0.7 between the modeled values (depending on soil texture) and the measured values of the samples that were carried out in (May/2000) was found. Figure (23) shows the relation between both values.

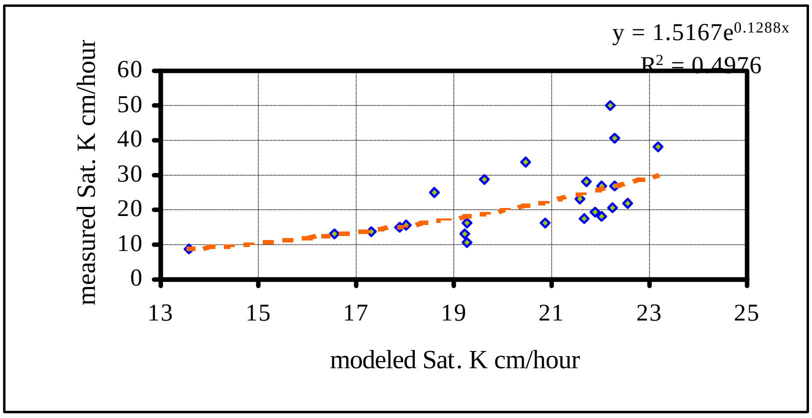


Figure (23): Correlation between modeled and measured values of the soil permeability.

2.3.9 Soil Water Chemistry

Soil chemistry was studied by taking samples along north-south profile crossing the study area. The profile started in the area directly south of Aqaba International Airport passing through the city, the Aqaba sea port into the industrial zone in the southern part. Three samples were taken in each location at different depths in order to investigate the soil attenuation capacity relevant to the different pollutants with depth. Four depths were chosen; surface sample, 33 cm sample, 66 cm and one meter depth sample. Thirty grams of every soil sample were washed with one liter of distilled water for 24 hours continuous shaking. The results were multiplied by a factor of 33.3.

Table (12): Spatial distribution of measured and modeled soil permeability values.

SAMPLE NOMBER	X LOCATION	Y LOCATION	SAT .H.C CM/HOUR MODELED	SAT. H.C CM/HOUR MEASURED
1	157178.582	887029.546	16.55	13
2	157232.997	890372.023	17.31	14
3	155134.13	890426.436	17.9	15
4	151737.073	890636.312	22.3	27
5	149132.923	888179.98	20.87	16
6	153299.564	883655.975	18.03	16
7	151853.677	885280.575	13.6	9.0
8	150197.904	885575.957	18.62	25
9	149249.526	884246.739	21.59	23
10	149164.017	886493.195	22.28	41
11	148067.942	886734.164	21.7	28
12	147624.847	887293.835	85 ?	37
13	147741.451	886050.122	23.16	38
14	151674.885	881526.117	22.18	50
15	150819.79	881821.499	22.54	22
16	149785.904	881673.808	19.63	29
17	149070.734	883477.192	19.21	13
18	148658.734	883687.068	21.9	20
19	149164.017	882886.428	22.03	18
20	148604.319	884192.326	19.25	11
21	149809.225	883065.212	22.03	27
22	146948.546	863437.872	22.26	20
23	147096.244	866243.999	21.66	18
24	152086.885	885226.162	20.47	34
25	148391.213	884834.343	19.28	16

The northern part is assumed to be free of pollution, while the southern one is assumed as a polluted zone. Therefore, the impacts of industries can be approached by comparing those hydro-chemical results of the northern part with those of the southern part.
The chemical composition of the soil water is a function of rain water chemistry, geochemical aspects of the soil itself, dissolved gases within the present solutions, present organic matter and the impacts of urbanization and industry. Table (13) shows the resulted hydro-chemical analyses on the soil sampling depths of the different locations in the study area.
The results were represented in term of every sampling location with the different depths as the percentage distribution of the chemical constituents. (Figure 24). They were plotted in a correlation diagrams aiming to show the different proceeding fits between the different items. (Figure 25).
To show the quality of the soil water in the study area the results were brought to Piper Diagram. Figure (26).
The plots revealed two major groups of soil water; one locates on the contact between the earth alkaline water with increased portion of alkalies with prevailing sulphate and the other of alkaline water with prevailing sulphate-chloride. The second group locates on the contact between the normal earth alkaline water with prevailing bicarbonate, and the earth alkaline water with increased portion of alkalies and prevailing bicarbonate.

Table (13): Hydrochemical analyses results of the soil cover in the study area.

		CHEMICAL ANALYSES											
Sample Location	**Depth of sampling cm.**	**EC** µS./cm	**T.D.S** p.p.m	**Ca++** Meq/l	**Mg++** Meq/l	**Na+** Meq/l	**K+** Meq/l	**Cl-** Meq/l	**SO4--** Meq/l	**CO3—** Meq/l	**HCO3-** Meq/l	**NO3-** Meq/l	**PO4---** p.p.m
South of Aqaba International Airport.*	**0**	2164.5	1398.6	45.954	14.319	21.978	1.665	4.662	19.980	3.660	24.980	40.293	5.690
	33	1798.2	1165.5	57.610	8.658	12.990	1.665	4.662	1.332	3.660	40.300	40.960	8.523
	66	1864.8	1198.8	22.980	5.660	10.320	1.670	8.000	0.670	7.000	35.630	33.300	5.594
	100	1559.2	1026.7	20.531	6.112	9.670	1.630	9.500	0.380	7.320	30.754	30.142	4.566
South of Phosphate Sea Port.	**0**	47186.1	30669.3	172.161	51.615	401.265	67.600	325.674	20.313	0.000	53.280	27.640	12.250
	33	30036.6	19513.8	85.914	120.880	285.381	9.657	124.875	83.250	7.000	13.990	43.623	10.823
	66	27541.2	16324.1	81.231	112.210	156.110	4.219	85.544	75.632	7.012	9.668	45.634	13.320
	100	9072.8	6221.4	27.016	45.260	56.834	2.864	33.731	15.142	6.502	14.964	38.914	13.694
South of Aqaba Main Sea Port.	**0**	17549.1	11388.6	63.270	62.940	74.260	50.280	67.930	50.280	0.000	46.290	29.604	6.990
	33	4213.1	2985.2	42.618	30.954	105.642	8.146	24.330	46.376	8.512	38.305	34.513	8.532
	66	3564.7	2564.0	34.427	15.337	63.4329	4.950	9.745	7.632	3.012	20.441	38.681	7.664
	100	2546.6	1564.9	26.541	7.803	10.124	3.842	6.001	3.864	3.837	15.641	31.100	5.230
North of the Fertilizers Factory.	**0**	3363.3	2164.5	40.293	86.250	16.320	3.330	7.990	4.662	3.663	28.305	28.971	8.924
	33	1431.9	932.4	16.983	51.615	8.991	0.666	9.324	11.322	6.993	28.305	40.626	5.894
	66	1764.9	1132.2	40.293	17.316	26.640	0.999	6.327	1.1320	10.656	31.968	38.295	8.924
	100	1502.6	1002.4	35.600	11.332	21.300	0.789	5.421	1.021	7.221	20.364	28.541	4.954
South of Fertilizers Factory.	**0**	17316.0	11255.4	40.293	132.201	72.594	14.985	12.654	5.661	0.000	17.649	27.639	11.122
	33	2830.5	1831.5	51.615	34.299	75.591	32.967	6.327	156.177	6.993	24.975	32.967	9.191
	66	2464.2	1598.4	28.638	28.638	23.310	3.663	9.324	0.666	3.663	24.975	39.627	9.058
	100	2197.8	1398.6	34.299	5.661	130.869	2.997	7.992	39.294	3.663	17.649	30.636	8.891

.reference values (out of any urbanization impacts).

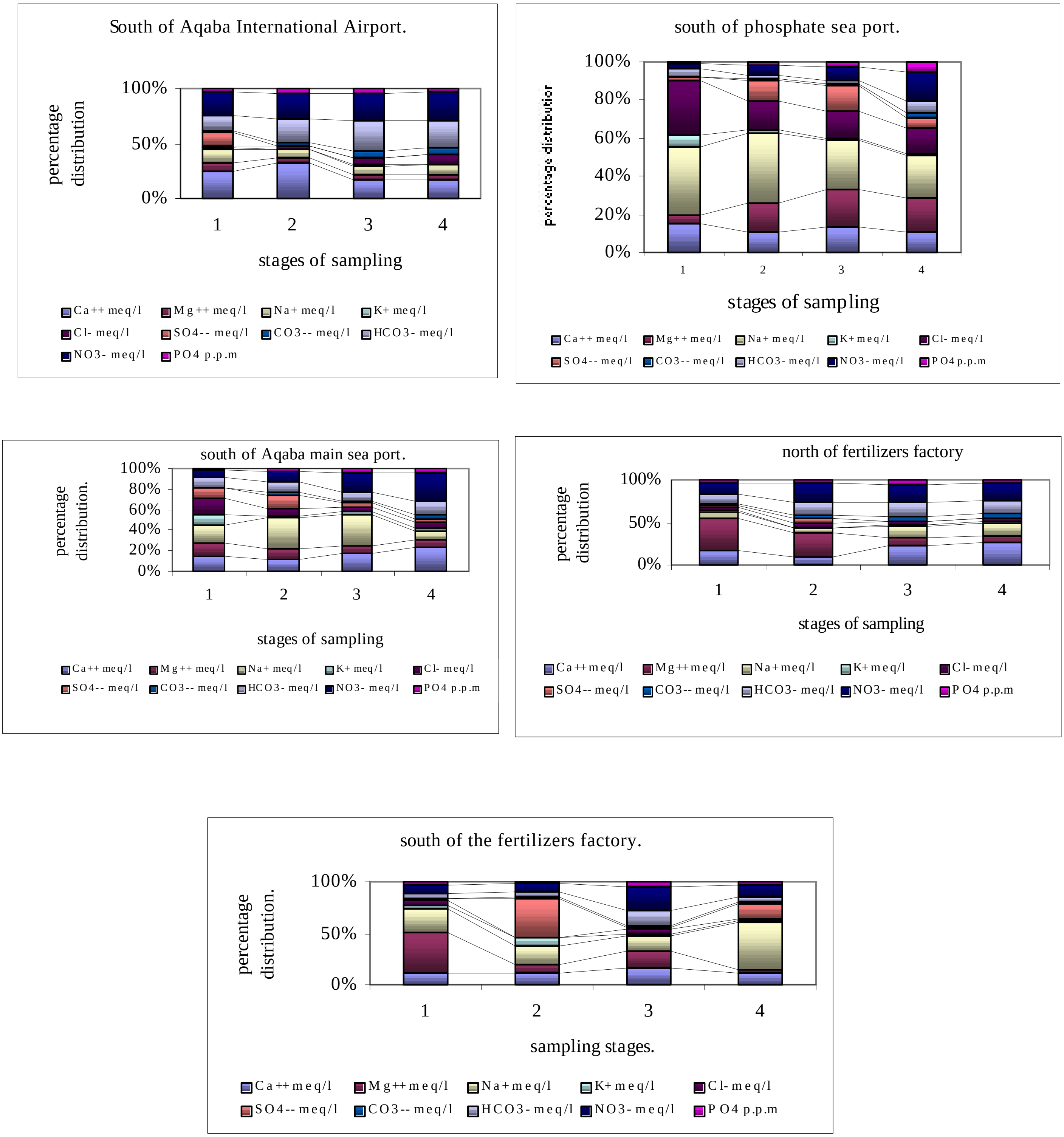


Figure (24): Relative abundance of chemical constituents in soil depths.

Figure (25): Correlation between the different soil water constituents.

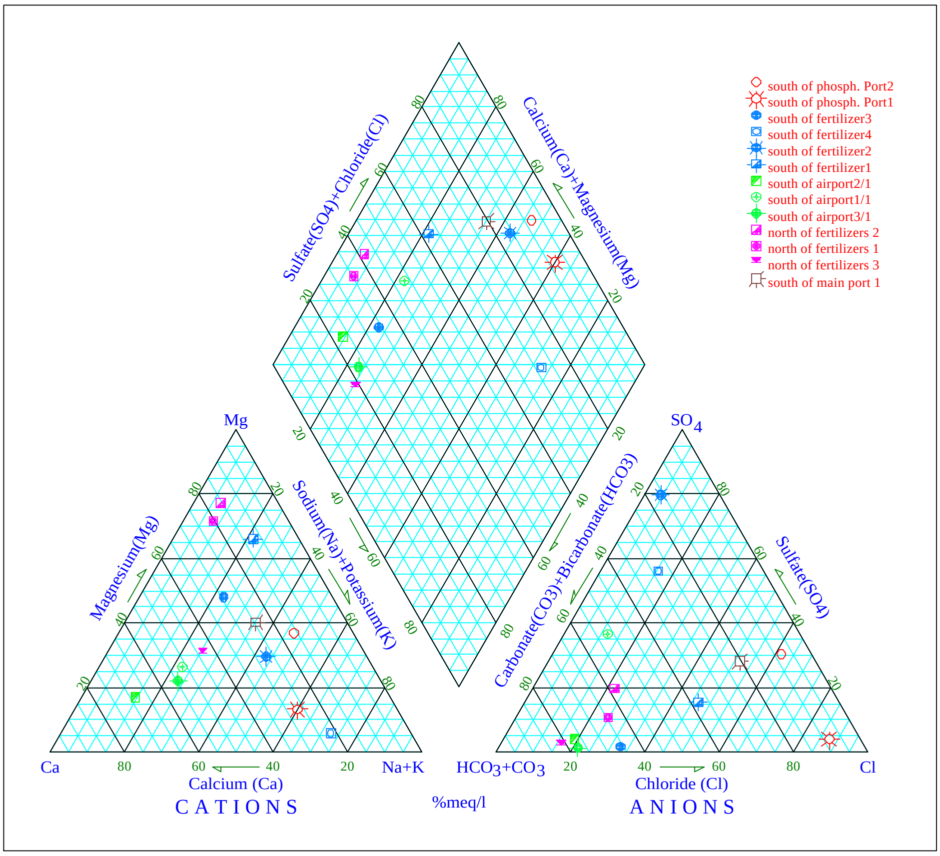


Figure (26): Piper diagram for soil water types.

2.3.10 Buffering Capacity Study of Soil Zone

The concentration of chemical components with depths does not follow a stable decreasing pattern in the soil of the study area. This refers to the presence of finer texture layers which receive and/or retard the down ward percolation of dissolved chemicals.

A method was used to estimate the buffering capacity of the different soil depths against pollutants. The concentrations of $PO4^{3-}$ in part per million (ppm) for each sampling location and depth were plotted in a diagram. The concentrations seem generally to decrease with depth, where the surface samples were considered as the **reference** concentration for each location. The mathematical slope for each location was considered as the natural buffering capacity with depth. (Fig. 27)

The transported phosphate (Abatite (Ca5[F,Cl,OH) (PO4)3]), which comes from the sea port of Aqaba from porting process was reflected on the soil water quality as tetra phosphate $PO4^{3-}$. For the marine ecology this chemical item is a major cause of eutrophication.

Figure (28) shows the behavior of concentrations with depths, while Table (14) shows the resulted mathematical trends.

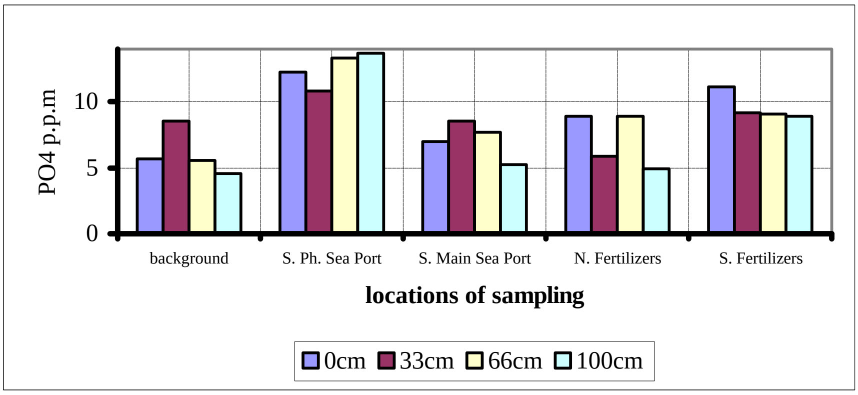


Fig. (27): $PO4^{3-}$ concentration for the different locations and depths (ppm).

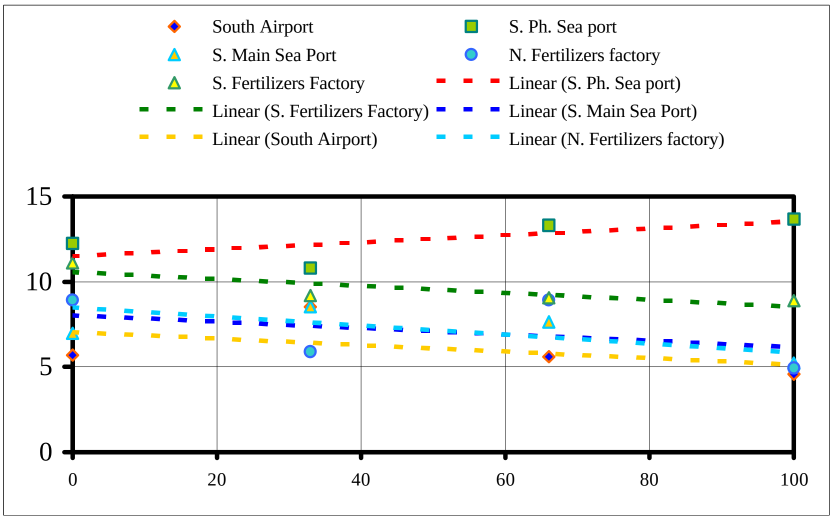


Figure (28): Trends of concentrations with depths in term of tetra phosphate, for the different sampling locations.

Table (14): Mathematical relationships illustrating the buffering capacity of soils to tetra phosphate.

LOCATION	EQUATION OF BUFFERING CAPACITY	CORRELATION COEFFICIENT
S. Aqaba Airport (Ref. Conc.)	$Conc.=-0.0190*Depth+7.0398$	$R^2=0.2321$
S. Ph. Sea Port	$Conc.=0.0205*Depth+11.5$	$R^2=0.4703$
S. Main Sea Port	$Conc.=-0.0186*Depth+8.031$	$R^2=0.3275$
N. Fertilizers Factory	$Conc.=-0.0268*Depth+8.5086$	$R^2=0.3144$
S. Fertilizers Factory	$Conc.=-0.0204*Depth+10.582$	$R^2=0.7069$

Depths in cm. Concentrations in ppm.

2.4 Hydrology

2.4.1 Introduction

The average total amounts of rainfall during the rainy months of the year in Aqaba do not 37 mm. Rare frequent thunder storms sweep the area carrying casual intense precipitation in these rainy months resulting in total annual rainfall exceeding the previously mentioned value. The long periods of daily sunshine and the high temperatures around the year, the little vegetation cover enhance the process of actual evaporation, which makes direct recharge of groundwater rare. On the other hand the high infiltration rates, low soil field capacities, coarse textures (classified mainly as sands) and the revealed weakness structural zones as lineaments and active faults and the shallow groundwater table allow good parts of precipitation to percolate down to the groundwater body forming recharge. The high permeability of wadi beds and the contents of sand and gravel within the alluvial terraces provide good conditions for direct and indirect recharge.

Due to the low precipitation amounts, high infiltration rates and consequently the high actual evaporation and gentle slope, runoff does not exist often, but only when an intensive rainfall event sweeps the area. On the other hand, the barren impermeable rocks and steep slopes of the highlands provide good conditions for runoff.

Side wadis possess relatively wide surface watershed areas. They have extensions in areas where the annual rainfall is more than that of the Aqaba area. The high elevated granite mountains receive more amounts of precipitation due to their elevation. Accordingly the floods come from the eastern part along the alluvial fans especially during thunder storms, and form a risk.
Aiming at studying the surface water balance, calculations on the available field measurements and laboratory studies on the soil parameters, hydrological modeling on the digital elevation models (DEM), and long period –20 years- analysis of the daily meteorological registers of the study area were carried out.

2.4.2 General Climate Conditions in Aqaba

The study area is best described in term of its climate as arid; while max. annual precipitation values do not exceed 50 mm in the best conditions and are restricted to the winter season, the potential pan evaporation is estimated 4100 mm/year, (Ministry of Water & Irrigation Jordan, 1995). These factors give the area the dryness character, and the soil its salinization. With that, thunder storms can sweep the area in winter to create run off and then rapid surface flash floods. These are the responsible factors for the occurrence of recent wadi shapes within the deposits along the coastal area.

Wind direction in the study area is mostly directed from north to north-north west to south to south-south west. Dust and sandy winds are rare, average wind speed ranges from 11.5 to 23 miles per hour, it has a noticed role in dropping the humidity. South winds are rare. Since it crosses the hyper dry area of Wadi Araba it is very dry.

Relative humidity is high in winter time, it decreases during the hot summer months. Anyway it is characterized by being low during most of the year, and especially in the summer months when the temperature is high. Usually it is between 28-30% which makes Aqaba stand out among other cities on the Red Sea.

Sunshine The sunlight is intense especially in summer times. The highest sunshine hours are registered in May, June and July, and the lowest in December, January and February.

Table 15 gives the mean annual values of weather parameters in Aqaba for the period 1985 to 1997. (Airport weather station north of the city of Aqaba).

Table (15): Mean annual values of the weather parameters in Aqaba for the period 1985 to 1997. (Airport weather station north of the city of Aqaba).

Year	TEMPERATURE "°C"	PRECIPITATION "MILLIMETER"	RELATIVE HUMIDITY %	WIND SPEED "KNOT"	WIND DIRECTION "DEGREE"	SUNSHINE "HOURS"
1988	24.2	37.7	46.8	9.8	No data	9.2
1989	23.8	27.9	51.1	9.2	No data	9.6
1990	24.2	48.3	40.8	9.5	No data	9.7
1991	24.2	38.9	44.2	7.4	No data	9.3
1992	23.2	15.2	45.9	8.9	296.1	9.0
1993	24.1	46.9	45.4	10.0	295.4	9.3
1994	24.5	52.7	47.5	9.6	284.3	9.4
1995	24.1	11.1	48.9	10.2	262.2	9.6
1996	24.7	2.1	51.9	9.9	260.9	8.5
1997	24.0	41.1	52.3	8.8	178.8	9.2

2.4.3 Precipitation; Nature and Amounts

The rainfall season usually lasts from October to April, with the wetter period in December to February. The general trend of rainfall distribution along the most southern part of Jordan is of a decreasing pattern.
Five rainfall gauging stations are found in the study area and its surroundings. Table 16 shows that altitudes have positive impacts on the rainfall amounts. Fig. (29).

Table (16): Average total annual rainfall in mm/y with elevations contrasts.

STATION	ELEVATION (METER A.S.L)	Y -LOCATION	X -LOCATION	AV. TOTAL ANNUAL RAINFALL IN MILLIMETER.
Rum (QA Disi)	790	896000	199800	86
Ras En Naqab	1570	935000	197000	149
Quweira	800	914000	181000	66.3
Aqaba	40	881000	150000	37
Rahama	105	926000	162000	52

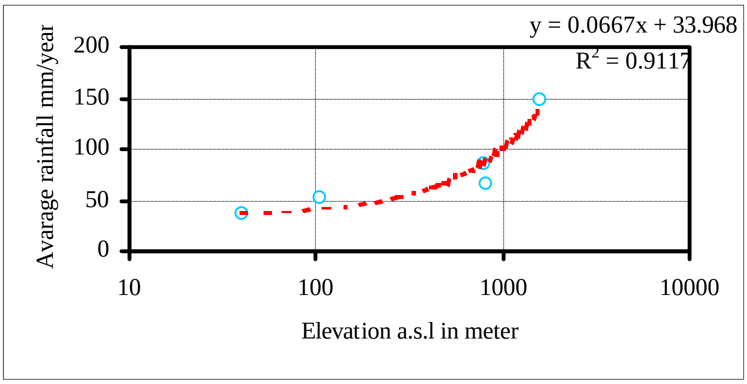


Figure (29): Correlation between elevation and annual rainfall amounts of different rainfall gauging stations in the neighborhood of the study area.

The correlation resulted in the following equation;

Average total rainfall (mm/year) = [0.0667 (elevation above sea level in meters) +33.968]

Both values are in high correlation with a correlation factor of 0.9177. Depending on this local positive relationship, it is possible to estimate the amounts of the average total annual rainfall over the elevated granite mountain series to the eastern of the study area. These are of an average elevation of 1200 meters, accordingly and by substituting in the former equation;

Average total rainfall mm/year = [0.0667*(1200 m) +33.9681]
Average total rainfall = 114 mm/year

This value represents what can the granite mountain series east of Aqaba receive due to their elevations. No rainfall data have been ever collected from this mountain series, but the extended side wadis which receive floods from these mountains can confirm this estimated value.
The logical spatial distribution of the results of Table 16 allows to construct the spatial distribution of rainfall (Fig. 30).

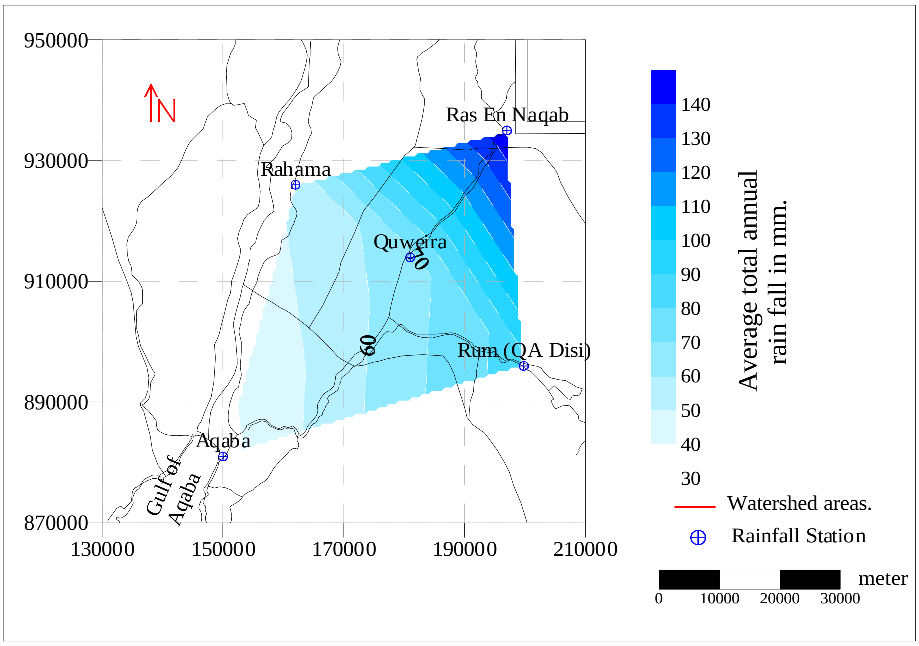


Figure (30): Spatial distribution of rainfall (mm/year).

Udluft, (2001) through a water balance modeling software put a standard value to estimate the rainfall in term of elevation, he supposed that the rainfall factor is going to increase with 4.4% from the reference value of a rainfall gauging station, for every 100 meters of elevation. (4.4[%/100m]). The analysis of the daily rainfall data of the last 20 years (1980-1999) (Figure 31) indicates that under normal precipitation the daily rainfall doesn't exceed about five millimeters per a day. But under the occurrence of thunder storms these can approach values of around 15 mm/day.

The highest daily value that have been registered was in the year 1980, it was more than 42 mm. Relative to the produced curve and the study area, some years are dry years and other years are wet years. The time of the **re-occurrence** of the dry and wet years along the 20 years follows a specific pattern; between every two peaks of rainfall –wet years- exist 4–2 dry years.

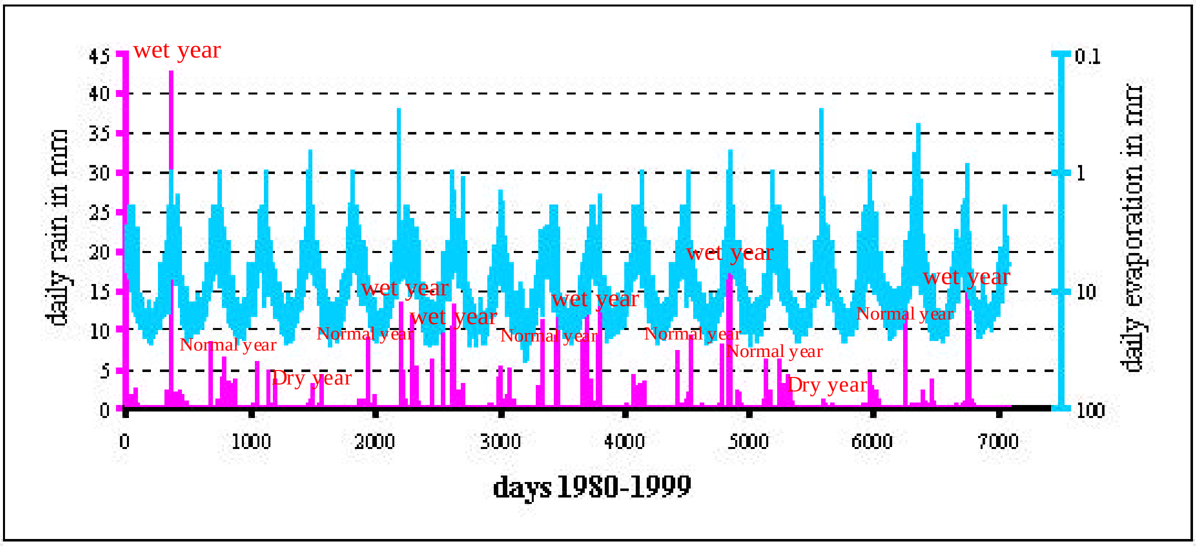


Figure (31): Daily rainfall and evaporation distribution in the study area (1980-1999).

<u>Statistics on the daily rainfall for the years 1980-1999</u>:

Number of values	7079
Number of missing values	0
Sum	664.2
Minimum	0
Maximum	42.5
Range	42.5
Mean	0.094
Variance	0.994
Average deviation	0.182
Standard deviation	0.997
Coefficient of variation	10.63

Looking at the produced curve of the daily rainfall from 1980-1999; the nature of rain distribution during the year seems to be restricted to 4 – 15 events, the total harvest of every one event ranges from 2-15 mm. The total of these events forms the annual rainfall for one year, which is about 37 mm/year. Depending on the previous analysis, the values of rainfall amounts which represent the **dry**, **normal and wet years** in the study area are; **10 mm/year, 37 mm/year and 48 mm/year** respectively.

2.4.4 Potential Evaporation in the Study Area

The pan annual potential evaporation is measured by the class A-pan. The ***annual potential evaporation*** of Quweira and Rum (Qa Disi) stations is 3478.45 mm and 3383.55 mm/year respectively, while the Aqaba station has the value of 5409.3 mm/year.

Figure (31) shows the distribution pattern of the daily potential evaporation records. It is clear here that the lowest values are attributed to winter period, and those high values are attributed to summer season.

Statistics on the daily evaporation data from1980-1999 of Aqaba station:

Number of values	7079
Number of missing values	0
Sum	86011.80
Minimum	0.3
Maximum	40
Range	39.7
Mean	12.15
Variance	39.72
Average deviation	5.376
Standard deviation	6.303
Coefficient of variation	0.519

2.4.5 Actual Evaporation

The ***actual evaporation*** is what the available surface water and/or soil water lose with respect to the evaporation potential of a specific area. The potential evaporation measuring in the majority of the methods assumes that the water is available all the time, the difference from day to day in the water head in the measurement tool, is attributed directly to the potential evaporation. (Wilson, 1990).

In the study area, the surface fresh water is not available, but only during the rainfall times, very short periods after the storm. Accordingly the actual evaporation is greatly affected by the soil cover captured rain water and field capacity.

Udluft (1994) developed a modeling software (MODBIL) to estimate the amount of direct recharge. Several parameters have been used in the software (see the section of recharge) actual evaporation was one of them. MODBIL depends the following formula to estimate the actual evaporation

$$\mathbf{AE = (PE * (8.5\ SP^{\exp o}))/100}$$

Where

AE : Actual evaporation.
PE : Potential evaporation.
SP : Soil saturation in percent.
$^{\exp o}$ *: Vegetation Factor.*

Soil saturation in percent is the percent value of the soil field capacity FC. The vegetation factor $^{\exp o}$ depends on the prevailing vegetation art of the area of concern. It equals 0.5329 for field areas, while it equals 0.57488 for forest areas.

The actual evaporation was estimated for the study area using MODBIL to be as 37.3 mm/year. The study was applied on the years 1980-1999. It seems here that the actual evaporation consumes theoretically more than the average total annual rainfall of the study area, where the excess is attributed to the natural soil-water moisture contents.
The actual evaporation is considered by the Water Authority of Jordan on 1995 in the Wadi Al Yutum catchment area, as 98%, 95% and 92% of precipitation for the dry, normal and wet years respectively.

2.4.6 Run Off

The most important property of the catchment in respect to runoff is the soil cover, its depth, permeability and slope (Wilson, 1990). The analyses of aerial photos indicated that erosion features as a result of floods and runoff are more concentrated in areas located directly downwards of side wadis, which receive the flood water from the elevated granite mountains catchments.
The low daily rainfall amounts in the rainy season, which were averaged as 5 mm can not inherit runoff. Accordingly the direct runoff in the study area in the dry and normal years is negligible. Indirect runoff is attributed to the floods coming from side wadis.

Delayed runoff defined as that portion of gravity water captured in the soil, but not joining the groundwater body and held over shallow clayey size lenses. The erosion and tectonic processes in the area (especially in the alluvial fans), outcrop the lower part of these lenses. The collected water over them flows by gravity to form run off. Confirmation on that can be derived from the aerial photos of the study area, where a lot of desert plants are present in the dry non-urbanized areas.

2.4.7 Infiltration

Not all of the infiltrated amounts of water soak into the groundwater body. Parts of which evaporates gets evaporated, and another part stays in the soil as soil field capacity – depending on the soil texture-. After reaching the degree of soil field capacity, the gravity water starts to percolate down. The in-excess of actual evaporation and both the soil field capacity and gravity water during the storm forms run off. The portion of water captured within the soil matrices by the soil filed capacity is reached after some days of the precipitation event. This amount of water is divided into two parts; a part gets evaporated, and the other part percolates slowly to the groundwater body.
Depending on the previous calculated value of actual evaporation, infiltration does not exist, because evaporation exceeds the average total annual rainfall values. But this value of actual evaporation modeled in the software MODBIL presumes that the soil possesses natural amounts of moisture. Accordingly the actual evaporation should be less than that estimated value. Another cause encourages to take higher values of infiltration is the high results of the field measured infiltration rates, and the presence of faulting processes within the alluviums.
The total area of interest is 270 km^2, including the northern and southern parts. General estimations of the direct surface water budget, were approached in respect to the dry, normal and wet years of rain (Table 17).

Table (17): Surface water budget of the study area, for the wet and dry years.

RAINY YEAR TYPE	RAINFALL MM/YEAR	ACTUAL EVAPORATION			RUNOFF			INFILTRATION			ANNUAL RECHARGE
		mm/y	%	MCM/y	mm/y	%	MCM/y	mm/y	%	MCM/y	LITER/M ^{2}
Dry	10	9.9	99%	2.673	0.00	0.0%	0.0	0.1	1%	0.027	0.1
Normal	37	35.89	97%	9.6903	0.37	1.0%	0.0999	0.74	2%	0.1998	0.74
Wet	48	44.64	93%	12.0528	0.96	2.0%	0.2592	2.4	5%	0.648	2.4

The infiltration was calculated using the simple equation of the water budget.

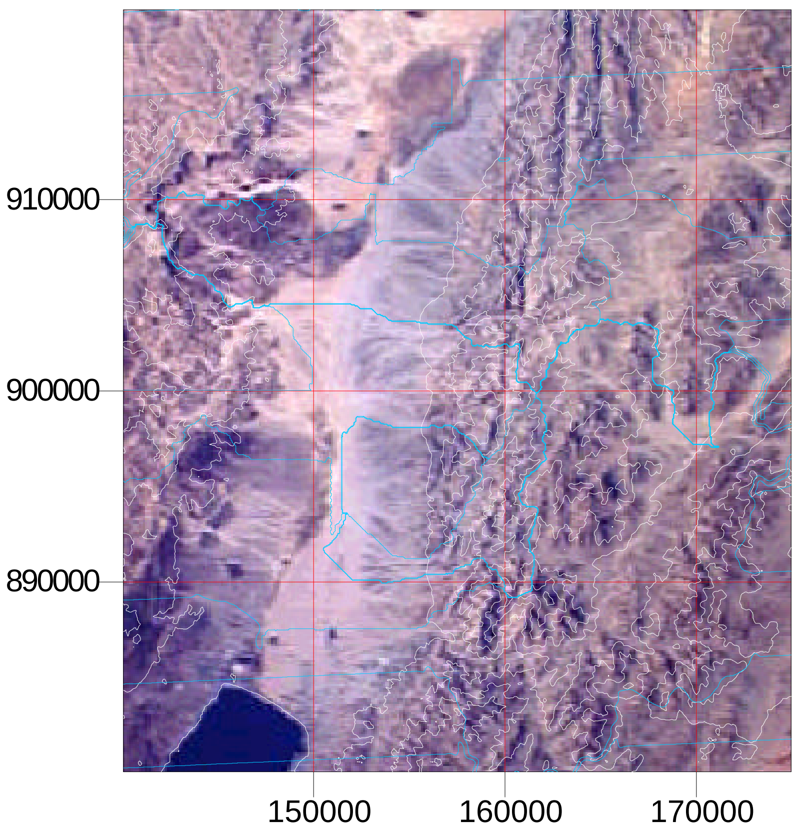
$$\text{Precipitation} = \text{Evaporation} + \text{Runoff} + \text{Infiltration}$$

$$\textbf{Infiltration} = \textbf{Precipitation} - (\textbf{Evaporation} + \textbf{Runoff})$$

The modeling results in Table (17) which approaches the existing situations respecting the values of precipitation. These values are general because other factors enhance also the process such as the floods which come from side wadis. This generalization leads to the concept of direct and indirect types of recharge. In the coming sections the conceptuality of the indirect type of recharge will be discussed.

2.4.8 GIS Modeling on Surface Watersheds and Drainage System in Aqaba

To approach the value of the indirect recharge to the groundwater relating it to land slope, land form, soil parameters, ability to receive additional indirect water as floods from the close watersheds, the available (DEM) was utilized using IDRISI software (GIS), to model the watersheds and divides. Surfer 7 was used to georeference the space photo. All the results were overlain on each other to produce Figure (32).



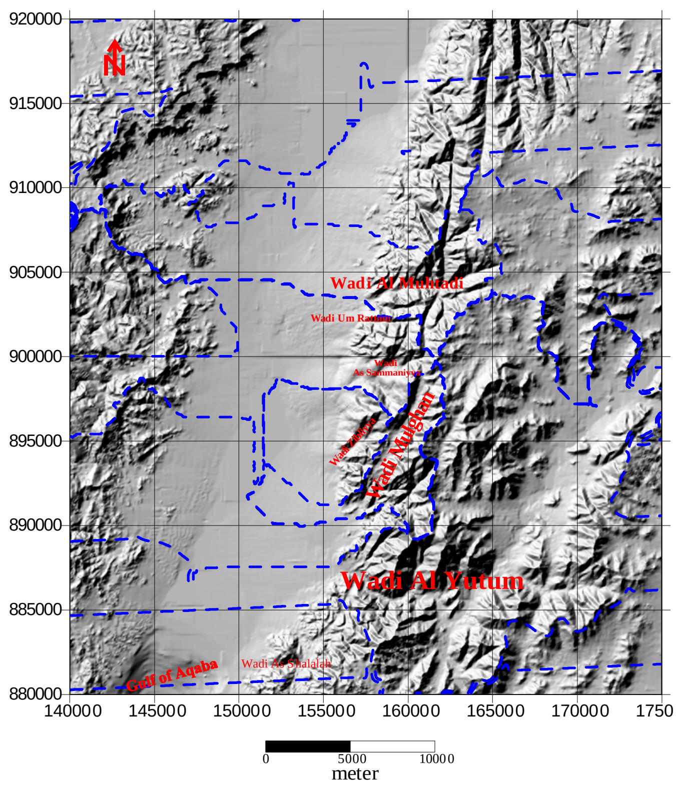
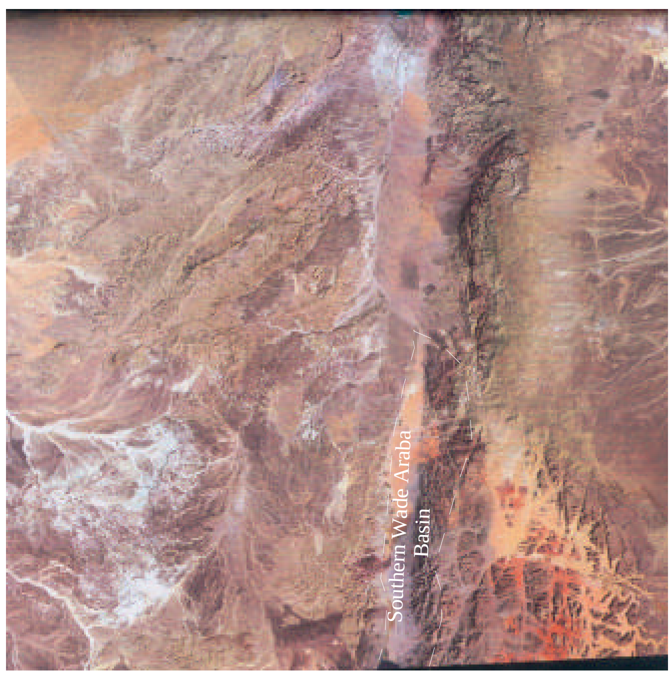


Figure (32): Watershed modeling using digital elevation model. Blue lines represent the local surface watersheds, while white lines represent the elevations. To the right down it is possible to see the Southern Wadi Araba basin.



Wadi Al Yutum possesses the largest watershed area of about 2200 km^2. The most northern part of the space photo within the graben zone is considered as the northern surface and local groundwater divides. The Gulf of Aqaba is the southern divide, the granite mountains in the eastern and western flanks of the graben are the eastern and the western surface and groundwater divides.

The catchment area of Wadi Mulghan was calculated as 80 km^2, Wadi Zibliyya 8 km^2, Wadi As Sammaniyya and Wadi Umm Rattam 50 km^2 and Wadi Al Muhtadi about 80 km^2.
The same DEM of the study area was used to produce the **drainage system** (Fig. 33). It was modeled using IDRISI (GIS). The method depends on connecting the neighboring pixels with each other independence on their slope. It is clear from the Figure that Wadi Al Yutum possesses the largest drainage system.

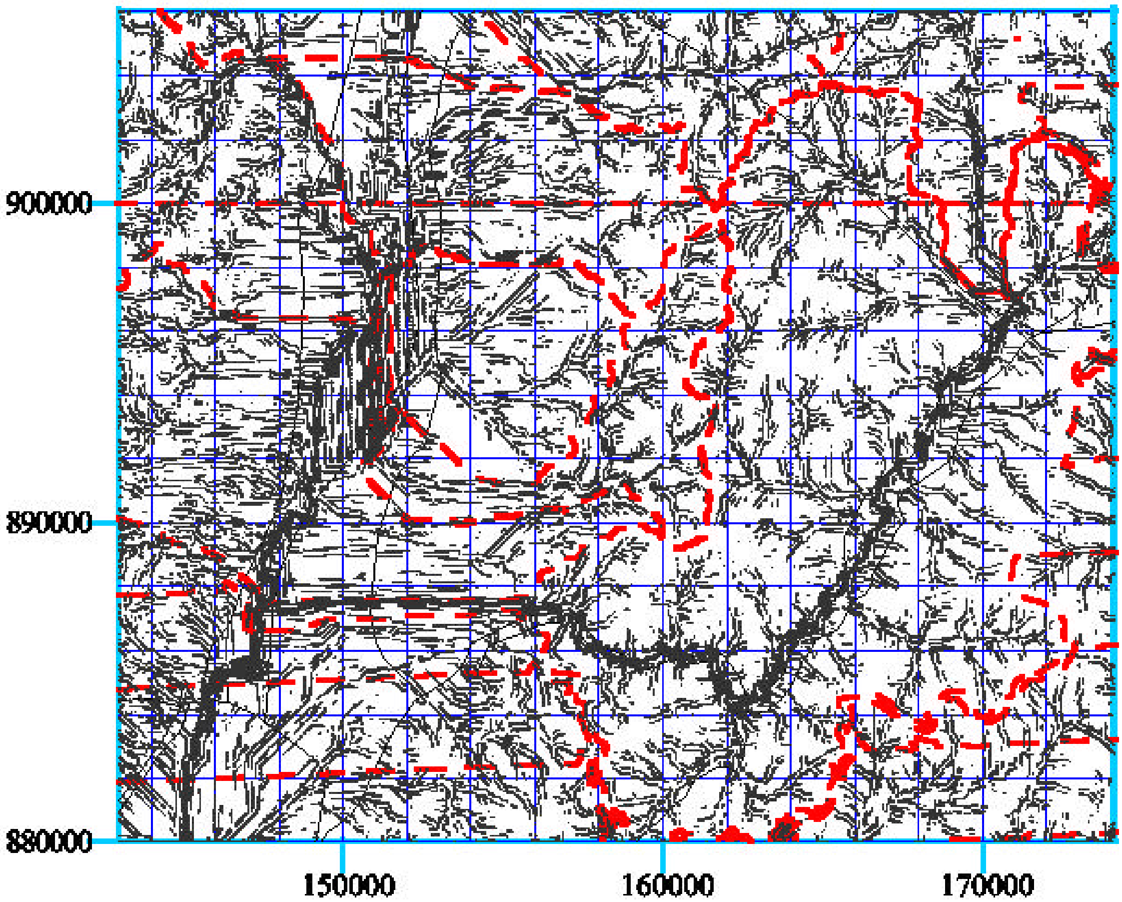


Figure (33): G.I.S modeled drainage system of the study area. It was modeled using IDRISI (GIS). The method depends on connecting the neighboring pixels with each other independence on their slope values and directions.

The produced drainage system shows that side wadis possess catchment areas which allow their floods and sediments to be discharged along their alluvial fans into the southern Wadi Araba. Accordingly they form an important part of the surface water balance of the study area. Their floods reach the apexes of the alluvial fans first, and slow due to the low slope. Here the infiltration rates are relatively higher than in other places respecting the gravelly texture of the soil.
The barren granite mountains possess no soil cover. The precipitation there is divided into evaporation and runoff. Infiltration is restricted to some connected cracks and joints, the steep slope of these mountains enhances the runoff, while the flood losses of water to the groundwater will not be high until it strikes the apexes of the alluvial fans. The floods after

that spread over the alluvial fans and infiltration takes place normally through the soil. Some direct infiltration takes place through the weakness zones of active faults. The side wadis share indirectly with their floods in the surface water budget of the study area. This is the conceptuality of the indirect type of recharge in the study area.

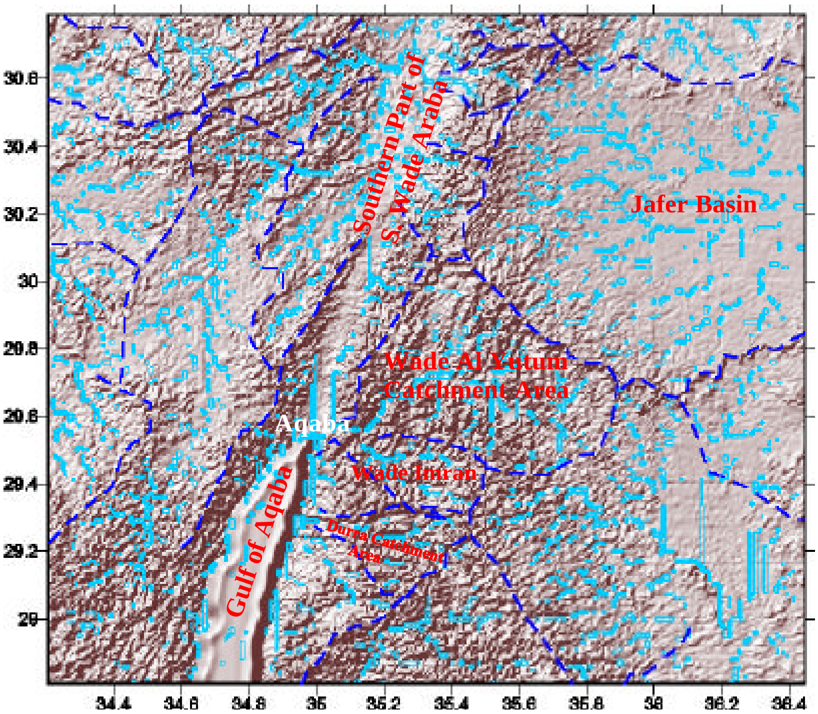


Figure (34): Regional drainage system, and surface watersheds around the study area, modeled with G.I.S using a 950 meters resolution DEM.

The regional pattern of surface flow of the flood water in the most southern part of Jordan has been modeled using 950 meters resolution (DEM) (Fig. 34), where degrees system was used. From the model, Wadi Al Yutum is extended to the north where higher rainfall averages and lower actual evaporation rates are found. The extension of the wadi catchment was calculated as 2200 km^2. Salameh (1996) calculated the total surface flood upon this catchment area as about 1.5 million m^3/y. Average rainfall was taken as 40.0 mm/y. Total amounts of received precipitation without losses is about 75.2 million m^3/y.

The rainfall over the northern granite series which includes the side wadis downward to the northern surface divide was estimated here as 60 mm/y. The total area as 200 km^2. The floods come from this part were estimated after subtracting the losses as 0.85 million m^3/y. The southern part of the study area (100 km^2) has coastal wadis which lead their water into the gulf depending on the rainfall conditions. Only one major wadi exists here; Wadi Al Durra. The total amounts of floods at the time of rainfall was calculated for this wadi as 0.31 million cubic meter/y (Water Master Plan in Jordan, 1979). Total amount of precipitation without losses is 20.70 million m^3/y. Another run off amounts come from the other smaller wadis in this area giving a total flood of 0.15 million m^3/y.

2.4.9 Final Surface Water Balance In the Study Area

The direct recharge in the normal conditions in the study area was found as 0.2 million m^3/y.

The surface re-distribution of the flood water of Wadi Al Yutum results in an infiltration of about 0.3 million m^3/y. The side wadis give 0.35 million m^3/y infiltration, and in the southern area 0.46 million m^3/y. The total amounts of the direct and indirect recharge coming from rain, upon the whole study area was totaled 1.31 million m^3/y.

2.4.10 Modeling Direct Recharge and Surface Water Balance

This study aims at relating as much as possible the hydro-ecosystems with the spatial factors of the study area. The direct recharge will be used as one of the most important components of the vulnerability study of the groundwater for pollution. Accordingly it is of great value to construct the map of direct recharge for Aqaba.

MODBIL (Udluft 1994) gives the ability to analyze the daily direct recharge of a specific area and to include the effective parameters in the concern of the groundwater recharge within the estimation process. The software depends on the daily rainfall and potential evaporation data for a specific period, the slope in degrees of the study area, the effective soil filed capacity considering the roots zones, the normal duration of rain events, the natural soil water saturation and the soil permeability. The outputs of the software are the daily rainfall, daily runoff, daily actual evaporation and the daily infiltration (direct recharge), all of them in millimeter. Then it gives them as averages relevant to the number of the given days. The program is best used for strategic studies of decision making in terms of spatial planning of land use, vulnerability studies of groundwater for pollution and for flood risk analysis.

The first step is to analyze the daily output data of direct recharge by using MODBIL for the period from 1980 to 1999.

The daily data of rainfall and evaporation for 1980-1999 were introduced, the soil field capacity was assumed as 15 mm, the rain factor was selected as 1, the slope was as 1.5 degrees, the soil natural moisture saturation 3.5 % and the permeability divided on the rainfall event in the study area was given as 650 mm/event.

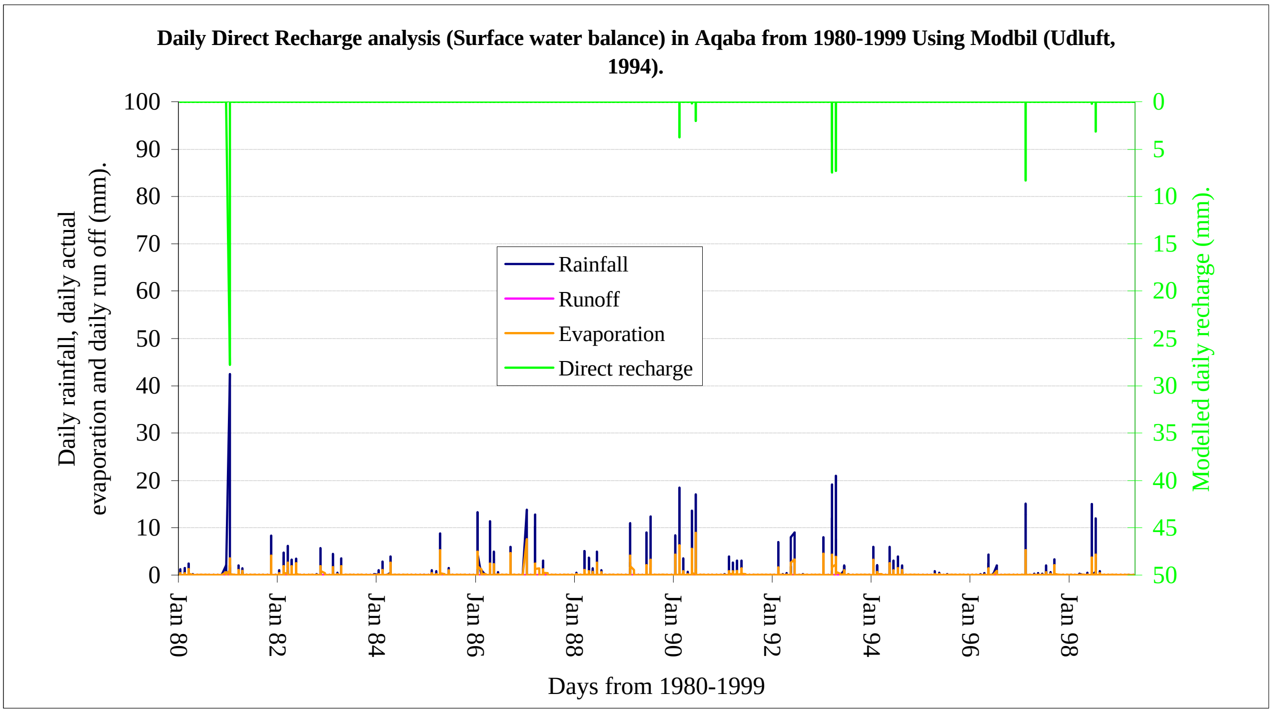


Figure (35): Results of recharge modeling using MODBIL (Udluft, 1994) for the years 1980-1999 in Aqaba.

The results of the daily recharge were plotted with the daily rainfall (Fig. 35). Depending on this figure, only 10 days out of 7056 days, the direct recharge existed, it was only when the daily rainfall amount exceeded 17 mm/day. The run off didn't exist all over the investigated period.

2.4.11 Mechanism for Mapping Recharge in Aqaba

The method of building the recharge map of the study area depends on the parameters to be given into MODBIL (1994) as input type of data.
The nodes of the grid which will be given the different input parameters to estimate the recharge should be built. The nodes should be taken to cover the different geological parameters in the study area, which affect the soil field capacity, and the soil permeability.
The derived equation relating rain and elevation can be used to construct the rainfall map. Land use units are considered to prevent the direct recharge.

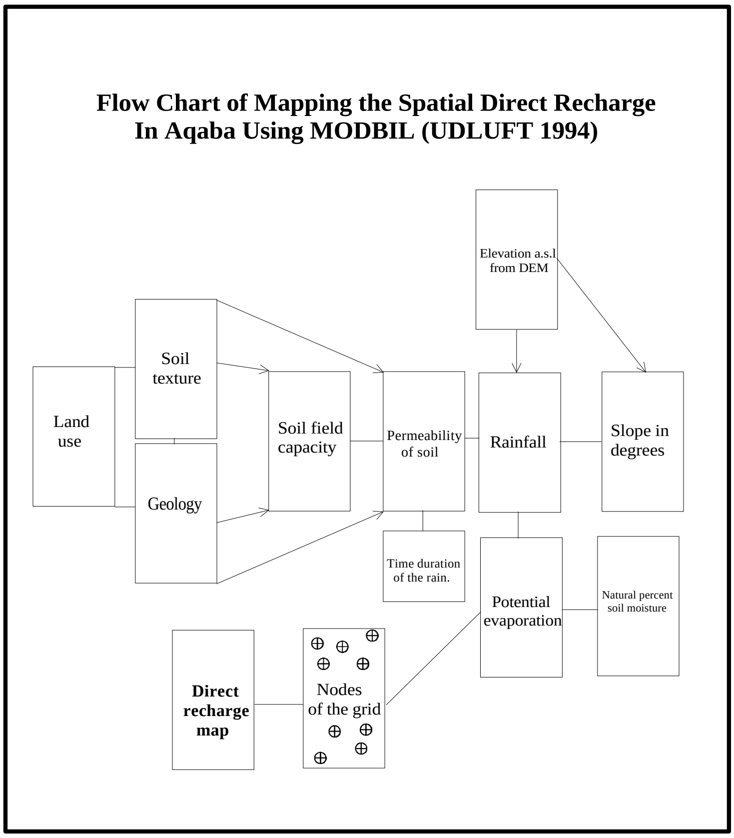


Figure (36): Flow chart of using Modbil (Udluft 1994) for mapping recharge in the study area.

For each node of the grid MODBIL should be run using the input parameters as shown in the flow chart (Figure 36).

2.4.12 Defining Recharge Zones Using Geoelectric Method

In the course of this study several Vertical geo-Electrical Sounding (VES) surveys were carried out. Other VES were collected from the Jordan Natural Resources Authority. These were modeled and calibrated using some known wells according to lithologies, water depth and salinity.

The Archie's law was used to approach the depth and thickness of VES;

$$r = \mathbf{(I/P^{\,a}) * (EC/S^{2})}$$

(Archie's equation is discussed in the section of "Environmental Geophysics").

Determining recharging zones using geoelectrical soundings benefits from the homogeneous character of the alluviums and their uniform lithologies in general. The low amounts of clay minimize the limitations of the Archie's law. According to that the components on which the formation's resistivity r depend are to a specific manner fixed. The major factor which governs it is water salinity which is here of wide range; in the coastal areas it is attributed to the encroachment of the sea water within the aquifer, but far from them the difference could be attributed to human impacts. Recharge process to the groundwater by rain water and piped water leakage from urbanization results in increasing the resistivity of the formations bearing water by supporting with water of lower salinity.
The modeling depth of 50 meters was selected to represent a saturated depth all over the area.
The resistivities range from 100-200 Ohm*m were considered as the layers bearing water which receive additional recharge, that inherited them an increase in their resistivities.
The resulting map (Figure 37) shows that recharge is concentrated closely to the side wadis, and the alluvial fan zones. Flat areas show also contrast due to the specified range of resistivites.

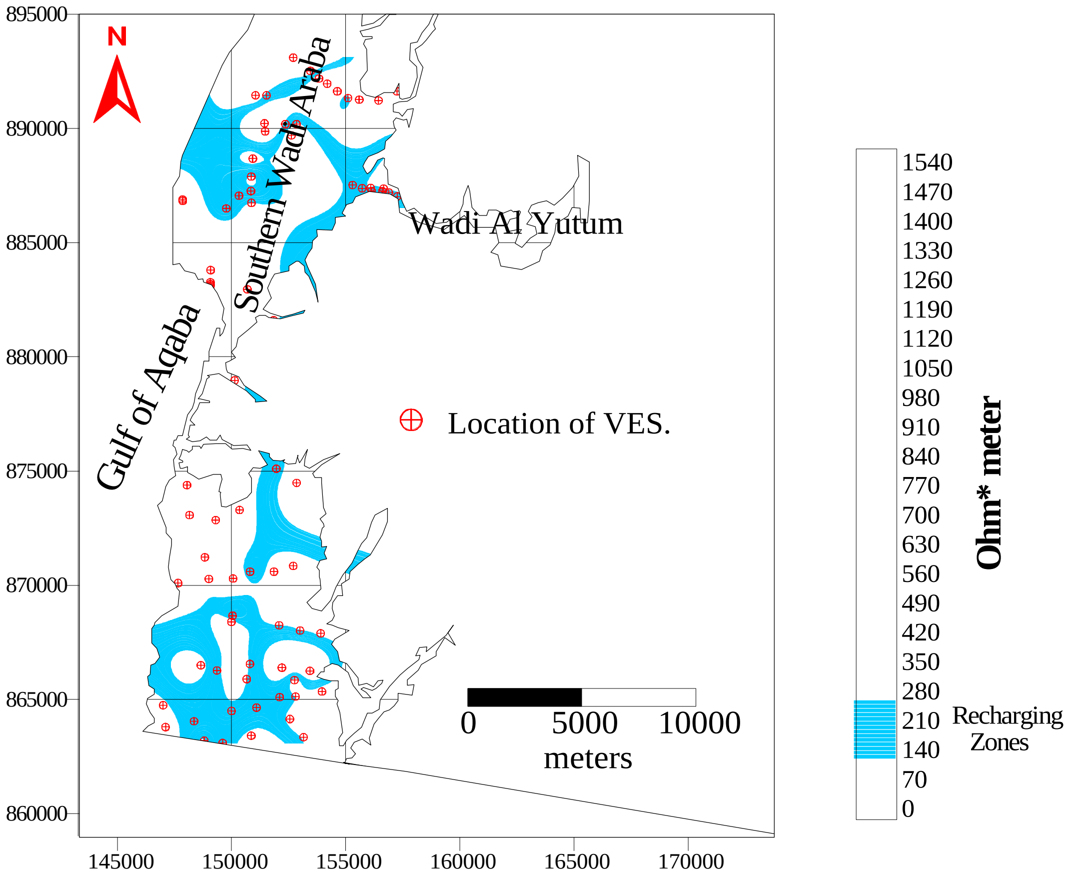


Fig. (37): Recharging areas by geo-electric soundings are concentrated closely to the side wadis and the alluvial fan zones.

2.5 Hydrogeological Aspects of the Study Area

2.5.1 Introduction

Lying between the ranges of the eastern mountains of the study area are tectonic troughs that have been partially filled with erosion products from the adjacent uplands and mountains. The sediments filling the valleys have been sorted into various size fractions by the action of the running water. Sand and gravel layers are found interlayered with silt and clay lenses. The fill materials of the rift valley under the study area are porous; hence, there are many permeable zones especially close to the mountains, where coarser debris were deposited within the alluvial fans.

Runoff coming from the mountains can infiltrate into the coarse deposits; however, rainfall over the basins themselves is low. The deep sedimentary basins hold vast volumes of water in storage and can yield good amounts.

As a small fishing town, Aqaba’s water needs were readily met from shallow wells dug near the sea which produced sufficient quantities of good fresh water permeating to the sea through the alluvial fan of Wadi Araba. But shortly the demand for water increased, boreholes were drilled further inland. Over-pumping of these wells resulted in depletion and quality deterioration. To satisfy the increasing demand, additional holes were drilled in the deep alluvial deposits of Wadi Al Yutum. Until the middle 1970s these wells provided the entire water supply for Aqaba, but, with the limited yield of the alluvial aquifer, there have been increasing shortages, especially during the hot summer months.

2.5.2 Geometry of the Aqaba Aquifer; Regional and Local Scales

The study area locates in the southern part of South Wadi Araba–Red Sea hydrogeological basin. The groundwater flows towards the Gulf of Aqaba, where the aquifers are water table type. Figure 38 shows the groundwater divides in Jordan. The groundwater in the study area occurs in several types of aquifers. The main groundwater body is the graben body.

Groundwater divides are defined as ridges in the water table or potentiometric surface, from which groundwater moves away at right angles in both directions. Or line of highest hydraulic head in the water table or potentiometric surface.

Mainly three different aquifers occur along the graben body. Bouger anomaly measurements of the study area, were plotted and analysed to locate the lateral extension of the aquifers. The resulted map, Fig. (38) revealed 3 aquifer basins. The basin that locates in the northern part of the map, and that in the middle (under the city of Aqaba) are connected to each other, but possess different depths. Hydrogeologically the aquifer at the northern part overspills the water in excess into the aquifer basin under the city of Aqaba. A barrier of granite seems to partially separate between them. The depth of these two basins is a function of the depth of the granite basement.

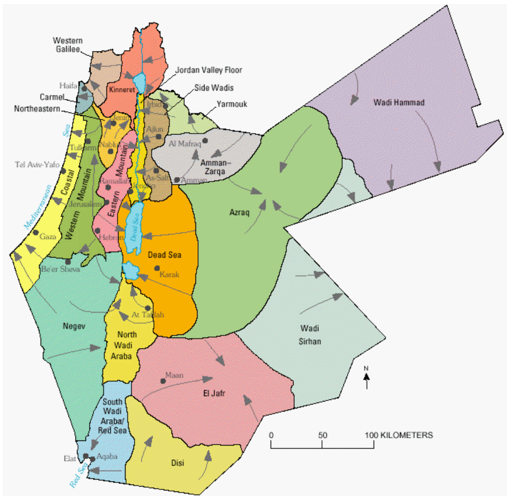


Fig. (38): Shallow groundwater divides in Jordan.

The third aquifer basin is found in the southern part of the study area, it is disconnected from the other two basins, where a portion of the granite basement separates between them.

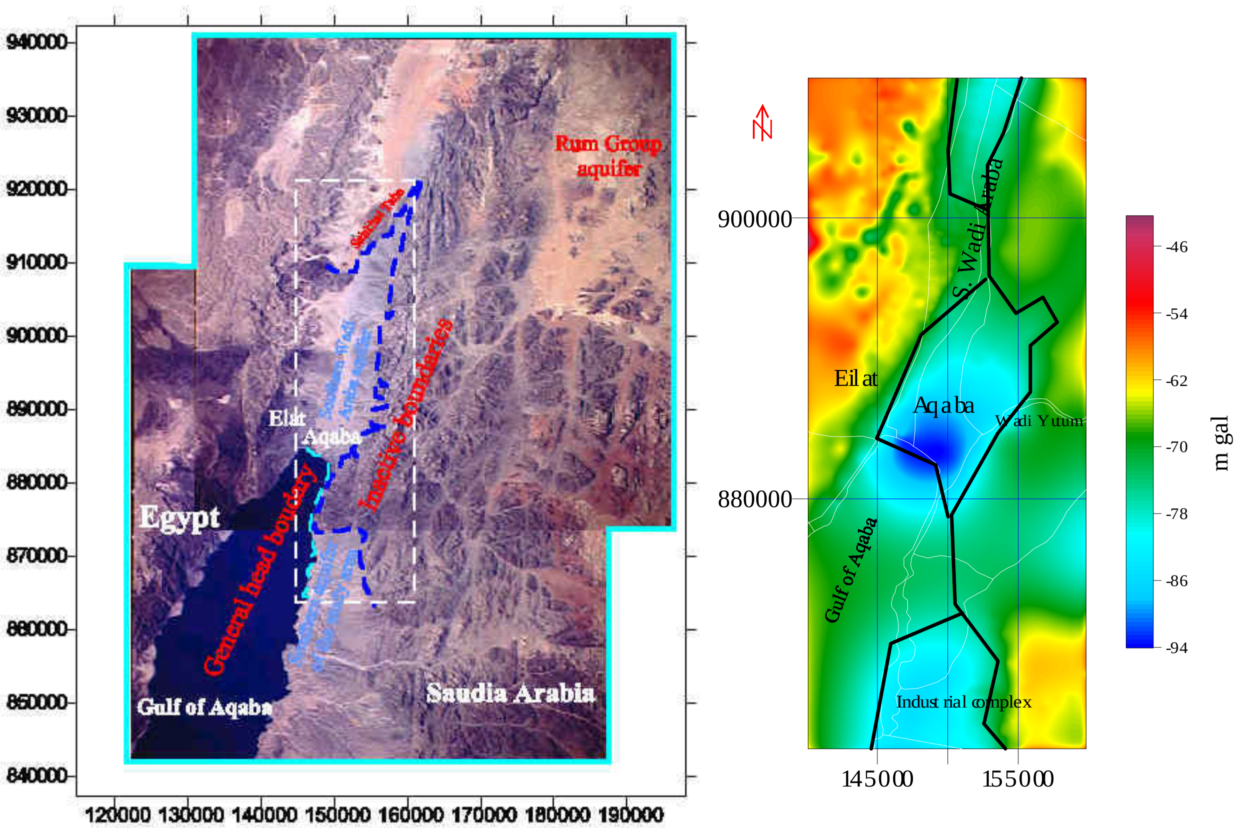


Fig. (39): Boundaries of the aquifers in the study area (right). (left) groundwater sheds in Aqaba (as indicated from the gravity survey).

The middle basin seems compared to the other two aquifers to be the deepest, it has also the lowest Bouger anomaly. Depths to these aquifer were discussed in the chapter of “geology” and were estimated as more than 2000 meters.

The local aquifer system in the study area is indirectly connected with other aquifer systems in the surround. It is connected with the aquifer system of Ram Group –to the north east- via Wadi Al Yutum, and connected to the Southern Wadi Araba basin, where a local ground water divide occurs between both of them as the Sabkha of Taba, which locates about 20 km to the north of Aqaba. The Gulf of Aqaba is considered as a general head type of boundary (i.e. fixed water head), which surrounds the aquifer with about of 26 km length (Figure 39).
The alluvial fan system and the side and coastal wadis groundwater systems are important components of the aquifer in the study area.

2.5.2.1 Rum Group and Wadi Al Yutum Aquifer Systems

Groundwater in the Disi area originates in the Um Sahm mountains, discharging in a north-easterly direction. An underground igneous dike called Kharawi and forms an underground barrier extending NW-SE for about 40 km. The new well field at Qa Disi intercepts a large proportion of the flow which passes round the northwestern limit of the dyke and is slowly developing a large depression centered at Disi. The extent and rate of development of this depression has been simulated by digital computer models (NRAJ 1982). From the model simulation studies it was concluded that the aquifer will support a maximum abstraction from the Qa Disi area of between 17 and 19 million m^3/year for at least fifty years. The maximum capacity of the scheme has therefore been fixed at 17.5 million m^3 per year.
The Aqaba water supply scheme comprises four main elements: (1) the well field and headworks complex, (2) the trunk main from Disi to Aqaba, (3) the trunk distribution main from Aqaba to a fertilizer factory near the Saudi border, and (4) a distribution network within the town. The scheme was completed and has been in operation since the end of 1981.
For the first-stage development to exploit 10 million m^3 per year, seven boreholes 400 m deep were drilled to penetrate the Disi sandstone aquifers. The finished diameter of the upper half of the boreholes is 219 mm and of the lower half 171 mm. Each borehole is equipped with twin submersible pumps delivering water through collecting mains into a reservoir from where the water gravitates to Aqaba. Power for the pumps is provided by a power station equipped with four diesel generating sets of 550 kW each.

Salameh & Gedeon (1999) studied the renewability of Disi-Wadi Al Yutum aquifers using isotopes and hydrogeological analyses. Through their study the throughput calculations and the analyses of the seasonal level fluctuations of the groundwater body of Disi aquifer, revealed that the aquifer which contains several billion cubic meters of water with TDS of 200-400 mg/l receives an average amount of recharge of 40-48 million m^3/y.
Their detailed study on the isotopic composition and the water salinities of different parts of the Disi aquifer reveals a variety of altitudes from which the precipitation recharge water originates. The Disi aquifer spills over to Wadi Al Yutum which also receives recharge water coming from the floods of the wadi. Tritium content of 0.5-6.2 TU shows that the aquifer is receiving recent recharge, where the rapid infiltration of precipitation water falling over barren highly permeable rocks results in highly depleted isotopic composition of the groundwater. They attributed the very low salinity of the groundwater in this arid area to the rapid infiltration into the rock matrix composed of almost pure quartz grains. They concluded that the ratio of recharge along Wadi Al Yutum relative to the overspill of Disi aquifer into it increases down-gradient, and results in younger water in this same direction.

They calculated the annual throughput of the Disi Aquifer as:

Annual throughput = Saturation thickness * Flow length * Gradient * Permeability * Drainable porosity

$$= 850 \text{ m} * (100 \text{ km} * 1000 * 10^{-3} * (1.3 * 10^{-5} \text{ m/s}) * 12\%$$

It was found to equal about 40 million m^3/y. This annual amount of throughput is the same of the annual estimated recharge amount. It allowed them to calculate the annual recharge as 12.5 mm/year, for an area of 32000 km^2 from the aquifer.

MACDONALD (1966) evaluated the benefit and impacts of constructing a sub-surface dam in the end part of Wadi Al Yutum, he studied in depth the hydrogeological, geological, geophysical, and hydrochemical aspects of the last 4.5 km of the wadi with a width of about 200 meters. Several boreholes were constructed in this part of the study area trying to reach the depth of the basement and to evaluate the hydrogeological and hydrochemical parameters of the wadi (some of them were added in the geology of the study area).

Two main sources of the water quantity and quality along the alluviums of the wadi have been concluded;

- *The direct infiltration of flood waters.*
- *Overflow from the large sandstone reservoir which underlies the southern desert of Jordan.*

Some pumping tests were carried out in order to investigate the hydraulic parameters of the wadi's alluvial sediments. The calculated permeabilities from these tests ranged from 30.43 to 0.36 m/hour. The presence of impermeable barriers was noticed through the tests, where breaks existed after some hours from the beginning of the tests of some wells. The average velocity of flow was estimated for the fully saturated area as 4451 m/year.
Using the data obtained from drilling, geophysics and well test, it was possible to make an estimate of the quantity of water moving down the Wadi Al Yutum.

Two estimations were carried out, the first one resulted on 2.98 million m^3/y, and the other on 3.96 million m^3/y of throughput. Accordingly they generalised their statement as that the annual received amounts of water as throughput by the Aqaba basin from Wadi Al Yutum range from 2 to 5 million m^3/y.

Two regional hydrogeological cross sections were modified in this research; one is to demonstrate the groundwater system from Ras El Naqab until Wadi Araba, and the second is to give the same on the area from Qa Disi to Wadi Araba. Figures (40) and (41).
The second cross section shows that it is possible for a part from the groundwater in the upper most carbonate group to leak down into the sandstone aquifers through the existed vertical faults among them.

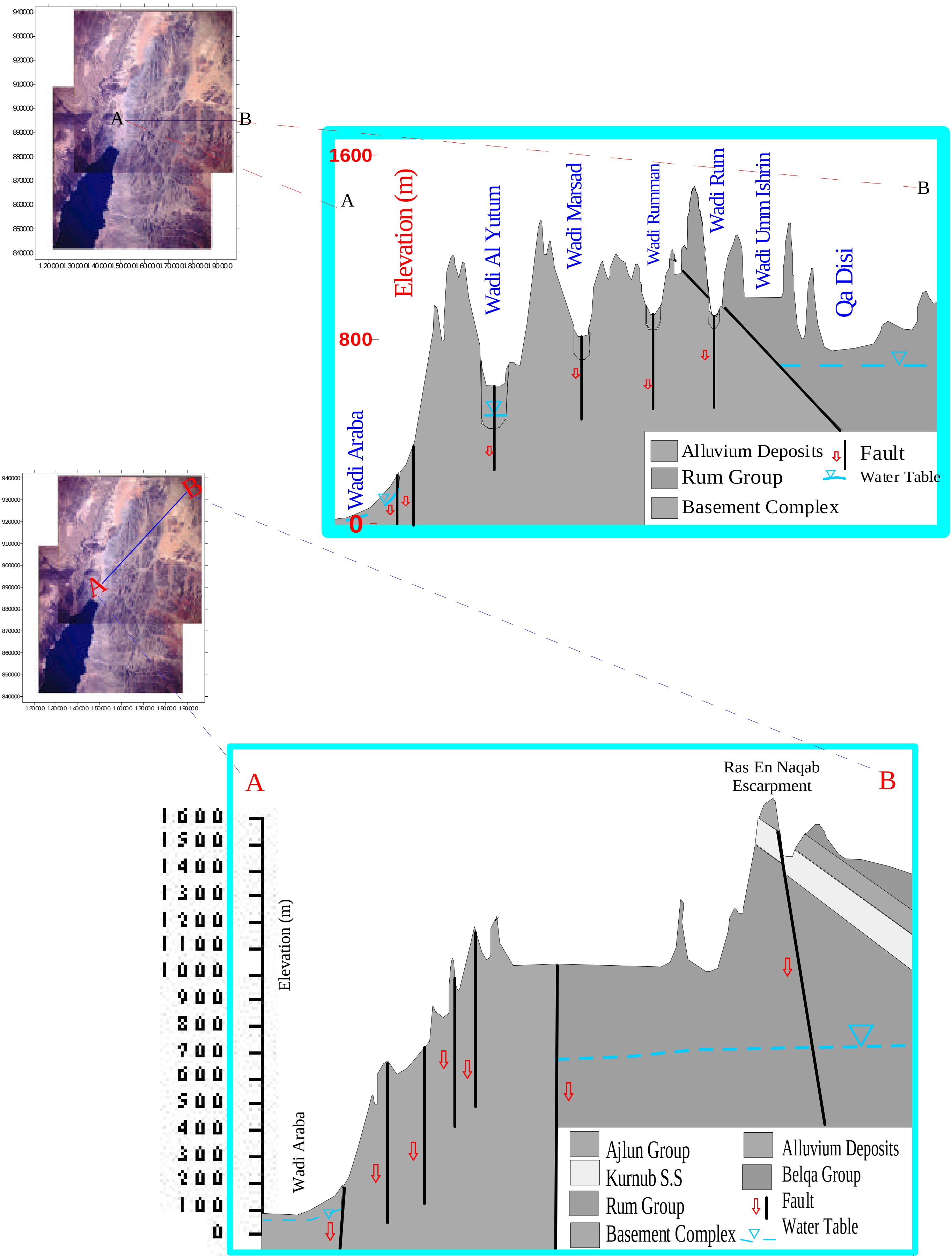


Fig. (40, 41): Geological cross sections along the study area and the surrounding and the resulted aquifer systems.

2.5.2.2 Southern Wadi Araba Aquifer System

This basin is a part of the basin present along the Dead Sea Transform Fault , which formed deep grabens filled with deposits. The study area is locally separated from the regional Southern Wadi Araba basin by the Sabkha of Taba, which is a small closed groundwater system in the area distinguished due to the high salinity of water.
The wadi receives its groundwater from several resources; from the floods come from the side wadis of both flanks -east and west-, alluvial fans on both flanks of the wadi, groundwater overspill and/or re-ejected excess recharged water from the northern Wadi Araba basin, the deep circulation and upward leakage from the deep aquifers and from direct recharge of precipitation.
There is no surface discharge taking place out of the aquifer, but the groundwater flows in general towards the Gulf of Aqaba. The Gulf of Aqaba receives these amounts of water as sub-marine groundwater discharge.
The water quality in this aquifer is of two type; fresh and brackish groundwater are found in the uppermost part of the aquifer. The salinity of the deep aquifer increases going towards Aqaba.
Salameh (1996) estimated the **throughput** through this aquifer system as million m^3/y of brackish water.

Salameh (2000) calculated the whole water balance of the Southern Wadi Araba basin as;

Recharge

- local recharge 3 million m^3/y
- Lateral alluvial and flood recharge of alluvial fans 4 million m^3/y
- Lateral from the deep sandstone aquifer system 5 million m^3/y

Discharge

- Discharge into the Gulf of Aqaba 6.8 million m^3/y
- Evaporation of seepages 5.2 million m^3/y

2.5.2.3 Alluvial Fans, Side Wadis and Coastal Wadis Aquifer Systems and their Water Availability

The geological conditions of grabens resulted in creating side wadis and alluvial fans between the flanks of the graben's shoulders. The wadis which discharge surface and ground water into the Gulf of Aqaba are called coastal wadis.
Al Qaisi (1976) investigated the groundwater settings along Wadi Mulghan, which is a side wadi to the north of Wadi Al Yutum. His study included the alluvial fan along the wadi. Geoelectrical method was used to apply this study. The results of study with locations of the different profiles were reconstructed (Fig. 42).
From the geoelectrical cross section, it is clear that the depth of groundwater table decreases towards the centre of the graben, it ranges from about 150 meters to about 50 meters going west ward. The groundwater here seems to be relatively of high salinity.
The salinity –using Archie's low- was found to be more than 1000 mg/l. It increases towards the central part of the graben, confirming that the water type in the upper parts of the side

wadis is receiving more recharge than that part of the centre of the graben. This additional recharge received by the side wadis and the upper parts of the alluvial fans is attributed to the indirect type of recharge which comes from floods.

The normal hydrogeological pattern of wadis and alluvial fans is to discharge their groundwater into the main aquifer system, i.e. into the body of the graben. They possess good permeabilities and high gradients. Indirect recharge is restricted during normal years to their upper parts. The groundwater table drops down in summer seasons to the extent that they may drain no water during dry years.
When granite barriers or tectonics prevent the lateral flow, the groundwater becomes retarded and captured to build local small scale yielding water wells with accepted salinity. Profile number 3 (Fig. 42) shows a fault that captured the groundwater.
Throughput of these wadis and alluvial fans was calculated by Salameh (2000) within the water balance of the Southern Wadi Araba.

An estimation was carried out for the side wadis starting from Wadi Mulghan to the north until Wadi Al Muhtadi using flow path of 22.5 km, gradient of groundwater depending on the geoelectrical survey as 0.038, saturation thickness as 100 meters, and permeability as $0.5*10^{-6}$ m/s. A throughput as 1.3481 million m^3/y was found. This value is in an agreement with what can the side wadis receive from both direct and indirect recharge. If the water flow here is under steady state conditions, then this amount of the annual throughput represents the received amount of the annual total recharge of direct and indirect types.

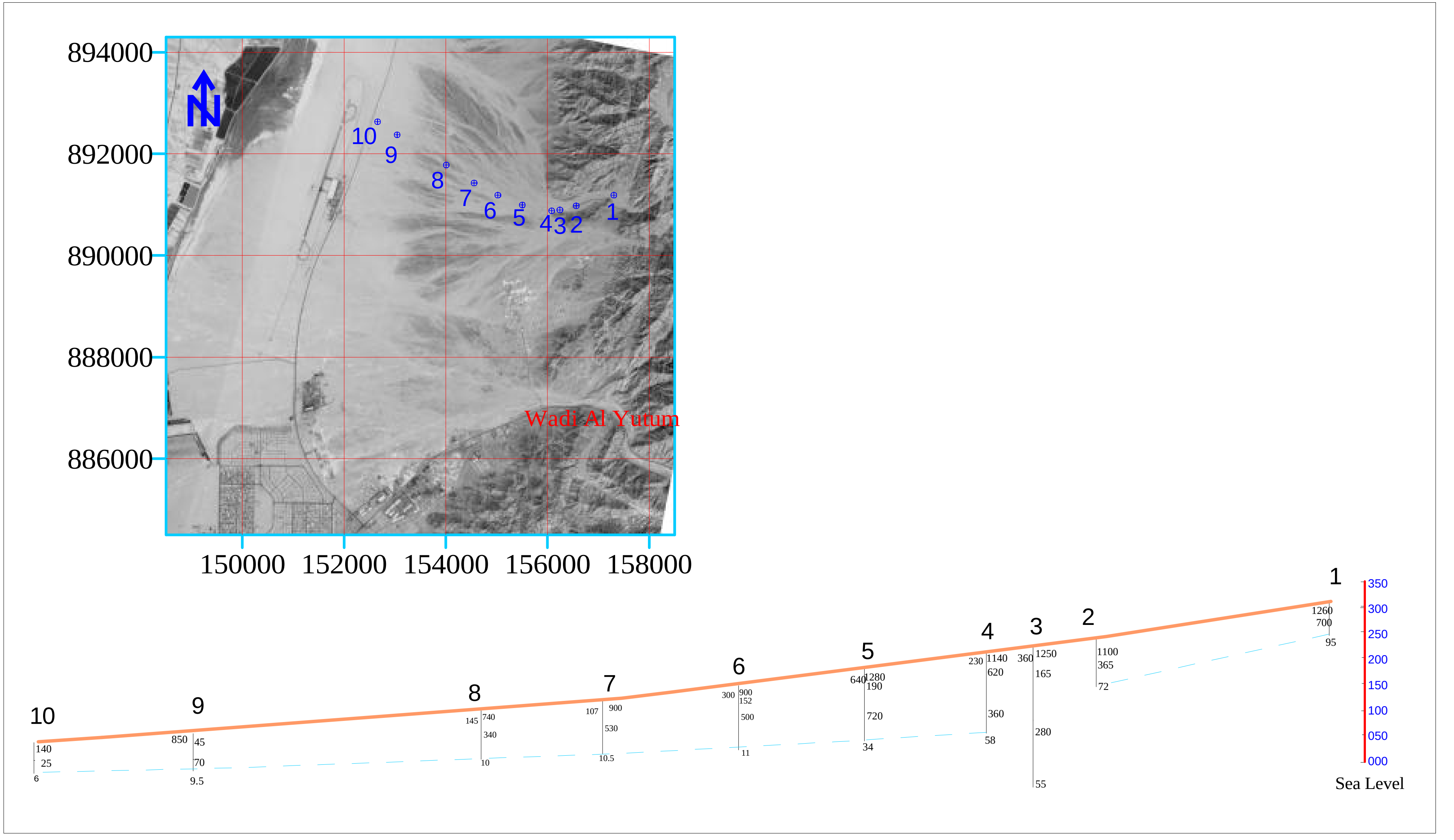


Fig. (42): Geoelectric cross section along Wadi Mughlan (resistivities in Ohm.m). (Blue dashed lines represent the water table).

2.5.2.4 Southern Aquifer System (Southern Subarea)

This area possesses industrial activities which are expected to increase in the future as planned.
The aquifer is separated from the aquifer of Southern Wadi Araba by a granite basement natural hedge. The eastern granite forms another natural boundary, while the sea forms the general head boundary (Fig. 39). It discharges its water into the Gulf of Aqaba. The coastal wadis are responsible for the indirect amounts of recharge the aquifer receive.
Only one water well was found in this area in the course of this study, it belongs to the fertilizers company, it is an observation well constructed to investigate the groundwater quality. The water depth was measured two times in August/1998, and May/2000, it was found to be 30.12 meters deep with a salinity of 13,000 mg/l. This very high salinity indicates without any doubt the encroachment of the sea water to the well site.

Two geo-electric VES were carried out here aiming at locating the interface between the fresh and sea water. Other VES have been carried out in the area by the Jordan Natural Resources Authority in 1998-2000 for the purposes of evaluating the groundwater resources at the area. These VES are well distributed over the area.
The output of all these profiles were put with each other in term of location, depths and resistivity. Accordingly it was possible to take slices of many depths for the aquifer in terms of resistivity. This enabled explaining many aspects of the groundwater, vadose zone, geology and some structures. A 3-D model has also been created (Fig. 17). The profiles were not corrected to their elevation above sea level. The reason was to slice the aquifer parallel to the topography.
From the detailed investigation on these slices it was clear that a groundwater barrier with low permeability occurs below the ground surface, it impedes the lateral movement of groundwater causing a pronounced difference in the heads on opposite sides of it. The barrier takes no regular shape, it possesses a resistivity as 150-300 Ohm-meter, and extends vertically down the aquifer as was noticed from the constructed 3D, and 2D models of the geo-electrical data (Fig. 43).
Rocks resistivity of 200 to 450 Ohm-meter can’t be explained as granite, because the granite has resistivities exceed 2500 Ohm-meter when it is free of water. Accordingly this barrier may be explained as carbonate rocks (see the geology of the study area and page 40).
The gravity survey was not able to show anomaly in the same location, it refers to the bad distribution of the measurement points over the area, or to similar densities of dike and bed rock. This barrier creates a disturbance in the flow net of the groundwater, it retards the lateral flow and makes a noticed difference in the water head on each side.

If in the calculated water head no consideration is taken for the difference in the head between the two sides of the barrier, the calculations on the throughput of groundwater into the Gulf of Aqaba can not be reliable. If the presence of the barrier was a fact, then an over-spill type of flow must take place.

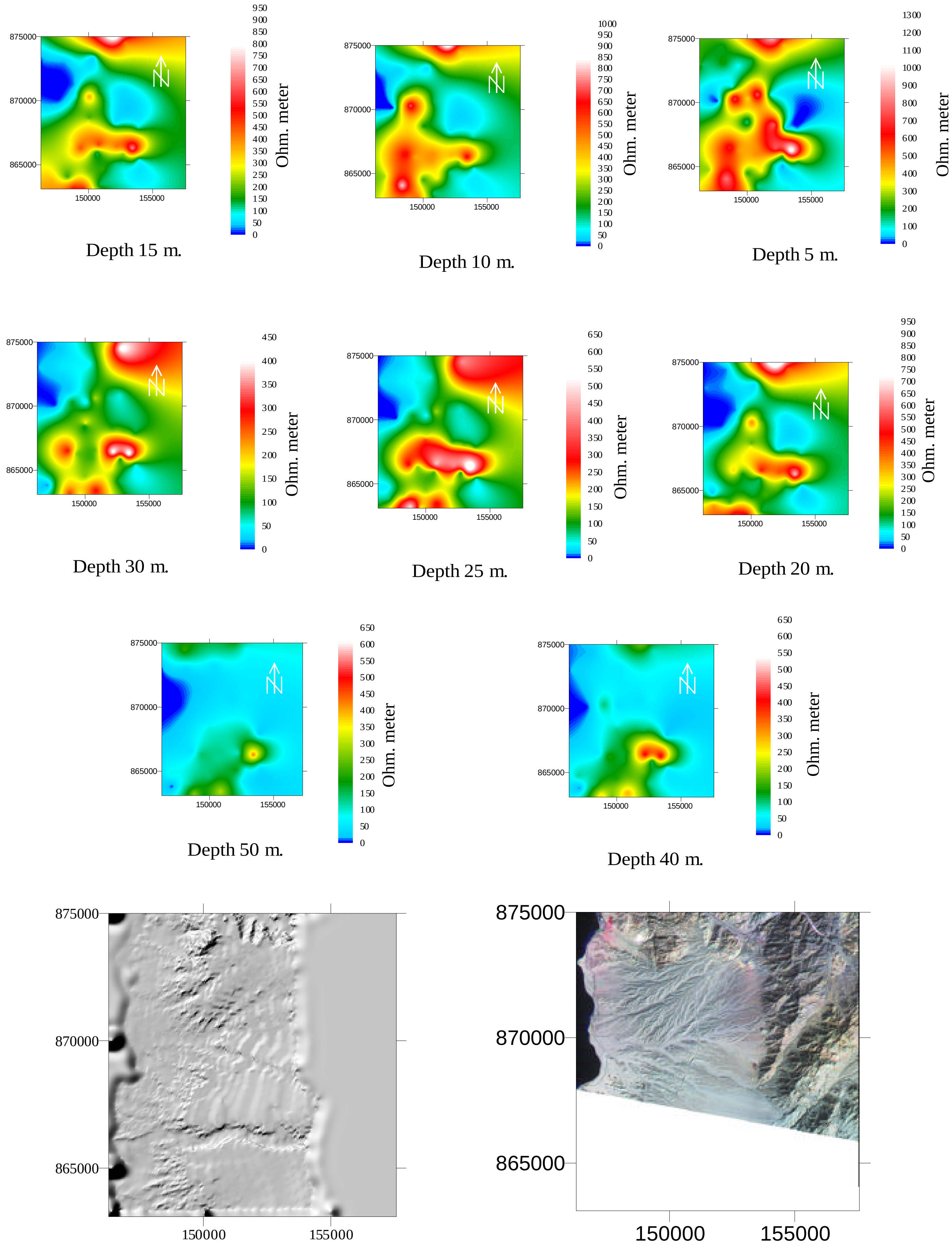


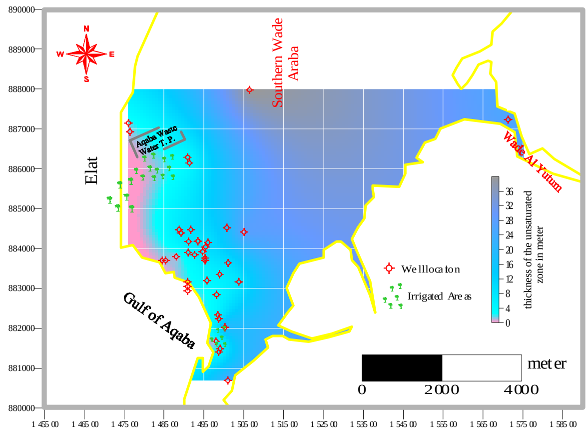
Fig. (43): The theoretical subsurface barrier with depths (southern part of the study area). Supported with location on Land-Sat image and DEM model.

However the throughput is mainly towards the gulf and it should not exceed the received volumes of recharge. Accordingly it is expected to equal 1.8 – 2.5 million m^3/y.

2.5.3 Groundwater Level Model, Water Flow Directions and Unsaturated Zone of the Aquifers

The groundwater table in the study area to a specific extent is a function of the topography. It was possible through the field measurements on the water wells in the study area to construct the groundwater potential lines to calculate the unsaturated zone thickness, and to construct flow net of the groundwater.

The hydrogeological and hydrochemical studies were carried out in two phase; in November/1998, and May/2000. The thickness of the unsaturated zone and static water levels were modeled depending on the field measurement and the digital elevation model (DEM). The wells were introduced in a digital (x.y.z) grid system. They were located in the map, studied in term of the water table depth and elevation above sea level (Fig. 44,a,b,c).



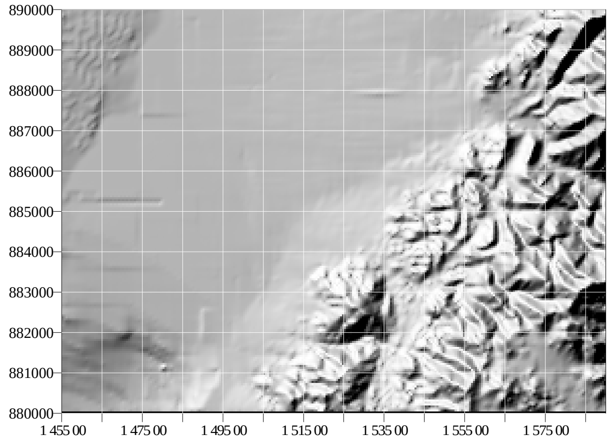


Fig. (44,a): Unsaturated thickness model of the area.

Fig. (44,b): Elevation model of the area.

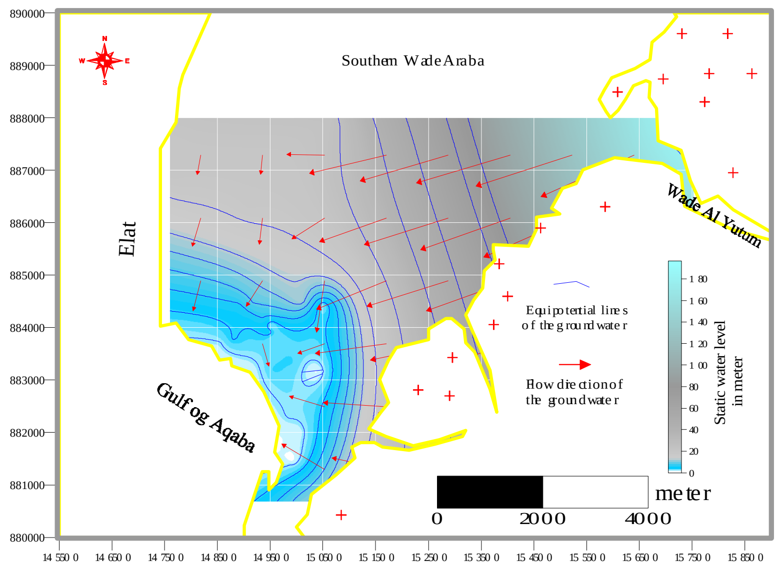


Fig. (44,c): Model of the static groundwater levels, and flow directions.

The water flows in the studied part towards the Gulf. The groundwater head decreases going towards the Gulf of Aqaba. The static water level is higher along the area between the mouth of Wadi Al Yutum and the northern part of the Gulf of Aqaba, it ranges between zero and 20 meters in the zone of the city of Aqaba. Here some disturbances can be noticed which may be attributed to human activities and to the waste water treatment plant of Aqaba which has a major role in raising the water level in its surroundings.
The unsaturated zone ranges from about less than one meter to about 40 meters, it decreases seawards. The zone is of primary importance in groundwater recharge and protection, as it acts as natural buffer between the land surface and groundwater. Hence it control both the amount of water (recharge) reaching the aquifer and the groundwater vulnerability to surface contamination. Furthermore, vulnerability to surface contamination (e.g. by chemicals released from industrial process, landfills, fertilizer and pesticide applications) depends on the downward flow and solute transport mechanisms in the unsaturated zone. Consequently, assessment of the movement of water and contaminants within the unsaturated zone is of environmental, economic and social significance.
The contrast in the water head leads the groundwater to move under the action of gravity. The presence of water head differences in the study area indicates that the area receives recharge and inflow from other resources. The main difference in the water head is attributed to the inflow from Wadi Al Yutum.
It seems from the steep slope of the most southern Wadi Araba aquifer that the inter-flow is small compared with the cross sectional area through which the groundwater pass.
Wadi Al Yutum possesses barrier conditions which were indicated during the pumping tests, it refers to the surface of the granite basement rocks under the alluviums along the wadi, where a discontinuity occurs between the different sub-basins. Accordingly the study area's basin receives from Wadi Al Yutum an overspill type of flow as excess of its groundwater. Otherwise the groundwater table in the wadi would be lower than what is found. Figure 45 presents a rough sketch of the situation.

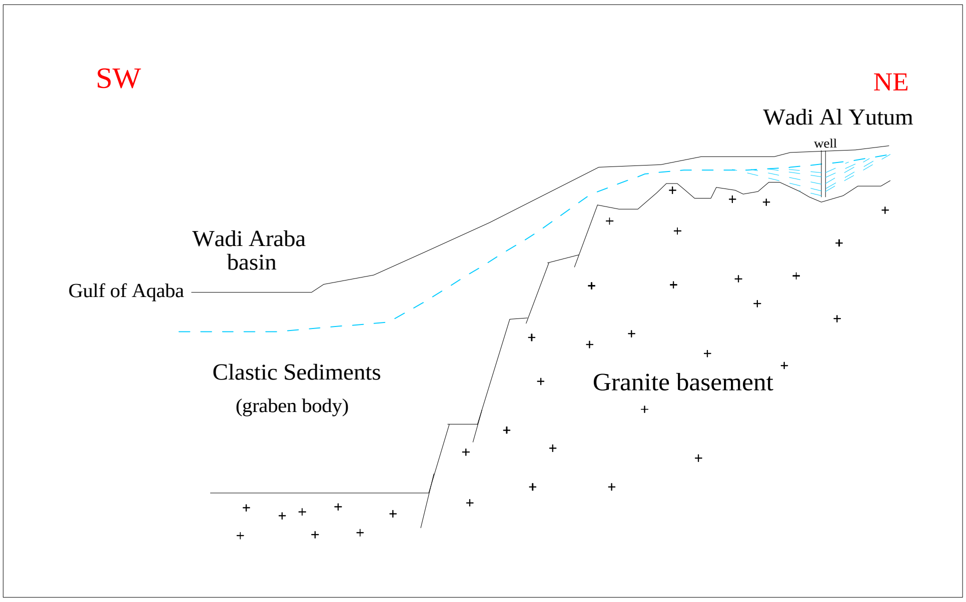


Fig. (45): Conceptuality of the flow pattern from Wadi Al Yutum to the aquifer under Aqaba.

2.5.4 Hydrogeological Parameters of the Aquifer as Obtained from Pumping Tests

The knowledge of hydraulic parameters that characterize the aquifers such as permeability, transmissivity, porosity and flow rate are required in any type of groundwater study such as delineation of protection zones, monitoring of landfills, groundwater pollution and resource evaluation. Quantification of hydraulic and mass transport parameters in a regional aquifer is only possible through numerous measurements in wells and boreholes. Domenico (1998) stated that a single well pumping test does not yield information on the storativity of the aquifer, where the tranmissivity can be obtained using the formula:

$$\mathbf{T} = \frac{2.3Q}{4p\Delta S}$$

Where T is the transmissivity of the aquifer,
Q discharging rate of the well,
△S is the drawdown per log cycle.

Another parameter which can be obtained from the single well pumping tests is the specific capacity $\mathbf{S}_C$. It is a basic figure of the performance of a well. High values indicate greater yield capabilities well.

$$\mathbf{S}_C = \frac{Q}{S}$$

the unit is expressed as the amount of water passing a unit of distance in a time unit m^3/m/hour, where S here is the stabilized drawdown in the well.

The Ram Group wells possess a permeability averaged as $1.6*10^{-5}$ m/s. (Water Authority, 1998).

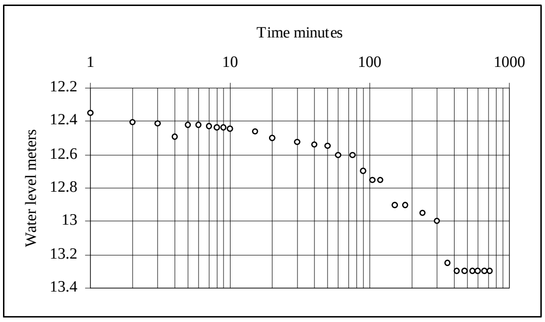
Wadi Al Yutum was investigated in term of its hydraulic parameters of the alluviums through the study carried out by MACDONALD (1966). The pumping tests carried out were able with the presence of observation wells to delineate the hydraulic parameters given in Table (18).

Table (18): The pumping tests carried results of the hydraulic parameters, in Wadi Al Yutum.

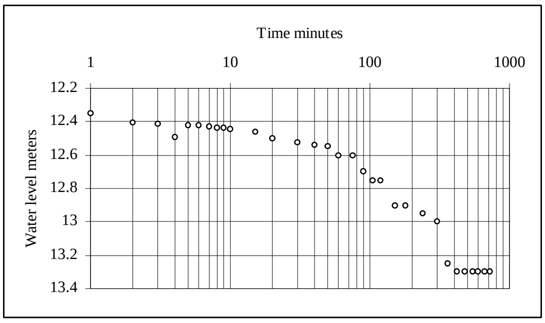
WELL NO.	METHOD	TRANSMISSIBILITY m^2/hour	THICKNESS meter	PERMEABILITY m/hour
2	Jacob Drawdown	126.6	4.16	30.43
	Jacob Recovery	103.8	4.16	24.95
	Average	115.2	4.16	27.69
3	Jacob Drawdown	46.56	21.4	2.17
	Jacob Recovery	49.67	21.4	2.32
	Average	48.11	21.4	2.25
5	Jacob Recovery	1.94	5.31	0.36
6	Theis	160.06	21.56	7.42

These tests have been performed with the presence of observation well only for borehole number 3. While the others have been treated as a single well case. Accordingly it was only possible to calculate the storage coefficient of the aquifer of Wadi Al Yutum for well number 3 which was found to be 4.2%.
Other data were collected from previous non-analysed pumping tests, which existed for different wells of the study area. They were handled as a single well pumping test because the tests have been carried out without observation wells. A single well pumping tests software (Single Well Solutions software, 1990) was used for this purpose.

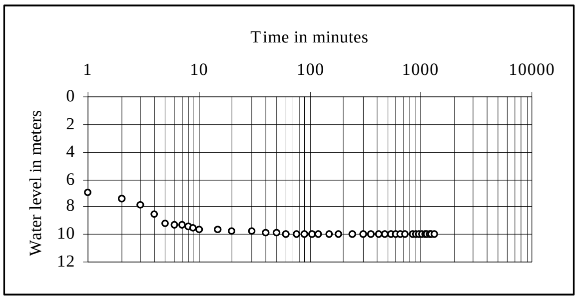
The rates of pumping in all the tests were constant (10 m^3/hour), until the level of water got constant, or approached a constant value. Accordingly the available software's option Hantush method (1964) was used.
One of the assumptions of this method is that the aquifer is confined or leaky confined. If the input data are from an unconfined aquifer the user must select the unconfined option, to allow the software to automatically correct the data for unconfined effects using Jacob correction. A representative specific yield value should be used (common range is 0.01 to 0.30). Figures (46, a, b, c, d, e) represent the plots of drawdown against time of the tests.



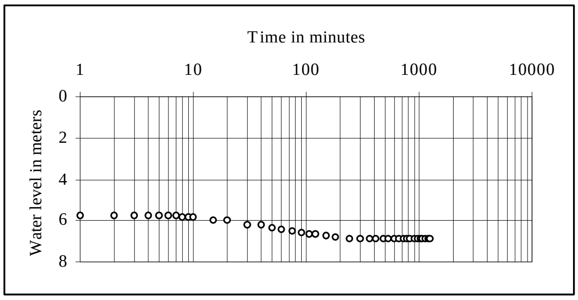
a. Hours Club well 1.



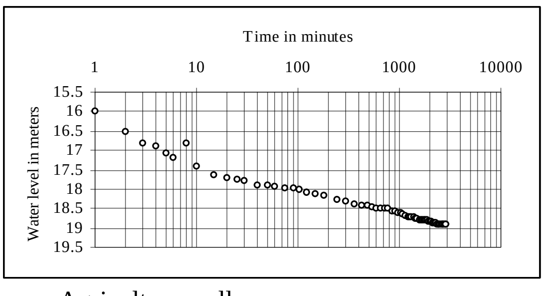
b. Aqaba Municipality well 2.



c. Hours club well 2.



d. Aqaba Municipality well 4.



e. Agriculture well.

Fig. (46, a, b, c, d, e): Drawdown against time of the different pumping tests carried out in the study area.

The pumping tests data processed by Hantush method for the unconfined aquifer resulted in the following permeabilities (K), and tranmissivities (T):

Aqaba Municipality well No. 4

T = $1.14*10^{3}$ m^{2}/day.

K = $4.34*10^{-4}$ m/s. Saturation thickness 30m.

Stabilized drawdown = 1.8 m.

Well specific capacity = 5.5 m^{3}/m/hour.

Aqaba Municipality well No. 2

T = $5.68*10^{2}$ m^{2}/day.

K = $2.16*10^{-4}$ m/s. Saturation thickness 30m.

Stabilized drawdown = 1.1 m.

Well specific capacity = 9.09 m^{3}/m/hour.

Hours Club well No. 2

T = $8.15*10^{2}$ m^{2}/day.

K = $3.10*10^{-4}$ m/s. Saturation thickness 30m.

Stabilized drawdown = 4 m.

Well specific capacity = 2.5 m^{3}/m/hour.

Hours Club well No. 1

T = $2.47*10^{3}$ m^{2}/day.

K = $9.38*10^{-4}$ m/s. Saturation thickness 30m.

Stabilized drawdown = 1.5 m.

Well specific capacity = 6.66 m^{3}/m/hour.

Agriculture well

T = $7.22*10^{2}$ m^{2}/day.

K = $2.74*10^{-4}$ m/s. Saturation thickness 30m.

Stabilized drawdown = 3 m.

Well specific capacity = 3.33 m^{3}/m/hour.

The permeabilities seem to be about an average of $3.5*10^{-4}$ m/s. It is anyhow less than those calculated in Wadi Al Yutum, which possesses higher values of permeability. That can be explained because of the presence of some permeable zones composed of larger grain sizes of sediments than those in the aquifer within the city of Aqaba.

The Archie's low is a formula derived from the theory which relates the geological formations in term of their water contents resistivity, formation resistivity, and porosity with each other.

If a geoelectric survey was applied in an area known for its groundwater resistivity – *the inverse of the electrical conductivity EC-* and rock type of the water bearing formation, then it is possible to calculate the dominant porosity of the formation. The formula was applied to

derive the porosity of some locations in the study area using a geoelectrical surveys that were applied close to the pumped wells.
The formula was applied on the layers considered to be saturated with water. Accordingly the formula has been modified to:

$$\textbf{Porosity} = \left(\frac{1000 * I}{r * EC}\right)^{\frac{1}{a}}$$

Where
The porosity is expressed here as a decimal number.
EC *is the water electrical conductivity, expressed as m S/cm.*
r is the formation resistivity in Ohm.m
I *and a are factors depend on the type of porosity and cementation, and they have been set here as 1.15 and 1.85 respectively.*

Accordingly the formula becomes:

$$\textbf{Porosity} = \left(\frac{1150}{r * EC}\right)^{0.541}$$

Some derived porosity's in the study area are shown in Table (18).

Table (18): Porosities of some wells in the study area, permeabilities and salinities.

LOCATION	X	Y	EC m S/cm	RESIS. Ohm.m	POROSITY %
Jamal Riati R.h	149159.39	883104.76	2280	6.20	25.73
Aq. Airport	151523.84	891897.17	3000	9.50	17.61
Wadi Al Yutum	153803.52	885680.61	1200	35.6	14.15
Ghabat Al Nakhel	148446.50	886312.80	3610	18.0	11.28
Wehdat Al Gharbia	149218.80	883722.60	1030	23.4	19.28
Eastern main police station	151012.93	883045.35	1800	6.10	29.50

The estimated values of the porosity using this method show a wide range, but comparing the different values with the spatial distribution of soils allows accepting these values, where the main parameters which control the value of the porosity are the grains sizes besides the sorting of the soil.

2.6 Hydrogeochemistry and Water Quality

2.6.1 Introduction

This section will be functioned to give information about the groundwater quality, besides the thermodynamics and mixing process, which may allow developing flow model of groundwater in the study area. Hydrogeochemical items of groundwater besides knowing the hydrogeological sets of the aquifer are the essential requirements to build the conceptual model which will assist investigating the aquifer.

The received amounts of water through the aquifer get naturally discharged by several processes such as evaporation from the shallow part of the aquifer and submarine groundwater discharge into the sea. There is no surface discharge occurs in the study area. Groundwater flow occurs mainly within the first 10-30 meters from the groundwater body, while the deeper parts also flow but slower because they cross longer pathway; along the sea-fresh water interface. Also as the depth increases, the compaction makes the sediments to be of lower yielding capacities comparing with the first 10-30 meters from the alluviums of the aquifer.
Encroachment of seawater into the aquifer rises the salinity of the groundwater in storage.

2.6.2 Methodology

The methods which are going to be followed to achieve the purposes expected from the section are:

- first to define the groundwater different chemical qualities, in term of several items. Classification of groundwater in respect of use and types will be carried out. Mapping the spatial distribution of the mobile conservative items as raster images, and the non-conservative types as points on the base map of the study area is useful to give primary indications on the relationship between the location and the concentration of the chemical items.
- the information of water quality, quantity and the spatial distribution of the different water end members will be used in developing a groundwater flow model in the study area. To achieve this purpose, a conceptual model should be built to understand the mechanism of recharge and discharge in the aquifer. Statistical study of water chemistry of the different locations, and resources should be carried out. Thermodynamics of the water-rock interactions in term of the geo-chemical processes will be calculated for the different water resources and locations. Inverse modeling by mixing different water end members and types is important in understanding their reaction pathways. Forward modeling to simulate the expected modifications on the water chemistry after evaporation, mixing and receiving other water types is important in adding understanding the expected processes to take a place within the flowing water in the aquifer. Calibration of the calculated results from the resulted model, with the observed and measured values in the field is of great importance in approaching the real processes.

2.6.3 Groundwater Quality

Through the phases of this research, the groundwater was defined to its quality. The analyses were carried out at two phases; in the spring of year 1999, and in the summer of year 2000.

Measurements on the physical items were carried out in the field, while the collected samples were analyzed for the first phase in the University of Jordan / Department of Geology, and for the second one in the laboratories of the University of Wuerzburg / Institute of Environment and Hydrogeology.
The samples included tap water from the drinking water net, groundwater, surface water from the Aqaba waste water treatment plant, and sea water. The analyses included the following items, of the major and minor components, and heavy metals;

Temperature, EC, pH, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, F^{-}, $SO4^{2-}$, $SiO2^{2-}$, $CO3^{2-}$, $HCO3^{-}$, $NO2^{-}$, $NO3^{-}$, $PO4^{3-}$, OH^{-}, $NH4^{-}$, DOC, BOD, Fe, Mn, Pb, Zn, Ni, As, Cu, Cr, Cd. All in addition to the biological analyses carried out on some water types, including Fecal Coliform, and some known algae.
The selection of these items was based on the wish to study the water in the study area, due to the natural settings, and to assess the human and the man-made constructions on it. Previous results of chemical analyses on some locations were collected.

The first approach to classify the water is in term of its contents of total dissolved solids (T.D.S) in mg/l. Table (19).

Table (19): Classes of water types due to the salinity.

CLASS	T.D.S (mg/l)
Fresh	0-1,000
Brackish	1,000-10,000
Saline	10,000-100,000
Brine	> 100,000

Accordingly, the majority of the samples gave a fit to the class of the brackish type of water, to indicate that it is out of the drinking regulations. See Figure (47).

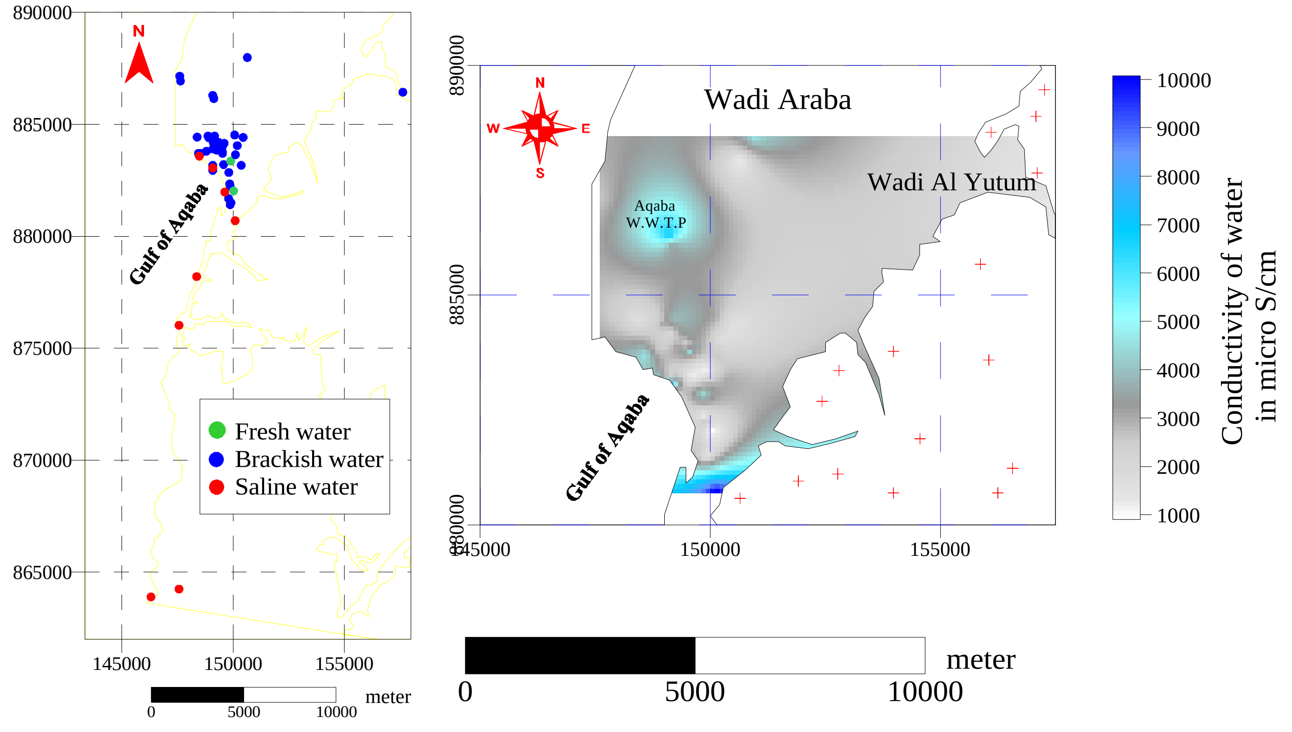


Fig.(47): Map of the spatial distribution of the water salinities (as EC value), and types in the study area, due to the filed measurements.

The natural trend of the aquifer zone under the city of Aqaba shows two water types; a brackish water, and a water type that approaches the fresh water in Wadi Al Yutum which has a conductivity less than 1200 m S/cm. From the *spatial analysis* of map Fig. (47) of water conductivity, it was possible to distinguish four major processes that affect the water quality:

- **mixing with fresh water types from Wadi Al Yutum, leakage of the drinking piped water, and from the recharge processes; the direct and indirect types**. *Light gray*.
- **mixing with the encroached sea water**. *Blue*.
- **Contamination from the pollution sources**. *Light blue*.
- **Evaporation from the shallow water bodies**. *Gray*.

The hydrochemical items of the groundwater in the study area, were exposed to a statistical analyses. Accordingly wide ranges were found to proceed in the chemistry between the different investigated locations; Table (20). These wide ranges indicate on different reaction processes that surely take place in the aquifer.

The electrical conductivity was found to range from 872-19650 m S/cm with an average of 3392. This wide range can be only attributed to the mixing with the sea water which is of a high conductivity (measured in this research as more than 45,000 m S/cm). A good example on that are the well of the southern Aqaba gas station which locates nearer to the main sea port, and the well of fertilizers company in the southern part of the study area. The distance between them and the shoreline is not more than 400 meters. They possess a conductivity of water as 10260 and 19650 m S/cm respectively.

The wide range of the temperatures of the groundwater here, is attributed to the mixing processes with other water phases from the surface, which are of lower temperatures. Good correlation was found between the depth of the groundwater and its temperatures, indicating to some extent on the geothermal gradient of the water.

Table (20): Statistical analyses on the hydrochemical constituents of the groundwater of the study area.

Item	Min	Max	Average	St. Dev.	Dev.	No. Samples
TC °	17.2	30.7	25.618	2.825	11.028	39
PH	6.83	8.35	7.563	0.429	5.673	41
EC m S/cm	872	19650	3392	3201.809	94.393	44
TDS mg/l	581.333	13100	2261.334	2134.54	94.393	44
Ca^{2+} mg/l	40.882	1373.622	195.115	215.579	110.488	43
Mg^{2+} mg/l	14.872	570.078	91.186	93.707	102.764	43
K^{+} mg/l	1.142	117.3	13.784	21.609	156.767	43
Na^{+} mg/l	49.658	551.76	237.611	105.105	44.234	43
Cl^{-} mg/l	120.53	3026.366	539.889	567.142	105.048	43
$SO4^{2-}$ mg/l	31.219	1755.496	494.94	385.082	77.804	43
$HCO3^{-}$ mg/l	38.076	512.568	175.154	92.011	52.531	43
$NO3^{-}$ mg/l	0	208.506	47.824	49.134	102.739	43
F^{-} mg/l	0.101	6.74	2.205	1.517	-	41

Piper diagram was used to represent the dominant water categories in the study area, and resulted on Figure (47). The diagram consist of three parts: Two trilinear diagrams along the bottom and one diamond-shaped diagram in the middle. The trilinear diagrams illustrate the relative concentrations of cations (left diagram) and anions (right diagram) in each sample. For the purposes of a Piper diagram, the cations are grouped into three major divisions: Sodium (Na^{+}) plus Potassium (K^{+}), Calcium (Ca^{2+}) and Magnesium (Mg^{2+}). The Anions are similarly grouped into three major categories: Bicarbonate ($HCO3^{-}$) plus Carbonate ($CO3^{2-}$), Sulfate ($SO4^{2-}$) and Chloride (Cl^{-}). Each sample will be represented by a point in each trilinear diagram.

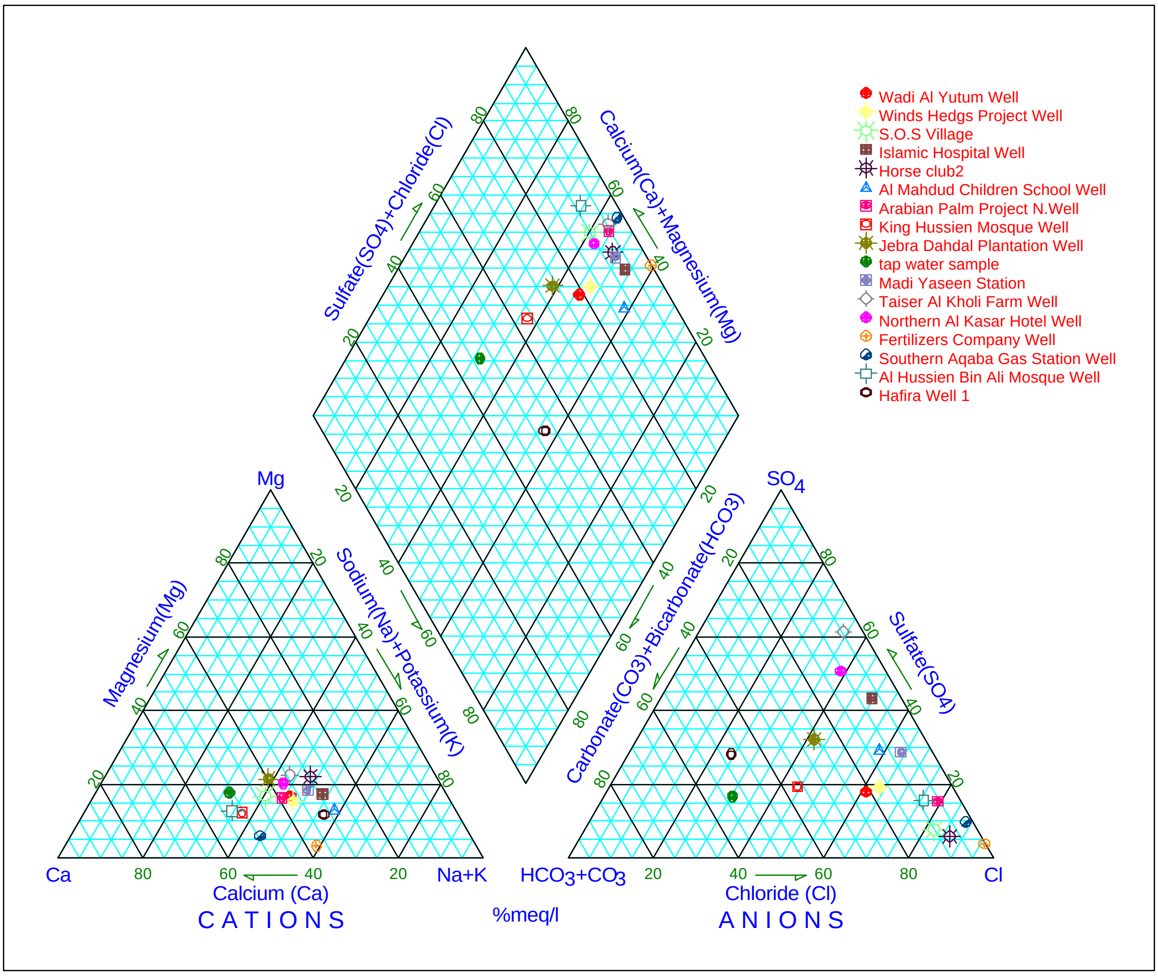


Fig. (47): Classification results of the groundwater using Piper diagram.

The classification resulted on two major groups of water;

1. Earth alkaline water, with increased portion of alkalies, with prevailing sulphate.
2. Alkaline water, with prevailing sulphate and chloride.

<u>Discussions on the quality of some representative and extreme samples from the groundwater in the study area in term of the general drinking water regulations, water types, and the suitability for irrigation are available in **appendix A.** Also it includes **Table (21)** about Water hardness classes, and **Table (22)** about Drinking Water Quality for Humans, Livestock & Poultry (*Recommended Maximum Levels).*</u>

It is clear from the detailed discussion in **appendix (A)** that the groundwater is of high salinity in general and possess relatively high sodium absorption ratios –SAR-. The samples fit in term of their hardness as hard and very hard water. For the majority of the samples, they exceeded the maximum allowed drinking water regulations. **Accordingly the groundwater of the study area is out of drinking purposes.**

Biological oxygen demand of five days (BOD_5): This reflects the need of groundwater for oxygen to decompose the organic compounds. The value should be zero when the water is free of organic pollutants. The tests which were carried out within this study at the University of Jordan showed zero values. Only a few samples had values of around 10 mg/l, which confirms their pollution.

Dissolved organic carbon DOC, is the simplest measure of the total concentration of organic solutes, it can be measured by converting all the organic material in solution to CO_2 and then measuring the produced CO_2. *Normally the value should not exceed 0.5 mg/l* to indicate good water quality. *Values exceeding that indicate pollution (Drever, 1982).*
DOC was measured in the laboratories of the University of Wuerzburg on 17 samples. The average value for all of the samples was 3 mg/l. This indicates the presence of dissolved organic matters in the aquifer.

Fecal Coliform, and Coliform bacteria occur naturally in the human digestive tract assisting in the digestion of food. They get into the groundwater bodies by direct leakage of septic waters. The presence of this type of bacteria in water gives indications on the presence of other more harmful pathogenics. Coliform bacteria are virtually everywhere in the environment. Their presence does not necessarily indicate contamination by human or animal wastes. All water should be 100% free of Fecal Coliform to be considered as safe drinking water.
Samples collected from the study area, and sent in the same day to the laboratory of the University of Jordan were free of the Fecal Coliform, only the inlet waste water of Aqaba waste water treatment plant contained some 2500 Coliform/ml.

Heavy metals give indications on the possibility of the industrial pollution if values are in excess of the expected concentrations of the aquifer. The collected groundwater samples were analyzed on their contents of Zn, Fe, Ni, As, Cu, Cr, Cd, and Pb. Respectively the maximum world admissible concentrations are 100, 300, 50, 50, 50, 50, 5 and 50 p.p.m (WHO, 1996). The groundwater samples showed low concentrations of the above mentioned heavy metals. Only the well of Horse club 2 (Racing club), and the Fertilizers Company well showed high values of Zn and Fe. The southern part of the study area includes industrial activities, but within the city no such activities exist. The high values are attributed to corrosion processes of wells casings.
The behavior of the hydrochemical constituents of the different wells is shown in Figure (48). The relative abundance of constituent is very similar for the areas waters.

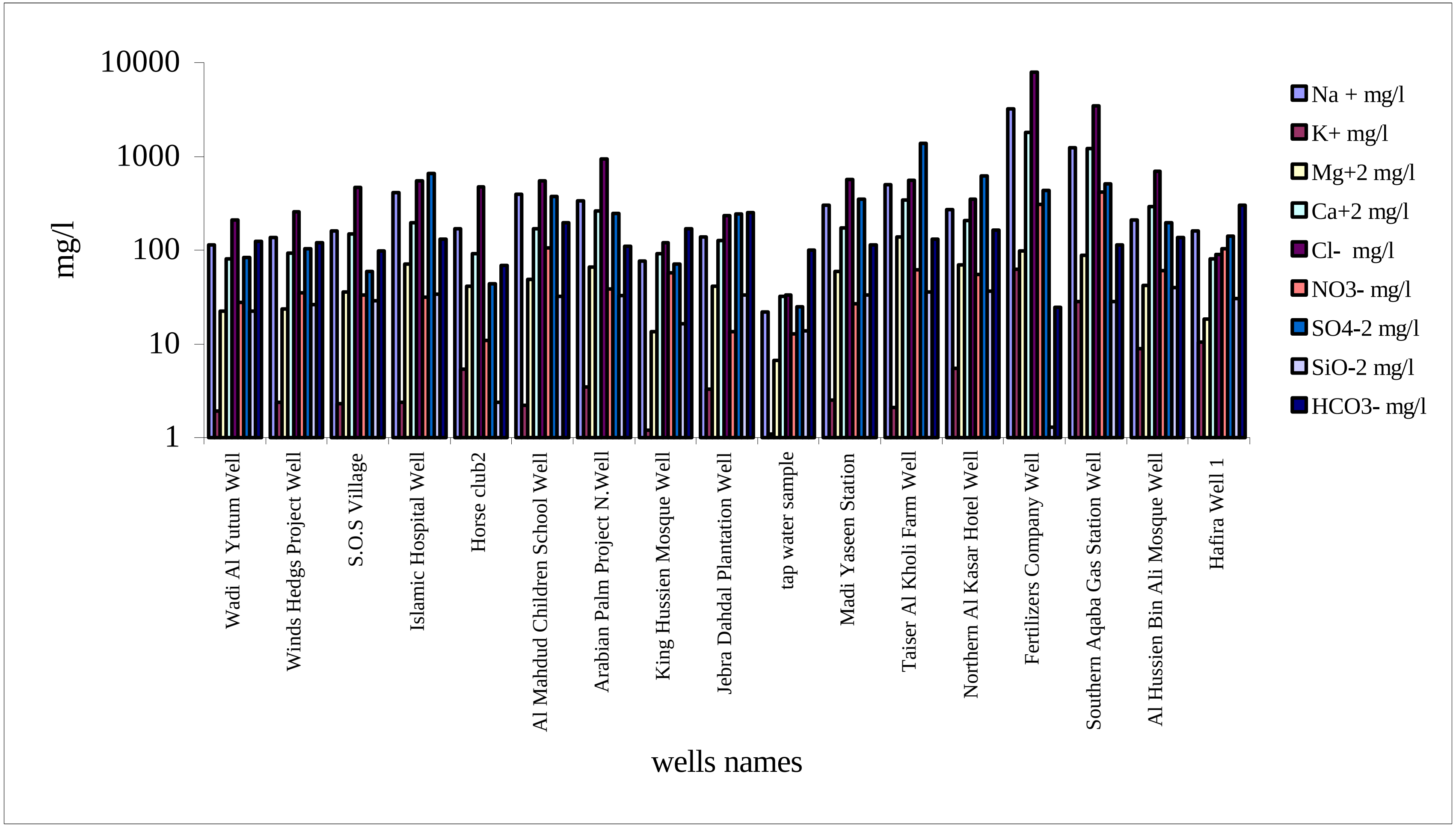


Fig. (48): Hydrochemical constituents in the different wells.

Some representative samples of the aquifer water are given in Table (23) to illustrates the water quality in terms of major and minor chemical components. These analyses were carried out in June/2000.

Table (23): Hydrochemical composition of the groundwater in the study area.

NAME	X	Y	PH	E.C	Na + mg/l	K+ mg/l	NH4+ mg/l	Mg2+ mg/l	Ca2+ mg/l	OH- mg/l	Cl- mg/l	NO2- mg/l	NO3- mg/l	SO42- mg/l	PO43- mg/l	SIO2- mg/l	HCO3- mg/l	F- mg/l	BOD mg/l	DOC mg/l	Zn mg/l	Fe mg/l	*Ni* mg/l	AS mg/l	CU mg/l	CR mg/l	CD mg/l	PB mg/l
Wadi Al Yutum	157637	886429	7.79	1048	114	1.9	0.0228	22.2	80.3	0.0105	210	0.087	27.5	83.8	0.05	22.1375	124.44	1.5	0	1.3	0.014	0.021	0.0002	0	0.0008	0.0043	0	0.002
Winds Hedges P.	150644	887976	7.96	1205	136	2.4	0.018	23.5	93.1	0.0155	256	0.067	35.3	104.2	0.09	26.1338	119.56	1.4	0	1.9	0.014	0.069	0.0016	0	0.0013	0.0141	0	0.002
S.O.S	150454	884411	8.04	1647	160	2.3	1.3642	35.7	150	0.0186	461.6	0.055	33.2	59	0.05	28.875	97.6	1.5	0	2.2	0.171	0.516	0.001	0	0.0012	0.0056	0	0.0016
Islamic Hospital	150109	883639	7.85	2225	411.4	2.4	3.441	71.4	195.8	0.0120	548.4	0.096	31.2	649.2	0.05	34.034	131.76	2.1	0	4.3	0.015	0.183	0.0008	0	0.001	0.009	0.00014	0.0041
Horse club 2 (Racing club)	148387	884423	7.56	1636	169	5.4	2.9862	41.6	92	0.00617	470.8	0.027	10.8	43.4	0.05	2.4	68.93	1.4	0	4.8	6.595	10.63	0.002	0	0.003	0.0028	0.00001	0.0072
Children School	150074	884518	7.49	2592	396.2	2.2	2.687	48.2	167.8	0.00526	542.4	0.096	105.2	375.6	0.05	32.186	193.98	1.8	0	2.8	0.141	0.019	0.0013	0	0.0012	0.0103	0.00003	0.0017
Palm P. N. Well	149088	886289	7.61	2258	338	3.5	0.3593	65.9	261	0.00693	932	0.027	38.6	246.6	0.05	32.9175	109	1.5	0	1.6	0.014	0.012	0.001	0	0.001	0.0083	0.00004	0.0013
King H. Mosque	150026	882023	7.45	745	76.4	1.2	1.2075	13.5	91.6	0.00479	119	0.052	57.3	70.5	0.05	16.43	168.97	0.7	0	2.5	0.026	0.087	0.0003	0.0001	0.0014	0.0042	0.00001	0.0013
J. Dahdal Plantation	149099	883900	7.57	1085	138.9	3.3	1.1565	41.4	126	0.00632	233	0.067	13.4	244	0.05	33.18	250.1	2.4	0	2.6	0.047	0.06	0.0004	0	0.0011	0.0068	0.00002	0.0011
tap water	-	-	7.58	344	21.9	1.1	1.7193	6.7	31.8	0.00647	32.96	0.023	12.7	24.76	0.05	13.77	99.4	0.3	10	3	0.063	0.046	0.0003	0	0.0029	0.004	0.00014	0.0012
M. Yaseen	150193	884043	7.66	1661	301	2.5	2.1428	59.2	171	0.00777	568	0.058	26.7	346.2	0.087	33.30	113.46	2.3	0	2.7	0.013	0	0.0003	0	0.0012	0.0078	0.0001	0.0011
T. Kholi Farm	149171	884471	7.48	3510	497	2.1	26.468	137.4	343.6	0.00514	556.8	0.069	61.6	1364.4	0.05	35.67	130.54	3.6	10	4	0.014	0.064	0.001	0	0.0013	0.0108	0.00004	0.0017
Al Kasar Hotel	149812	882843	7.48	2127	271.6	5.5	2.5195	69.2	206.8	0.00514	350.4	0.093	54.8	622	0.05	36.28	163.48	3	10	3.1	0.048	0.086	0.0005	0.0001	0.0023	0.0057	0.00018	0.0012
Fertilizers Company	147571	864241	6.36	21080	3192	62.8	0.7315	98.2	1788	0.00039	7920	0.075	304	428	0.05	1.28	24.4	0.45	10	4.5	0.059	24.28	0.002	0.0002	0.0014	0.0044	0.00006	0.0148
S. Aqaba Gas Station	150098	880692	6.68	7150	1220	28.5	0.913	87.8	1200	0.00081	3424	0.205	419	511	0.05	28.41	112.85	1.5	0	2.5	0.018	0.047	0.0011	0	0.0038	0.0095	0.00038	0.0028
H.Bin Ali Mosque	149872	882237	7.41	2193	211	8.9	0	42.4	288.8	0.00437	696	0.057	60.4	195.6	0.05	39.88	135.42	2.3	10	2.8	0.238	0.094	0.0005	0	0.0026	0.0043	0.00017	0.0025
Hafira Well 1	149872	881405	7.53	990	159	10.5	0	18.3	80.5	0.00576	89.4	0.11	104	141	0.05	30.60	302.56	1.8	10	3.5	0.041	0.167	0	0	0.0016	0.0051	0.00014	0.0026

2.6.4 Mathematical Approaches on the Relationships Among the Different Hydrochemical Constituents

The groundwater quality is a function of the water origin, geochemistry of the aquifer and aquifer internal and external processes. When the aquifer receives some waters from leakage of sewerage, an excess in nitrate, phosphate, potassium and sulfate in the groundwater can be expected. These parameters should correlate positively with each other for a population of samples from the same contaminated aquifer, since the waste water is rich with respect to these elements. If the aquifer receives some industrial liquid wastes, an increase in the concentration of industrial wastes -such as heavy metals- should be expected. The hydro-biogeochemical reactions have an impact on the mathematical relationships among the groundwater chemical constituents. They can reflect the lithology of the aquifer, the mixing processes between the water end members and the activities that take place on the aquifer including human impacts.

Several processes take place in the aquifer such as pollution from human and industrial activities, seawater intrusions, supply net work leakages and recharge along side wadis.
The results of (Table 23) were exposed to a regression analyses. Accordingly the obtained mathematical relationships from the regression analyses can be used to shed the light on the origin of the chemical constituent in the groundwater, and to estimate the groundwater chemistry of the southern part of the study area, which has only one well. The geoelectrical surveys gave estimates on the groundwater levels and salinity –using Archie's low- in areas with no wells.
The different constituents were plotted against the water EC. Strong positive relationships were revealed between the EC and Na^{+}, K^{+}, Mg^{2+}, Ca^{2+}, Cl^{-}, $NO3^{-}$ and $SO4^{2-}$. While a strong negative mathematical relationships were revealed between EC and pH, $HCO3^{-}$ and OH^{-}.
With the increase in the conductivity to more than about 10,000 μ S/cm

, the $SiO2^{2-}$ and F^{-} start to precipitate as a solid phases.
Figures (49;a,b,c,d,e,f,g,h,i,j,k,l,m) show the different regression diagrams. The trend analyses was repeated several times for each diagram to approach the best fit. Table (24) illustrates the different mathematical relationships and the R values.

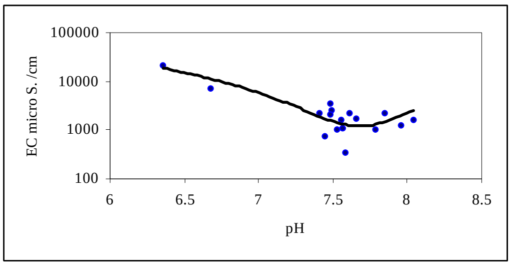


Fig. (49a): Regression between EC and pH.

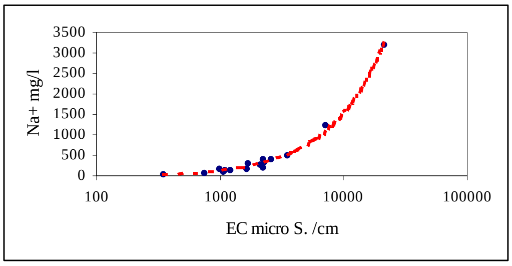


Fig. (49b): Regression between EC and Na^{+}.

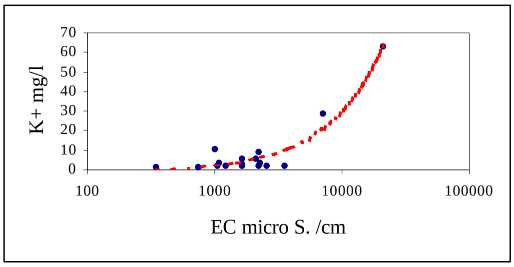


Fig. (49c): Regression between EC and K^{+}.

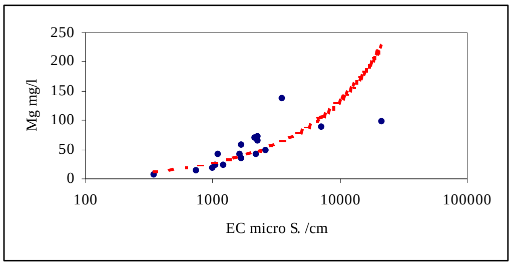


Fig. (49d): Regression between EC and Mg^{2+}.

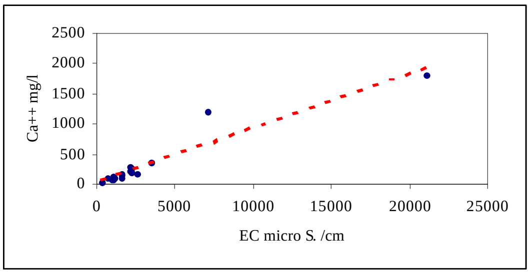


Fig. (49e): Regression between EC and Ca^{2+}.

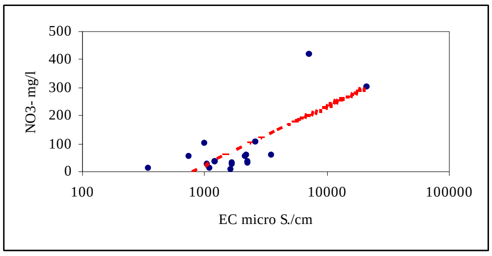


Fig. (49f): Regression between EC and $NO3^{-}$.

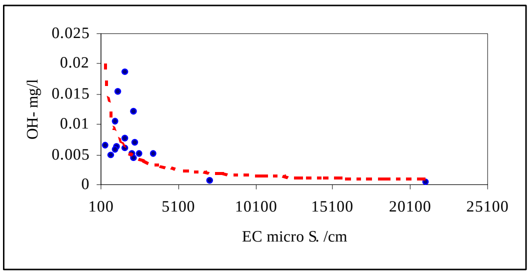


Fig. (49g): Regression between EC and OH^{-}.

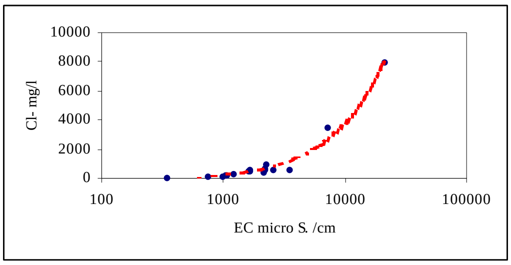


Fig. (49h): Regression between EC and Cl^{-}.

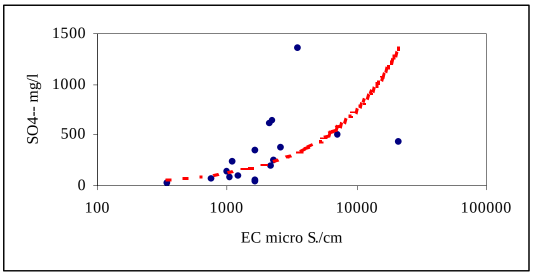


Fig. (49i): Regression between EC and $SO4^{2-}$.

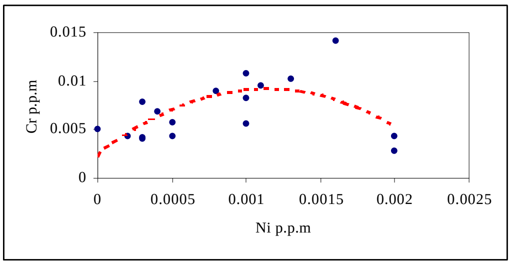


Fig. (49j): Regression between Ni and Cr.

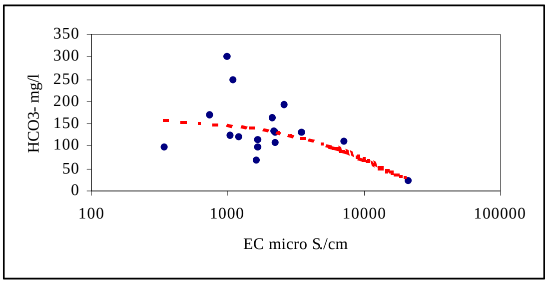


Fig. (49k): Regression between EC and $HCO3^{-}$.

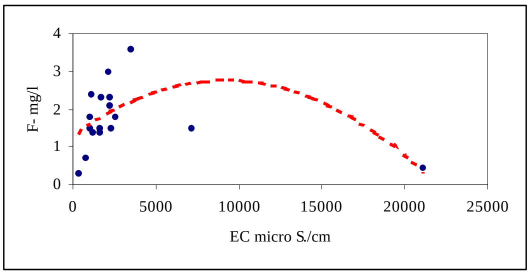


Fig. (49l): Regression between EC and F^{-}.

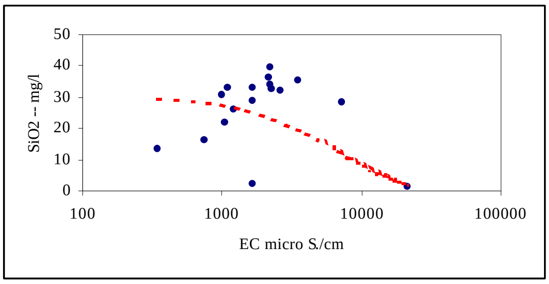


Fig. (49m): Regression between EC and $SiO2^{2-}$.

Detailed correlation plots were carried out for the different hydrochemical parameters in the groundwater for the two sampling phases. Figure (50) illustrates the correlation fits of the second sampling phase of the groundwater, while Figure (51) illustrates the correlation fits of the first phase. The general trend of the fits is in accordance with the hydrochemistry of the groundwater.

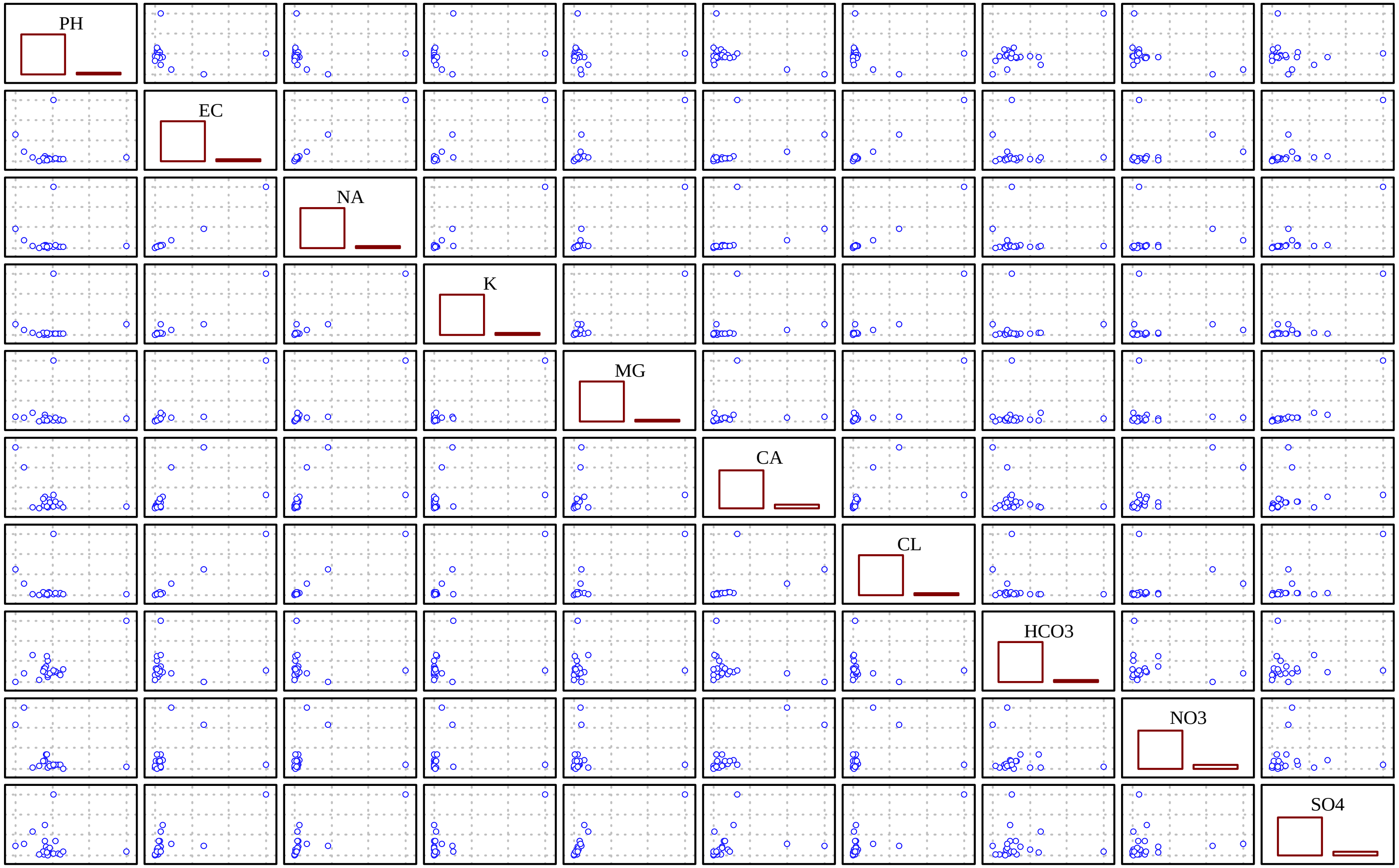


Fig. (50): Correlations of parameters for the second sampling phase.

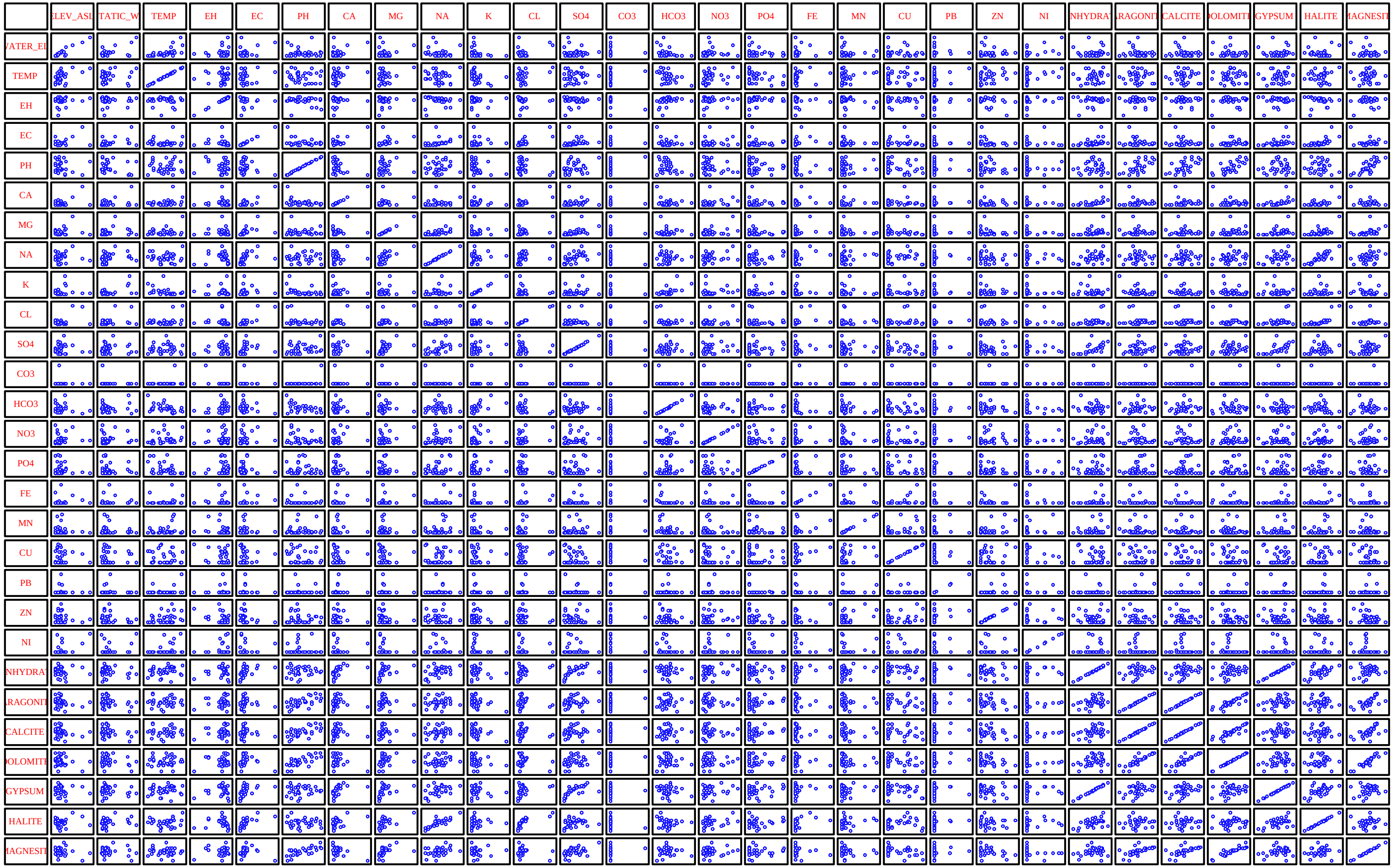


Fig. (51): Correlation of parameters for the first sampling phase.

Table (24): Mathematical relationships and R values for some parameters.

RELATIONSHIP	EQUATION	R^2
PH-EC	**EC = (10111pH^2)-(155214*pH)+596884**	0.9133
EC - Na+	**Na = (0.1546*EC)-26.895**	0.9936
EC - K+	**K = (0.0031EC)-1.0199**	0.9347
EC - Mg^{2+}	**Mg = 0.1972*EC$^{0.707}$**	0.6875
EC - Ca^{2+}	**Ca = 0.0905*EC+31.124**	0.9049
EC - Cl^{-}	**Cl = (0.3932*EC)-213.05**	0.9776
EC - $NO3^{-}$	**NO3 = [90.324*Ln(EC)]-599.32**	0.5529
EC - $SO4^{2-}$	**SO4 = 0.4747*EC$^{0.7991}$**	0.4417
EC - SiO2	**SiO2 = 30.973*e$^{-0.0001*EC}$**	0.4246
EC - $HCO3^{-}$	**HCO3 = 160.08*e$^{-8E-05*EC}$**	0.5669
EC - F^{-}	**F = (-2E-08*EC^2)+(0.0003*EC)+1.2921**	0.2954
N i - Cr	**Cr = (-5147.9*Ni^2)+(11.783*Ni)+0.0024**	0.4237

2.6.5 Water-Rock Interactions, Thermodynamic and Geochemistry of the Groundwater

Due to its molecules physical properties, water, being an excellent solvent, can dissolve gases, liquids and solids and thereby increase concentrations of solutes in ground water.

Domenico & Schwartz (1998) stated that there are three important acid-base reactions commonly occurring in ground water. First is the *dissociation of water* into hydrogen ions [H^+] and hydroxide ions [OH^-].

$$H_2O + H_2O = H^+ + OH^-$$

Second are the reactions involved in the *solution of CO_2 gas into water*.

$$CO_2(g) + H_2O = H_2CO_3$$
$$H_2CO_3 = HCO_3^- + H^+$$
$$HCO_3^- = CO_3^{2-} + H^+$$

The third are the reactions involving the *solution of solid silica into water*.

$$SiO_2(s) + H_2O = H_2SiO_3$$
$$H_2SiO_3 = HSiO_3^- + H^+$$
$$HSiO_3^- = SiO^{2-} + H^+$$

The second reaction set is measured by pH while the third by alkalinity.
The pH of groundwater controls which type of carbonate or silicate occurs in solution. In acidic solutions, H_2CO_3 is the dominant carbonate anion, followed by HCO_3^-, then CO_3^{2-} as solutions become more basic. A similar progression would be seen in silicates from H_2SiO_3 to $HSiO_3^-$ to SiO^{2-} as solutions pass from acidic to basic conditions. The carbonate and silicate ions serve as strong bases.
Alkalinity is defined as the net concentration of strong base in excess of strong acid with a pure CO_2 - water system as a point of reference. It is controlled by pH and the concentrations of strong bases such as carbonate and silicate ions.
Strong acids are not common in natural ground water. Their occurrence represents contamination from human activity. The solution of silicate and carbonate minerals does provide strong bases in solution in natural situations. Consequently, as groundwater flows through an aquifer, it dissolves more carbonate and silicate minerals thereby increasing the alkalinity and the pH.

Gas enters (i.e., is dissolved) groundwater in large concentrations in the aeration zone through the soil atmosphere (i.e., the part of the intergranular spaces not filled by water). The greater the concentration of the gases in the soil, the more gas dissolved into the capillary films. Photosynthesis and atmospheric diffusion add O_2 into the soil atmosphere. Moreover, respiration and decomposition of organic matter provides additional CO_2 to that diffused from the atmosphere. In addition, decomposition and bacterial metabolic processes also provide gaseous H_2S, CH_4, and NH_3 into the soil atmosphere. These, in turn, may oxidize in the soil atmosphere, forming CO_2, CO, SO_2, NO_2, and N_2. All these gases are diffused into capillary films and are then dissolved. The concentration depends on the concentration in the soil and the solubility of the individual gases.
These gases are generally held in solution as hydrostatic pressure increases down the ground water flow path. But once approaching ground water discharge sites, the hydrostatic pressure decreases, thereby stimulating ex-solution (i.e., the formation of gas bubbles) and volatilization (i.e., the return of these gases from the liquid environment of ground water into the gaseous atmosphere).
The saturation states of the minerals in the ground water of the study area were calculated by using the software HYDROWIN version 3.
The method is to calculate ion activities, CO2 pressure, ion strength and mineral saturation indices of a selected sample.
The activity (a) of an ion (i) is related to the measured concentrations (m) by the expression $a_i = g.m_i$ where g is the activity coefficient which can be calculated by means of the Davies equation valid up to an ionic strength of 0.5:

$$g_i = -Az_i^2 \left(\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3*I\right)$$

where, A is a temperature dependent coefficient and I is the ionic strength:

$$I = 1/2 \Sigma m_i . z_i^2$$

Where, zi = charge of ion i, mi = molality of ion i (mol/l).
The distribution at equilibrium between the species of the generalized reaction aA+bB ⇔ cC+dD is described by the expression:

$$K(T)=\frac{[C]^c.[D]^d}{[A]^a.[B]^b}$$

where K is the equilibrium constant for a given temperature and the bracketed quantities denote activities or effective concentration.

Saturation Index **SI = Log (IAP / KT)**

Where IAP is the ionic activity product.

When the ionic activity product IAP is more than the reaction constant KT, the mineral in question will be precipitated from the solution, in the other hand when IAP is less than KT, the mineral in question will be exposed for more dissolution. If both of the values are equal, then the logarithm of the division result which is 1, will be zero, accordingly it indicates that there occurs an equilibrium.
Samples below SI=0 are undersaturated, and above that are oversaturated. Values approaching zero represent the equilibrium state of the water with the mineral in question (Lioyd & Heathcote, 1985).

The average EC of the groundwater in the study area is 3392 μ S/cm, pH as 7.56, and the temperature 25 C degree. The mineralogical composition of the aquifer's matrices through which the groundwater passes is a reflection of the country rock granite whose weathering products contain silicate rich minerals.
Calculations on the water-rock interactions of different groundwater samples, and piped drinking water samples were carried out including calculations on ion ratios of Na/Cl, Ca/SO4 and Ca/Mg that were compared to the same ratios in seawater. Other calculations on the dissolved minerals which are defined as weight in mg/l of the following minerals: halite, sylvite, sulphate, calcite, chalcedony (quartz) or Na feldspar, were carried out. The minerals are numerically "precipitated" according the following procedure:

- *Build sylvite (KCl), subtract Cl.*
- *Build halite (NaCl), subtract Na, Cl.*
- *Build Anhydrite, subtract Ca, SO4.*
- *Build dolomite, subtract Ca, Mg.*
- *Build calcite with the remaining amount of Ca.*
- *Build either quartz or Na feldspar (if still any Na available) with SiO2.*

Appendix (B) contains the calculations results on the water-rock interactions.

Calculations on the saturation indices on minerals in the groundwater were carried out. It was important to investigate these indices of the present minerals within the aquifer's matrices. The investigated minerals included, Calcite, Aragonite, Dolomite, Magnesite, Quartz, Chalcedony, Gypsum, Anhydrite and Fluorite. Table (25).
The resulted saturation indices for the different minerals indicate as a general trend that the groundwater is saturated with respect to them with exception of Gypsum, Anhydrite and Magnesite, which tend to be in the under-saturation state. The Fluorite was of two trends; a part of the samples was tending to precipitate Fluorite, while the other part was tending to dissolve it. This fluctuation refers to human impacts on the aquifer; groundwater samples which showed positive saturation indices are those taken from wells of farming or plantation areas, where some types of fertilizers with components of fluorite are in use.

Figure (52) shows a plot between the different well's groundwater and the saturation indices of the minerals.
Positive trends are found between the SiO2 concentration and the pH values. It is the normal case in groundwater, where the soluble phase of SiO2 ions increases with increasing the alkalinity (pOH). Figure (53) illustrates this trend.

From the other point of view, heavy metals show a negative correlation with the pH value because they are soluble in waters of low pH. Figure (54,a,b,c,d), shows correlation between the pH, and some different heavy metals from the study area.

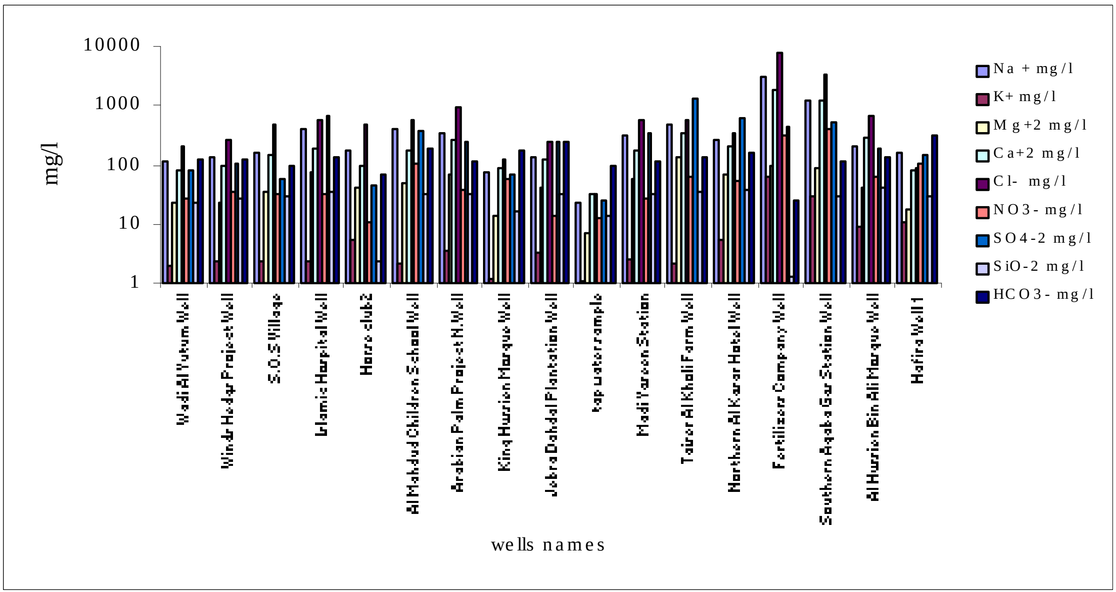


Fig. (52): Saturation indices of the minerals in the groundwater of the area.

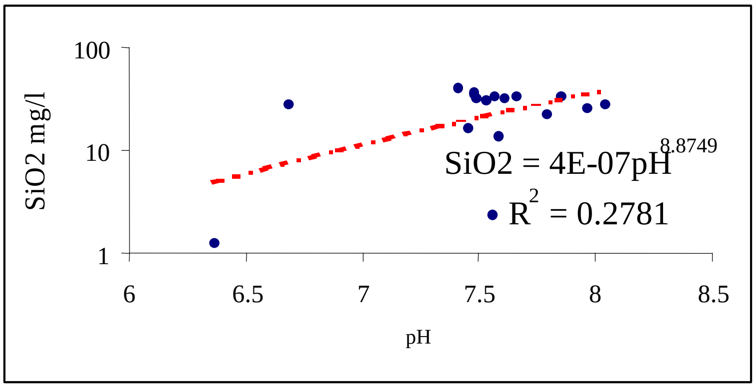


Fig. (53): Trend between pH and SiO2--.

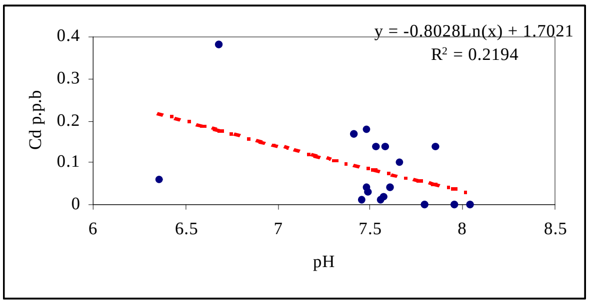


Fig. (54a): Correlation between pH and Cd.

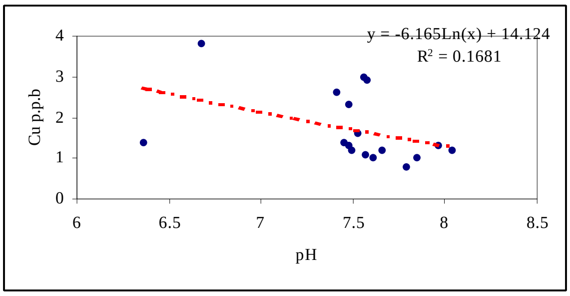


Fig. (54b): Correlation between pH and Cu.

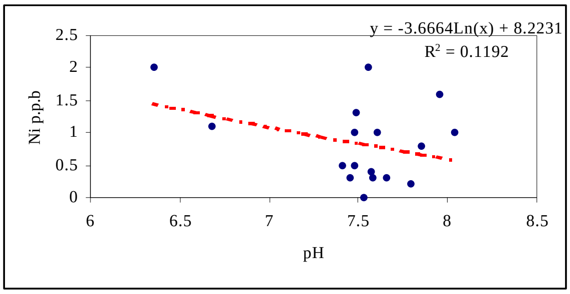


Fig. (54c): Correlation between pH and Ni.

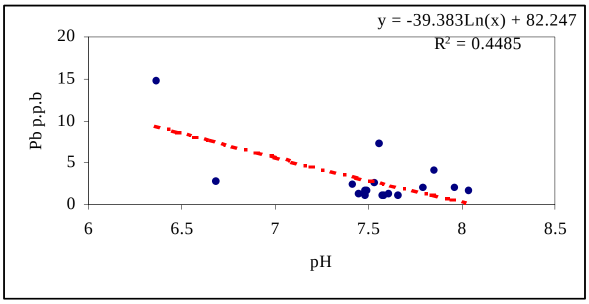


Fig. (54d): Correlation between pH and Pb.

Mixing of two kinds of groundwater saturated with respect to calcite tends to increase its solubility –lowering SI- in water. Mixing processes generally shifts the water chemistry of the two mixed solutions in a middle state between them depending on the mixed ratios (Bloom 1978).

Also mixing of groundwater with waste water from septic systems tends to lower the saturation indices of the carbonate minerals. That can be attributed to the organic matter content of waste water producing CO2 gas by the decomposition in the presence of oxygen, which in turn dissolves in water to lower the pH value, making it more aggressive. Accordingly the solubility increases. An example on the mixing process of two water types is the Winds Hedge well. Here the groundwater flows from Wadi Al Yutum mixes with that which flows from the southern part of Wadi Araba and the recharge waters from the side wadis.

An example on the mixing process between the groundwater and waste water is the well of King Hussein Mosque, where the surrounding residential area discharges its waste water into instead dug holes.

The industrial complex at the southern part of the study area has impacts on the saturation states of the minerals. The water of the Fertilizers Company's well possesses pH value of 6.36, which was reflected on the saturation indices of the different minerals. They were as a whole under-saturation. The salinity has a noticed role in increasing the saturation indices of the minerals –shifting them to the saturation state- in the groundwater. The different saturation states of the different minerals were plotted against the water electrical conductivity EC, and resulted in Figure (55).

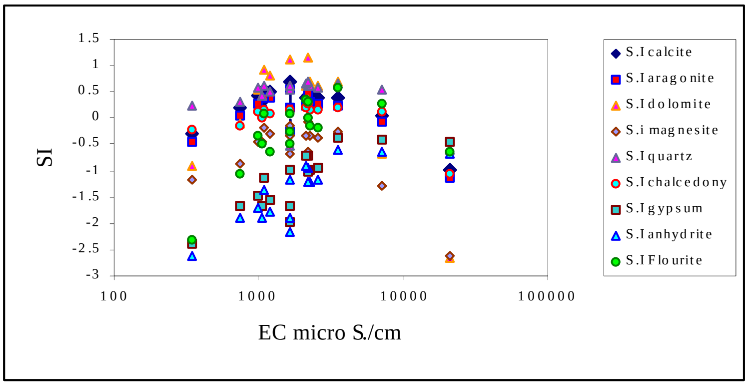


Fig. (55): Correlation of the EC values and the calculated saturation indices.

It seems that the SI-values decrease after the EC value exceeds of 10,000 µ S/cm. The cause here is that some of these SI-values are of Fertilizers Company well which possesses a lower pH. Accordingly the pH was stronger in lowering the SI than the EC, which tends generally to rise it. Increasing EC-value leads to over-saturation states.
The saturation states were correlated with the pH values of the water. It was found that with increasing pH, minerals in general tend to show higher values SI (Figure 56).

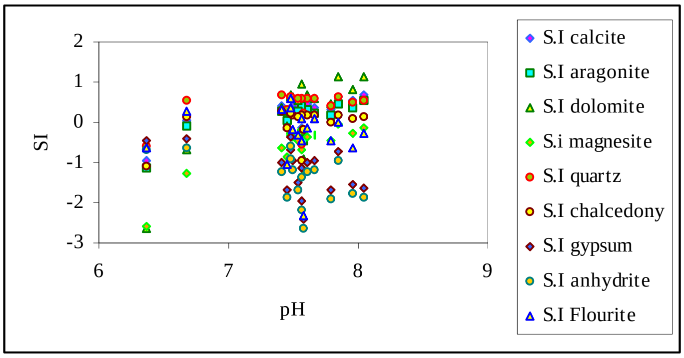


Fig. (56): Correlation of pH-values and the minerals SI-values.

The spatial distribution of the SI of calcite, quartz and gypsum (Figure 57,a,b,c), illustrates the role of mixing processes with seawater in decreasing the SI-values. The water coming from Wadi Al Yutum seems to possess relatively low SI-values.

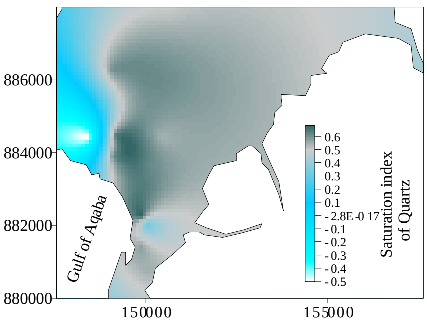
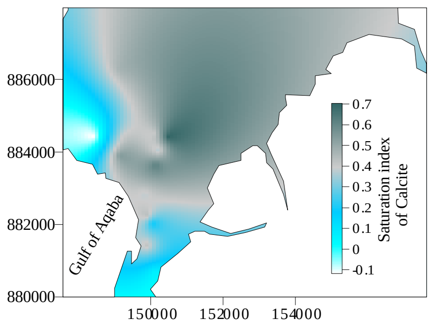


Fig. (57,a): Spatial distribution of Quartz S.I of the groundwater.



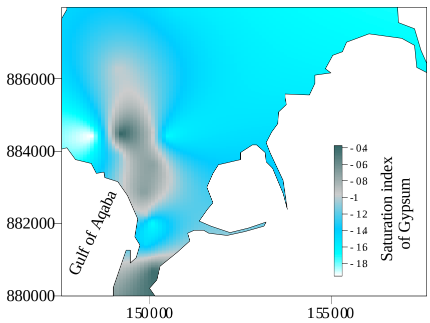


Fig. (57,b): Spatial distribution of Gypsum S.I of the groundwater.

Fig. (57,c): Spatial distribution of Calcite S.I of the groundwater.

NAME	X	Y	S.I CALCITE	S.I ARAGONITE	S.I DOLOMITE	S.I MAGNESITE	S.I QUARTZ	S.I CHALCEDONY	S.I GYPSUM	S.I ANHYDRITE	S.I FLOURITE
Wadi Al Yutum Well	157637.7	886429.68	0.326	0.182	0.441	-0.452	0.431	0.002	-1.667	-1.887	-0.471
Winds Hedgs Project Well	150644.6	887976.23	0.526	0.383	0.802	-0.292	0.502	0.072	-1.542	-1.762	-0.652
S.O.S Village	150454.49	884411.74	0.704	0.561	1.134	-0.138	0.545	0.116	-1.656	-1.876	-0.257
Islamic Hospital Well	150109.92	883639.43	0.621	0.477	1.141	-0.048	0.619	0.19	-0.723	-0.944	-0.003
Horse club2	148387.09	884423.62	-0.123	-0.266	-0.241	-0.686	-0.531	-0.961	-1.957	-2.177	-0.473
Al Mahdud Children School Well	150074.28	884518.67	0.407	0.263	0.614	-0.38	0.598	0.168	-0.95	-1.171	-0.164
Arabian Palm Project N.Well	149088.1	886289.04	0.471	0.327	0.689	-0.349	0.607	0.177	-0.985	-1.205	-0.133
King Hussien Mosque Well	150026.75	882023.53	0.187	0.043	-0.11	-0.865	0.304	-0.126	-1.665	-1.885	-1.05
Jebra Dahdal Plantation Well	149099.99	883900.83	0.539	0.396	0.939	-0.168	0.61	0.18	-1.138	-1.359	0.079
Madi Yaseen Station	150193.1	884043.41	0.365	0.221	0.612	-0.321	0.611	0.182	-0.965	-1.185	0.087
Taiser Al Kholi Farm Well	149171.28	884471.14	0.385	0.241	0.699	-0.254	0.644	0.215	-0.36	-0.581	0.573
Northern Al Kasar Hotel Well	149812.88	882843.36	0.38	0.237	0.622	-0.326	0.65	0.22	-0.7	-0.921	0.358
Fertilizers Company Well	147571.1	864241.8	-0.962	-1.114	-2.652	-2.601	-0.605	-1.074	-0.433	-0.686	-0.652
Southern Aqaba Gas Station Well	150098.04	880692.78	0.063	-0.081	-0.665	-1.295	0.55	0.121	-0.41	-0.631	0.292
Al Hussien Bin Ali Mosque Well	149872.29	882237.4	0.431	0.287	0.375	-0.623	0.691	0.262	-1.005	-1.226	0.334
Hafira Well 1	149872.29	881405.68	0.424	0.281	0.552	-0.44	0.574	0.145	-1.481	-1.701	-0.313
Tap water	-	-	-0.293	-0.437	-0.914	-1.188	0.227	-0.203	-2.4	-2.62	-2.301

Table (25): Saturation indices in the groundwater samples.

2.6.6 Spatial Distribution of Hydrogeochemical Constituents In the Aqaba City Zone

A spacing of 95 meter was used to grid the hydrochemical data of the analysed samples of the Aqaba city zone. The distribution of pH, $HCO3^-$, F^-, SiO2, $HCO3^-$, Cl^-, and $SO4^{2-}$ in mg/l was prone to grid and mapped as pixel rasters. The locations of the wells and the grids were overlain over each map. Figure (58) illustrates the spatial distribution of the different parameters.

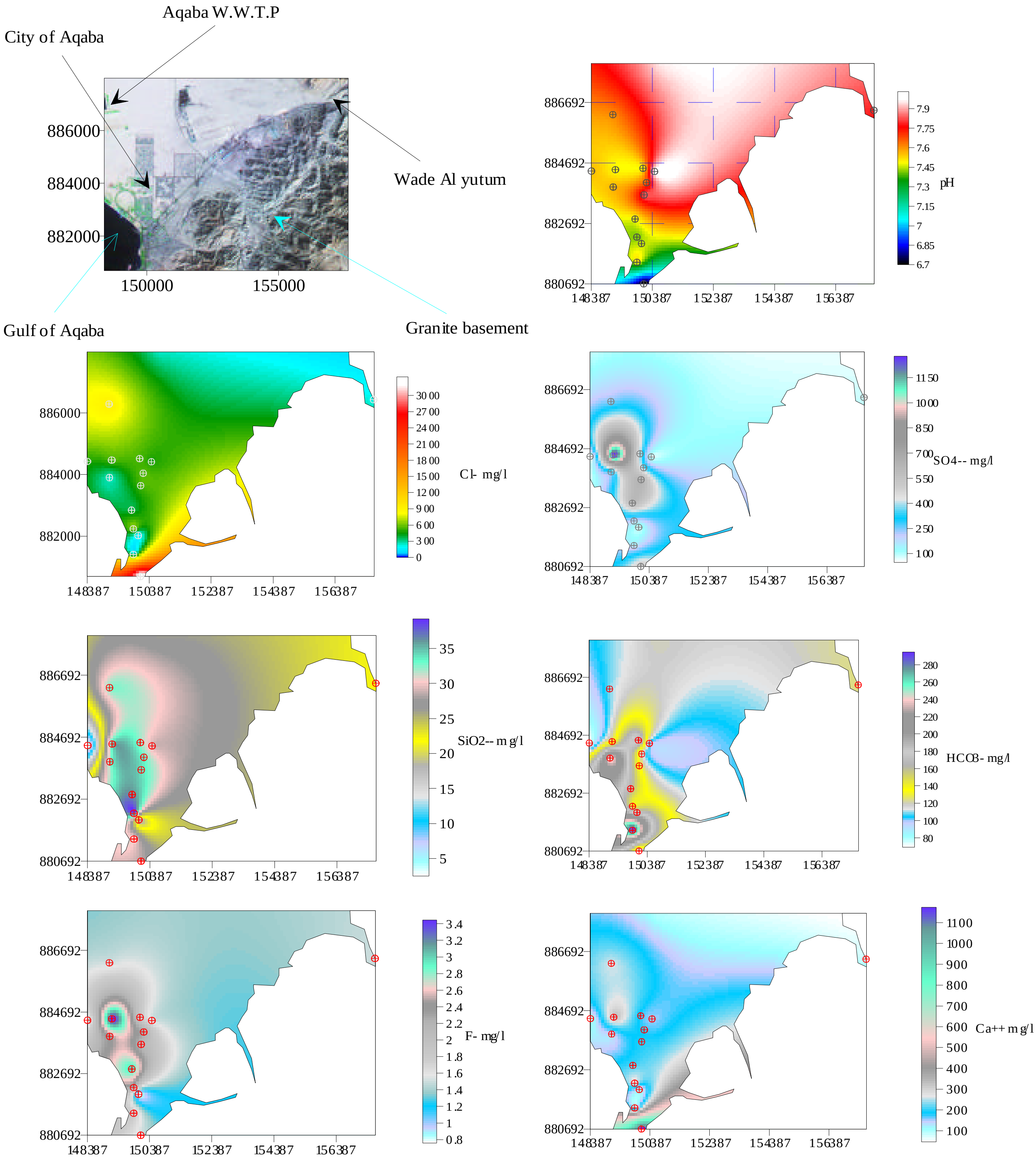


Fig. (58): Spatial distribution of some hydrochemical parameters in the Aqaba city zone.

The spatial distribution of the different parameters leads to the following conclusions:

- The pH decreases with increasing salinity. The salinity in groundwater increases going to the central part of Wadi Araba, where the city locates. This part is occupied by land use which has pollution potentials on the groundwater. Pollution processes are responsible about lowering the pH value when they support the aquifer with dissolved organic matters which release CO_2 gas by decomposition, this in turn decreases the pH-value of water. The analyses of the dissolved organic carbon (DOC) in the groundwater indicate somehow high values, confirming the presence of organic matter.
- The concentrations of Cl^- ,F^-, Ca^{2+}, SO_4^{2-} and HCO_3^- increase going closer to the shorelines of the Gulf. The cause is attributed to the mixing process with seawater, and the precipitation of the aerosols particles coming from the seawater in soils cover, which end in the groundwater body with the aid of the washing by rain.
- SiO_2 is related to the pH value. It increases going towards the Gulf of Aqaba, because the pH-values is higher i.e. higher alkalinity.
- The area between Wadi Al Yutum and the zone where the most wells locate is poor with data. Here exists no land use units, the matter which allows no sudden changes to take place, but only increase in mineralization with flow.

2.6.7 Geoelectric Use in Approaching the Spatial Distribution of the Hydrochemical Parameters Concentration

The EC-value of a groundwater body is reflected in the resistivities as revealed by VES-soundings. At the same time the different constituents of a groundwater are somehow corralable with the EC. Since VES and regression analyses were carried out for the study area, an attempt will be done to work out the concentrations of the different constituents of the groundwater.
Archie’s law (Reynolds, 2000) allows estimating the water EC-value from the electric resistivity of the rock formation. Some improvements can be introduced into the equation in terms of the factors of porosity and rocks types according to:

$$r = (\mathbf{I/P}^{a}) * (r_{w}/\mathbf{S}^{2})$$

where ;
r : is the formation resistivity in W.m
I : is a factor and depends on the type of porosity of the formation , slightly less than 1 for rocks with intergranular porosity, and slightly more than 1 for joint porosity.
ρ_w *: is the water resistivity - the formation content of groundwater, and equals the reverse of the EC in Milli S/cm-*
P : is the porosity of the formation rocks, expressed as in decimals.
a : is a factor and depends on the sorting and cementing conditions of the formation rocks, it is somewhat larger than 2 for cemented and well-sorted granular rocks , and somewhat less than 2 for poorly sorted and poorly cemented granular rocks.
S : is the rock saturation with water, expressed as in decimals.

Calibrating Archie’s equation by applying geoelctric surveys close to a well with defined water chemistry and lithology is of a great importance in approaching the EC-values in other locations of the same aquifer. *Such a step was carried out in the section of hydrogeology, when the porosity values were estimated.*

A porosity ratio of 20% was supposed to prevail all over the aquifer (page 88). The values of I and *a* were chosen as 1.15 and 1.85. The equation becomes:

$$\mathbf{EC} = \frac{22583}{r} \qquad \textit{formation factor of the study area.}$$

Where EC-values are expressed as m S/cm.

In the section on hydrogeology the water bearing layers were revealed from the geoelectrical surveys. Accordingly, it was possible to apply Archie's law on these layers' resistivities to obtain the EC-values. By applying the derived equations of the different hydrochemical parameters, raster models of the whole study area were built in term of the mobile chemical constituents. Figure (59,a,b) shows the resulting EC maps and chloride concentration.

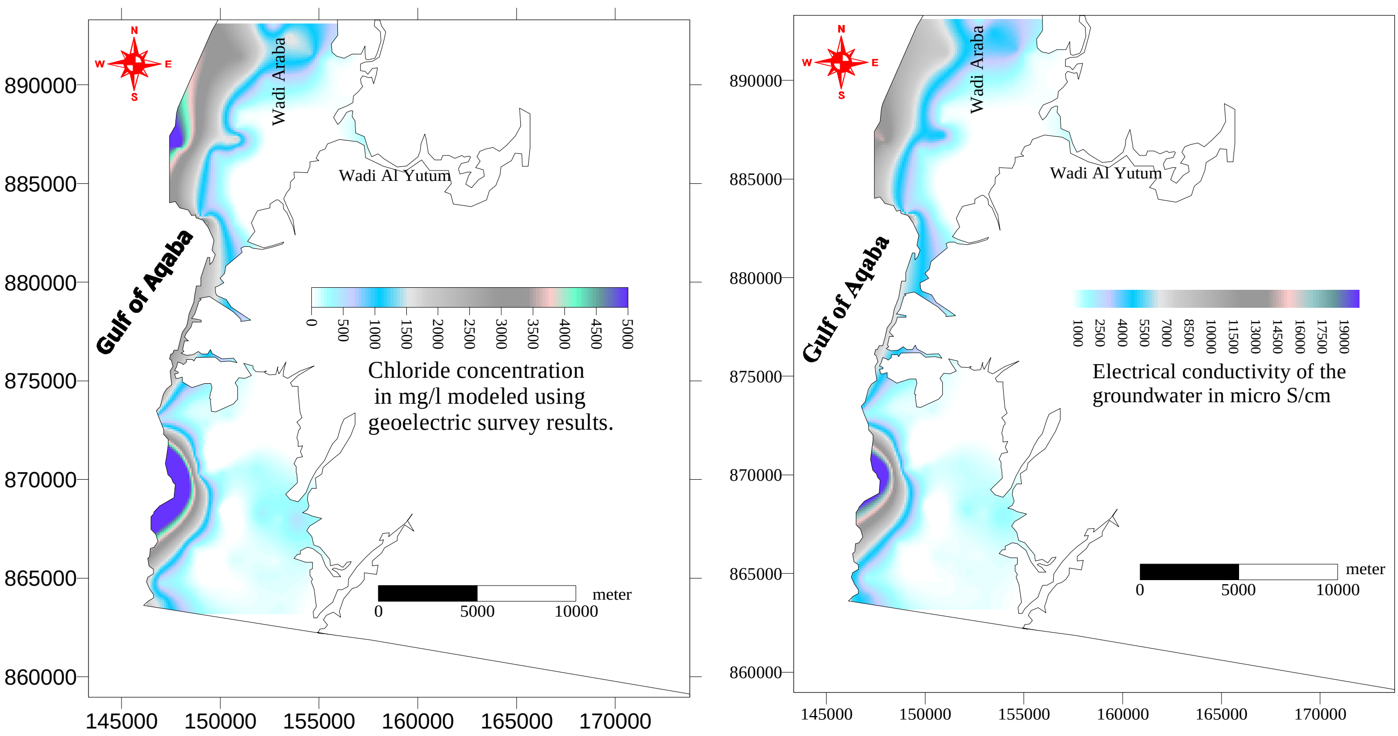


Fig. (59,a,b): Modeled EC and chloride concentration maps depending on the geoelectric surveys.

The obtained EC and Cl- maps represent the true within the zone of the city of Aqaba, where many wells with known hydrochemistries are available. The correlation between the observed and modeled values of EC and Cl- leads to the calibration of the geoelectric survey carried in the study area.
In the resulting maps the high salinity is attributed to seawater encroachment, and high EC-values going towards the central Wadi Araba.

2.6.8 Redox Conditions of Groundwater

The redox conditions of groundwater affect the concentration and solubility of many substances, which in turn affects the water's suitability for drinking uses.

Redox is the general term for the chemical reactions involved in the transfer of electrons; when a molecule is oxidized, it gives up electrons to another molecule which is thereby reduced.
Oxygenated (aerobic) water has a higher redox potential (Eh measured in mV) than water devoid of oxygen (anaerobic). Redox potential is thus an index of water's capacity to support redox reactions.
A low redox potential indicates several risks, including: the release of hydrogen sulphide and methane; precipitates of iron (Fe) and manganese (Mn); and difficulty in reducing the water's concentration of those metals in soluble form.
Positive values of Eh indicate an oxidizing medium, while negative value indicates a reducing one.
The redox potential of groundwater can be estimated by measuring and comparing levels of iron, manganese and sulphate. Those levels are affected by redox conditions in the water and, taken together, indicate redox potential.
The redox conditions of groundwater indicate whether or not certain kinds of problem can be anticipated when water is pumped from a well.
Groundwater with low redox potential may not be suitable for drinking. If repeated measurements indicate that the redox potential of a well has changed, the cause could be some sort of human impact. It is usually a question of activities that have affected groundwater currents or the local atmosphere. Examples include pavement of the land surface and water logging, both of which hinder the transfer of oxygen from the atmosphere and thereby lower the redox potential of the groundwater. The presence of organic matter demands more oxygen for decomposition processes. Accordingly, the groundwater becomes reducing when the available oxygen is depleted.

The normal condition prevailing in the study area are oxidizing. The natural recharge water is well oxygenated, especially while direct recharge comes from a thunder storms origin with high intensity. The low field capacities of soil and the high infiltration rates, besides the presence of some weakness zones make the leakage and infiltration processes fast. This means that the leaking water into the groundwater body is not exposed to reactions in the soil cover to lose any of its dissolved oxygen. Therefore, good amounts of dissolved oxygen in the groundwater are expected .
Along side wadis no human impacts to release organic matter into the aquifer are present. The less available agricultural cover inherits the soil no organic matter to start reactions with the soil water which may consume the dissolved oxygen in the recharge water. Therefore the aquifer is well oxygenated, and accordingly has positive Eh-values.

The value of Eh was measured for all wells and mapped (Fig. 60). From this produced raster map it was possible to distinguish zones of contrast in the Eh-values of the groundwater.

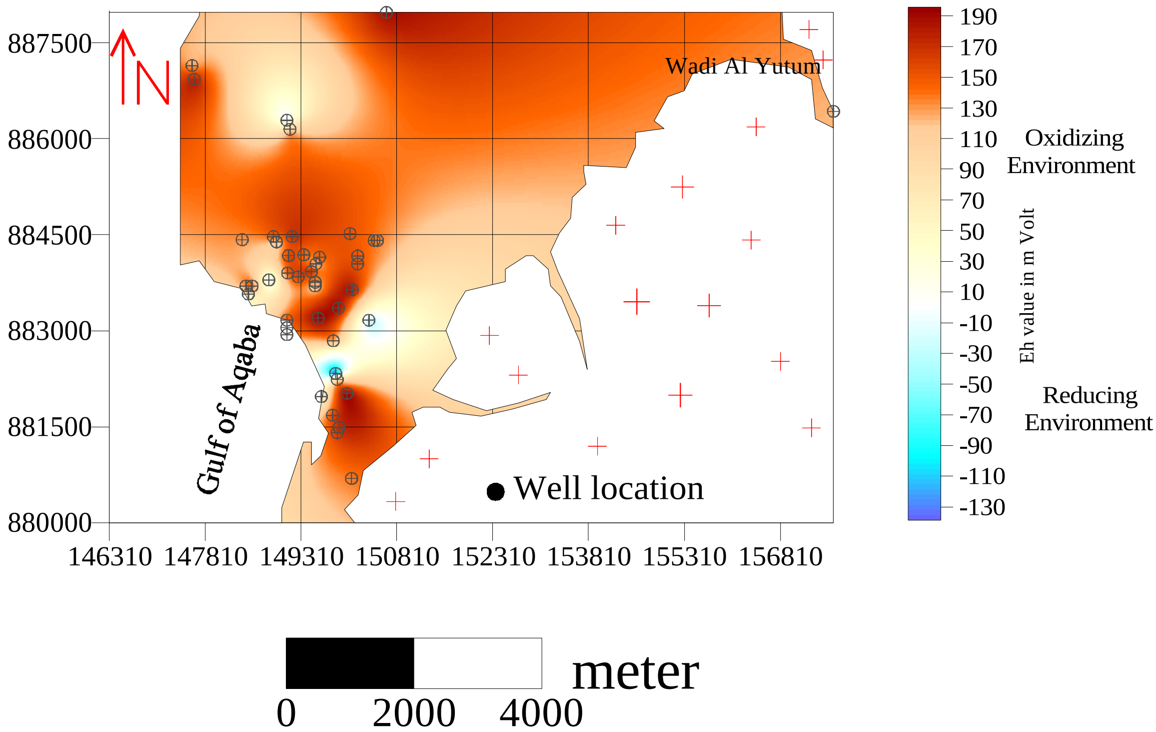


Fig. (60): Raster model of the spatial distribution of the Eh-values.

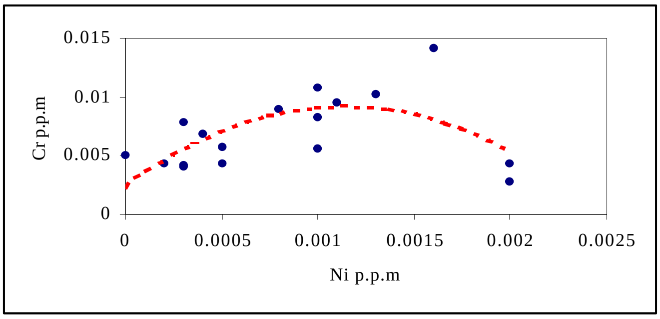


Fig. (61): Correlation between groundwater depths and Eh-values.

Zones of high oxidizing conditions –due to the study area- are present. The only possible cause for their presence is the impact of the leakage from the drinking water supply networks that has Eh-value of 450 (mV). The groundwater in Aqaba in areas out of this impact has Eh-value of about 100 (mV). Mixing of groundwater with this leakage results in Eh-values of about 180 (mV).

The houses unconnected with the waste water treatment plant were another cause in adding contrast to the groundwater Eh-values by lowering them. The zone of low values is clearly located in the zone of these houses (white to light yellow color in the map).

The Eh value gave a good positive correlation with the wells depths. The shallower the water table, the greater possibility the mixing with the atmospheric air (Fig. 61).

Two wells were abnormal with a very low Eh-values of less than –150 (mV). These two wells are out of use, and it has been noticed that their iron casing has totally rusted. Hence the absorbance of high amounts of dissolved oxygen from water.

2.7 Environmental Geophysics and Modeling on the Hydrodynamic Interface of Fresh and Salt Waters

2.7.1 Introduction

Reynolds (2000) defined the environmental geophysics as "The application of geophysical methods to the investigation of near-surface physico-chemical phenomena which are likely to have (significant) implications for the management of the local environment".
The geoelectrical method depends on utilizing the ability of the geological formations to transmit electric currents. Once they are saturated with saline water, the conductivity increases. The cause is attributed to the ionised water constituents which can transmit the current.
Pollution processes mainly supply the water aquifers with solutions, which may decreases or increases the water salinity. The contrast between the two water types the host and the received one, can be easily detected.
Encroachment of seawater towards the groundwater body is a kind of pollution with respect to the groundwater, it inherits the groundwater higher salinity.

All over the world coastal aquifers are considered as an important source of water, with the fact that many of coastal areas are heavily urbanised, the need for fresh water becomes even more acute. The proximity of the sea, with the contact between freshwater and sea water in a coastal aquifer, requires special management techniques. (Bear & Verruijt, 1987).

Under natural conditions, the flow of fresh water toward the sea limits the landward encroachment of seawater. With the development of groundwater supplies and subsequent lowering of the water table or piezometric surface, the dynamic balance between fresh and sea water is disturbed, permitting the seawater to intrude usable parts of the aquifer. Salt water intrusion is a special case of groundwater contamination. (Domenico & Schwarz, 1998). According to Bear & Verruijt (1987), in coastal aquifers a hydraulic gradient generally exists toward the sea, that serves as a recipient for the excess of their fresh water replenishment minus pumpage.
Owing to the presence of seawater in the aquifer formation under the sea bottom, a zone of contact is formed between the lighter freshwater (density γf) flowing to the sea and heavier, underlying, sea water (density $\gamma s > \gamma f$). A body of seawater, often in the form of a wedge, exist underneath the freshwater (Fig. 61).
Freshwater and seawater in the underground are actually immiscible fluids, and therefore the zone of contact between them takes the form of a transition zone caused by hydrodynamic dispersion (the spreading phenomena in a porous medium).

The depth to the salt water and its extension inland depends on the following variables

1. *The rate of discharge per meter length of the aquifer to the sea.*
2. *The saturated thickness of the aquifer.*
3. *The permeability of the aquifer.*

Variable number 1 can easily react with the possible human impacts on the coastal aquifers, where the abstraction quantities from the aquifer can play a major role in locating the new position of the hydraulic interface between the freshwater and seawater, and it refers to the dynamic balance between the two water types in the aquifer. Damage of an appreciable fresh water volume in the aquifer, when salt water occupies the place of freshwater may follow to that.

Domenico & Schwarz (1998), mentioned some previously suggested methods to control saltwater intrusion, including;

1. **artificial recharge.**
2. **a reduction or rearrangement of pumping wells.**
3. **establishing a pumping trough along the coast, thereby limiting the area of intrusion to the trough.**
4. **formation of a pressure ridge along the coast.**
5. **installation of subsurface barriers.**

Studies on the hydrodynamic interface, and the related hydrogeological conditions of coastal areas are very important in order not to lose productive areas of aquifers.

The long-term behavior of the saltwater interface in response to changes in population, water use, rainfall, and other actions which impacts groundwater, must have a means of assessing and modeling.

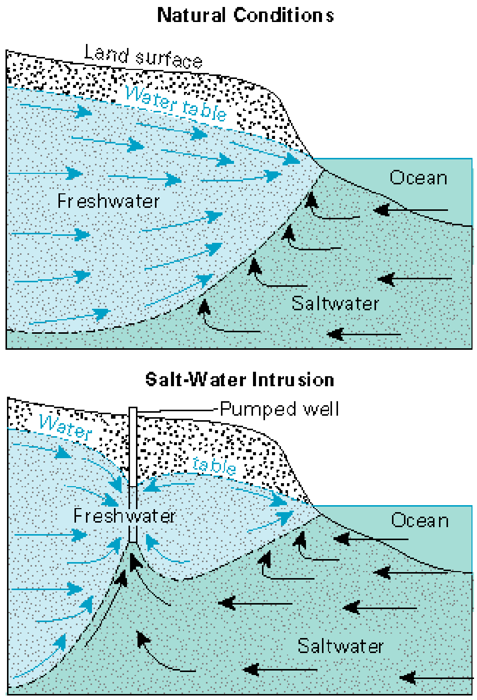


Fig. (61): Hydrodynamic interface of fresh and seawater.

2.7.2 Modeling on the Hydrodynamic Interface and Sea Water Intrusion in the Aqaba Coastal Aquifer

The hydrogeological and the hydrological nature of the aquifer in the study area as a shallow unconfined aquifer make the aquifer prone to high ***natural water losses***, such as evaporation from the shallow parts. This process is enhanced by the high temperatures in the area associated with low field capacities of soils. The low annual recharge inherits low groundwater discharges into the sea, which in turn make a kind of balance in the lateral location of the sea water intrusion under the Aqaba coastal zones.

The aquifer is disturbed due to its groundwater balance according to several processes; ***urbanisation and its impacts*** on the aquifer, over pumping, decreasing the exposed areas available for the infiltration of rain water and the recent extractions from Wadi Al Yutum groundwater which used to support the aquifer of the Aqaba city with about 4 million cubic meter/y (Salameh & Gedeon, 1998). There are now 3 operating wells in the Wadi producing 125 m^3/hr. These serve to cover some irrigation needs of the city of Aqaba.

On the other hand, urbanisation plays an important role in supporting the aquifer with water from several sources, including water leakage from the Aqaba waste water treatment plant and the cesspools of some houses, leakage from the city drinking water pipelines, and the leaking water from the irrigation process all over the city. This in turn reflects positively on the interface position

The critical environmental nature of the study area makes the need for modeling of all input and output water types with respect to their qualities and quantities a must, so as to approach a forward model which can represent the real conditions of the seawater intrusion that occurs into the aquifer.

Four different types of studies and calculations were carried out in the course of this study in order to locate the hydrodynamic interface (laterally and vertically), and to predict its future behaviour with respect to the dominant natural and human activities including:

1. ***A hydrogeological study using the estimated and available hydrogeological values by applying special formulas.***
2. ***A hydrogeochemical study using the hydrogeochemical data of some wells in the coastal aquifer.***
3. ***A geoelectrical modeling and slicing study using vertical electrical sounding methods (VES).***
4. ***Modeling the expected future behaviour of the interface.***

2.7.3 The Hydrogeological study:

Two hydrogeological studies on the hydrodynamic interface were done. They depended on known theories and formulas:

The Depth to the Interface

Depending on the Ghyben, (1889) & Herzberg (1901) in Domenico & Schwarz, (1998), *naturally seawater actually occurs at depths below sea level equivalent to approximately 40 times the height of fresh water above sea level,* and that is explained on the base of the simple hydrostatics. 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 sea water extending from the sea level to the same depth as the point on the interface. That is the weight of the column of fresh water of length $h_f + z$ equals the weight of the column of salt water of length z.
As ρf and ρs are the densities of fresh water and salt water respectively, the condition of hydrostatic balance is expressed as:

$$z = \frac{\rho_f}{\rho_s - \rho_f} h_f$$

where z is the depth below sea level to a point at the interface line, and h_f *is the depth from the water table to sea level at that point* (Fig. 62).

Taking the densities of the fresh water and salt water as 1 and 1.025 g/cm³ respectively, then:

$$\mathbf{z = 40\ h_f}$$

This formula can be applied to unconfined aquifers. Around the coastal lines of the sea in the study area, several wells are located near the shorelines.

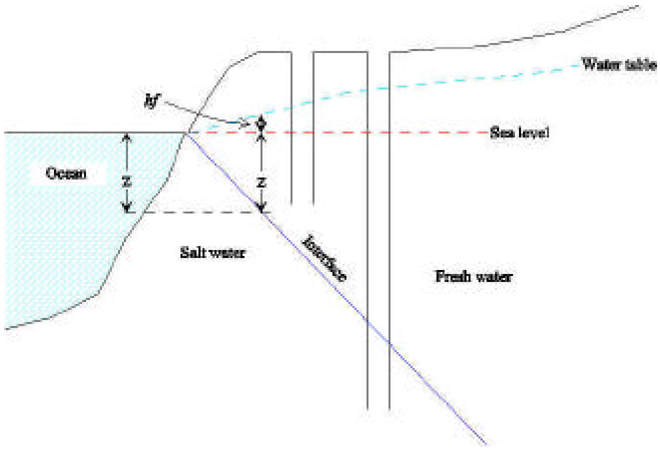


Fig. (62): Conceptuality for deriving the formula of the hydrodynamic interface.

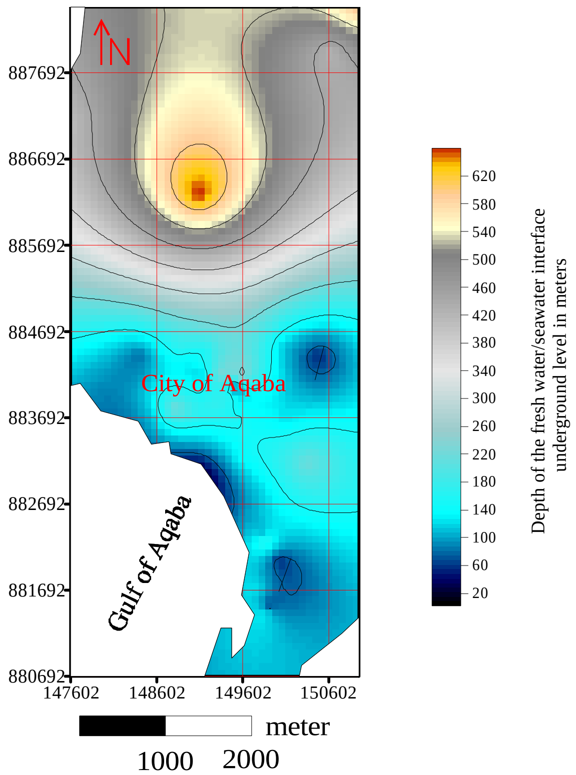


Fig.(63): The modeled theoretical extension of seawater under the city of Aqaba.

The formula was applied using the measured static water levels in the wells of the city zone as z values, and they were multiplied by 40, then the depth of the unsaturated zone of the aquifer was added. Accordingly, a pixel map of 100 meters spacing was produced (Fig. 63).
This is the natural case of the interface depth, as it should be under the city of Aqaba in term of the balance theory between the salt and fresh water. It has a range of depths from less than 2 meters near the bays until about 650 meters further north in the map.

2.7.4 Geoelectrical Vertical Modeling on the Interface and Salt Water Intrusion

Two areas along the coastal lines were chosen to be investigated geoelectrically –vertical sounding method- relevant to the dominant subsurface interface and the salinized fresh water by salt water. The study was carried out to draw cross sections vertical to the direction of the shore. Several soundings were measured.

According to Keller & Frischknecht (1982), the electrical resistivity of any geological formation is a function of the porosity and the resistivity of the water content of this formation, where the formula relates these variables is called ***Archie's formula***:

$$r = \mathbf{(I/P^{a}) * (}r_{w}\mathbf{/S^{2})}$$

where ;

r *: is the formation resistivity in W.m*

I *: is a factor dependent on the type of the porosity of the formation, slightly less than 1 for rocks with intergranular porosity, and slightly more than 1 for joint porosity.*

r_w *: is the water resistivity - the formation content of groundwater equals the reverse of the EC in milli S/cm.*

P *: is the porosity of the formation rocks, expressed in percentage.*

a *: is a factor dependent on the sorting and cementing conditions of the formation rocks, it is somewhat larger than 2 for cemented and well-sorted granular rocks , and somewhat less than 2 for poorly sorted and poorly cemented granular rocks.*

S *: is the rock percentage saturation with water, expressed in percentage.*

Calibrating Archie's equation by applying a geoelectric survey near a known well in terms of its water depth, salinity and lithology, is of great importance in approaching the real values of EC in other locations of the same aquifer.

A geoelectric survey using a DC resistivity method and a transient electromagnetic induction (TEM) method was carried out from 1986 to 1988, to help mapping the lateral and vertical distributions of the freshwater/salt-water interface in the Pei-kang area on the west coast of Taiwan. The DC and TEM soundings were performed on 79 localities over an area of 240 km2 of Quaternary alluvium. Significant changes in pore-water conductivity at some places were detected by these two methods. ***Due to that a low resistivity value (<1.5 ohm*m) implied salt-water contamination in groundwater****. (Yang, 1999).*

The wide range of difference in the electrical conductivity between groundwater of the study area (average 2000 µs/cm) and that of seawater (about 45000 µs/cm), besides the low range of differences between the dominant porosity of the clastic deposits allow to differentiate unsaturated zones, zones saturated with groundwater and zones saturated with seawater.

The first study was applied to the southern part of Aqaba coast in Al Yamaneah area (September/1998). Two soundings were done; one of them is 100 meters a way from the sea and 4 m a.s.l. and the other 200 meters a way from the sea, and 15m, a.s.l.. Both of them parallel to the shoreline.
The two soundings were drawn with respect to their layers resistivities and thickness in exact horizontal and vertical scales. *The hydrodynamic interface was modeled under the ground surface level to be 11.1m for that with 100m from the shoreline, and 51.8m for that with 200m from the shoreline.*

The clastics saturated with seawater have the resistivity range of 0.8 and 1.4 Ω.m for both geoelectrical profiles. This fits in Archie's law taking the EC-value of seawater as 42000 µs/cm, and a porosity about 20%. Table (26) shows the layers thickness' and their resistivities for the two soundings.

Table (26): Geoelectrical modeling results of thickness' and resistivities of the two soundings in Al Yamaneah area.

SOUNDING DISTANCE FROM THE SHORELINE AND ELEVATION METRES A.S.L	*RESISTIVITY (OHM.M)*	*THICKNESS OF THE LAYER (METER)*	*DEPTH TO THE LAYER'S LOWER BEDDING CONTACT (METER)*
100 meters 4m a.s.l	3019.3	0.5	0.5
	255.2	6.5	6.9
	52.7	1.2	8.7
	5.6	2.5	11.1
	1.4*	46.2	57.5
	1.0*	-	-
200 meters 15m a.s.l	5661.8	0.4	0.4
	302.6	4.2	4.6
	24.3	47.3	51.8
	0.8*	-	-

* *Resistivities of water mixed with and/or composed of sea water.*

This approach of the interface depth is expected to assist in calculating the groundwater balance, and throughput into the sea in the southern part of the study area.

The second study was applied to the northern part of the coastal shorelines in the hotel's area (March/1999). Six soundings were applied parallel to the shoreline; the first one is 11m from the shoreline, the second 100m, the third 150 m, the fourth 200m, the fifth 250m and the sixth one 450m.

The six soundings which have nearly the same elevation above sea level (4 meters a.s.l) were put to a grid to build a cross-section, through which changes of risistivities with depth can be recognized. It was easy to understand the behaviour of the cross section at a specific depth, where the resistivites tend to be low to the degree that they can indicate the hydrodynamic interface at a depth of 50m under the surface level, at a distance of 100m from the shoreline. Figure (64) shows the calculated cross section with the different layers and resistivites, and Table (27) shows the layers and their risistivities of the six soundings.

A ***mixing zone*** was delineated between the seawater and the fresh water, it has the grey colour in the cross-section. The light blue indicates the fresh water, while the seawater intrusion is indicated by dark blue. The groundwater level in this area is 2-6 meters deep, and it has an EC value of 2280 µ S/cm. The unsaturated zone here is characterised to contain a high salt as coating material around the soil grains. This is due to the high evaporation rates from this shallow water body, and the infiltration water flushing aerosols coming from the sea.

The systematic approach of the interface here indicates an accurate way in the interpretation method used for the geoelectrical profiles that were applied to the study area.

Table (27): Geoelectrical modeling results of thickness' and resistivities of the six soundings in the northern part of the coast.

	DISTANCE FROM THE SHORELINE IN METERS																	
	11m			***100m***			***150m***			***200m***			***250m***			***450m***		
Layer *No.*	**App. R Ohm.m**	**Thick. m**	**Depth m**	**App. R Ohm.m**	**Thick. m**	**Depth m**	**App. R Ohm.m**	**Thick. m**	**Depth m**	**App. R Ohm.m**	**Thick. m**	**Depth m**	**App. R Ohm.m**	**Thick. m**	**Depth m**	**App. R Ohm.m**	**Thick. m**	**Depth m**
1	3.4	0.9	0.9	8.1	1.6	1.6	3.6	2.1	2.1	22.6	0.6	0.6	2.3	2.1	2.1	54.5	0.7	0.1
2	1.6	1.0	1.9	5.0	1.1	2.7	6.3	3.3	5.4	6.2	6.7	7.3	11.5	3.4	5.4	35.0	0.8	1.5
3	10.4	2.5	4.4	2.4	2.3	4.9	27.6	9.3	14.7	15.4	11.2	18.5	39.9	17.6	23	123.4	1.0	2.5
4	1.5	2.9	7.3	9.1	7.9	12.9	41.9	20.7	35.5	49.8	19.5	38	33.1	31.9	54	127.3	1.9	4.4
5	0.8	4.1	11.4	33.1	16.1	32.0	4.9	-	-	26.8	8.1	46.1	8.5	-	-	23.4	10.8	15.2
6	4.7	8.7	20.1	2.7	-	-	-	-	-	5.9	-	-	-	-	-	27.7	11.3	26.5
7	8.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17.2	-	-

The closest sounding to the shoreline 11m from the shoreline indicates a fresh water captured within a clayey to silty size lens. This can be noticed on the resistivity of layers 4 and 5 indicating the interface with seawater.
After that layers 6 and 7 show higher resistivities indicating a lower conductivity zone under the interface. The only possibility to explain that in a clastic type of sediments is the presence of clay lenses, which capture some fresh water at the time of the sea level lowering due to the tide effects.

From this cross section it was possible to deduce that the interface between the fresh groundwater and the seawater is not a sharp line, but a transitional zone with a range of salinity gradually decreasing from that of fresh water to saline water. Its resistivity is about 5000-8000 μ S/cm.

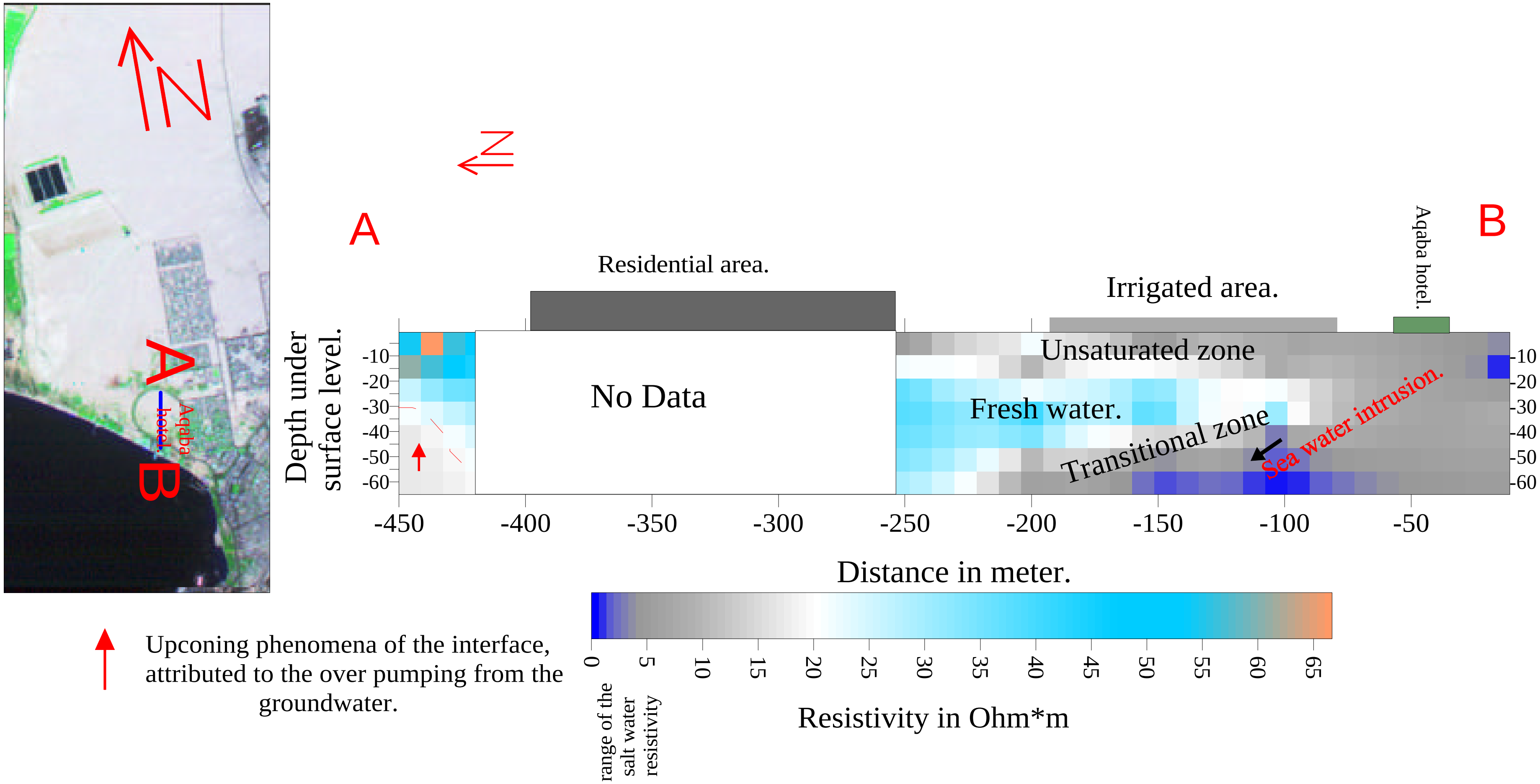


Fig. (64): Modeled geoelectrical cross-section with different layers and resistivities in the hotels area at the northern coasts of Aqaba.

2.7.5 Up-coning and Practical Indications on the Abstracted Amounts from the Aquifer Along the Northern Coastal Area of the Gulf of Aqaba

From a distance of about 425 m to 450 m to the north of the sea (Fig. 64), the values of resistivities tend to be lower than those at the same depths in the cross section, where the shape of the estimated hydrodynamic interface shows right flank of upconing. Refering to the urbanized area where the cross section was measured and to the pumping activities along it, an up-coning in the interface was revealed.

In Al Wehdat Al Garbia -residential area- pumping of appreciable amounts of groundwater takes place through shallow wells.

Domenico and Schwartz (1998) stated that according to the Ghyben-Herzberg's formula, any lowering of the groundwater head in unconfined aquifers result in a rise in the interface to take a new equilibrium elevation. The new equilibrium elevation could be calculated from the following formula:

$$Z = Q\rho f / 2\pi d K(\rho s - \rho f)$$

Where
Z : is the new equilibrium elevation
Q : is the pumping rate
K : is the permeability factor
And d is the distance from the base of the well to the original (pre-pumping) interface.

Taking this formula, including *Z* from the cross section, it is possible to approach the value of water losses above the up-coning area due to pumping activities.

Having an average *K* value as $6*10^{-6}$ m/sec, ρf as 1 g/cm³, ρs as 1.025 g/cm³, d as a group of wells an average distance from their bottoms to the pre-pumping interface location at about 130m, and the elevation of the interface above the original one at 20 m (cross section) then:

$$\mathbf{Q= [2*60m*p*130m*(0.5*10^{-5}\,m/sec.)*0.025g/cm^3] / 1.025g/cm^3}$$
$$\mathbf{= 0.188\ million\ m^3 / year.}$$
$$\mathbf{= 516\ m^3 / day.}$$

2.7.6 Horizontal Geoelectrical Depth Slicing and Modeling on the Interface and Salt Water Intrusions

84 VES were used to slice the aquifer with respect to resistivity due to several depths; 5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 100 and 120 m.
The soundings are well distributed in the study area (Fig. 65), and the slicing was made parallel to the relief (Fig. 66).

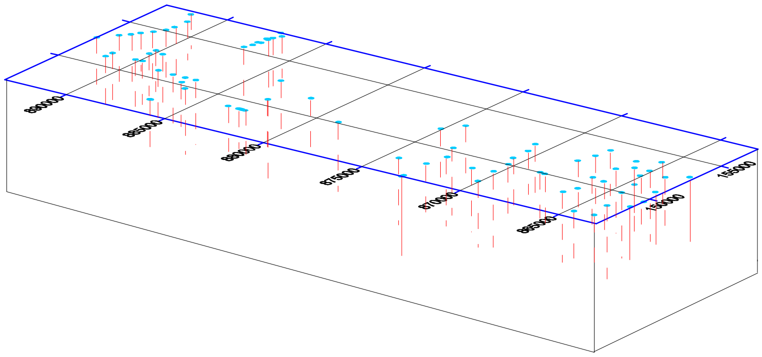


Fig. (65): Distribution of the VES.

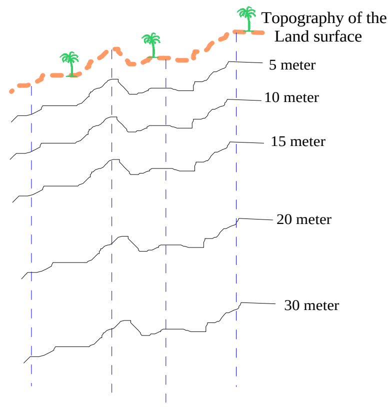


Fig. (66): Slicing parallel to the relief.

The slicing of the different depths and the search for resistivities between 0.8 and 13 Ohm.m revealed the spatial distribution of the water body with EC-values ranging from 1737 to 28228 Ohm.m.
The idea behind taking this wide range of resistivities in delineating the salt water intrusions and seawater encroachment into the land was dependent on the vertical cross section of Figure (64) where no sharp contact exists between the fresh and the seawater. Accordingly, it was better to show the gradual increase by including lower resistivities.

The produced 2-D slices of the different depths in Figure (67) are logically attributed to the spatial distribution of the groundwater's EC-values, which have the range from 1737-28228 µ S/cm.

The grid distribution can not reveal data between the co-ordinates 875000 and 880000 N, because the unavailability of suitable areas for applying vertical geo-electrical profiling, since shorelines are closely bounded by granite.

At a depth of 5 meters parallel to the topography of the study area, it is possible to show the early start of geoelectrical layers indicating the previously mentioned range of resistivities. Here soil grains bounded by salt coats, and the shallow groundwater exposed to high evaporation processes, besides the impacts of the seawater aerosols precipitation are responsible for this early (shallow) start.

At a depth of 10 meters the impacts of the Aqaba waste water treatment plant effluents are clear. It raised the groundwater level by about 10 m over the normal one. This water has in the observation wells an EC of 2700 µ S/cm. Accordingly, it is normal here at this depth to see a contrast, where the water salinity is within the range of the slicing detection.

At a depth 15 meters the salinity of the groundwater in the southern part of the study area could be noticed. With depths of 20, 25, 30, 40, 50 and 60 m, the interface and its transitional stages are clear especially along the shorelines.
Depths from 80 to 120 m reveal the presence of a salinity contrast in the southern part of the study area in terms of groundwater.

It was proofed in this study that for elaborating on the salt water intrusion in Aqaba’s aquifer, the geoelectric method is of a great value. The type of deposits and their relative homogeneity along the coasts cause the contrast in the resisitivity within the groundwater body as a result of the salinity contrast, which is in turn attributable to the seawater encroachment.

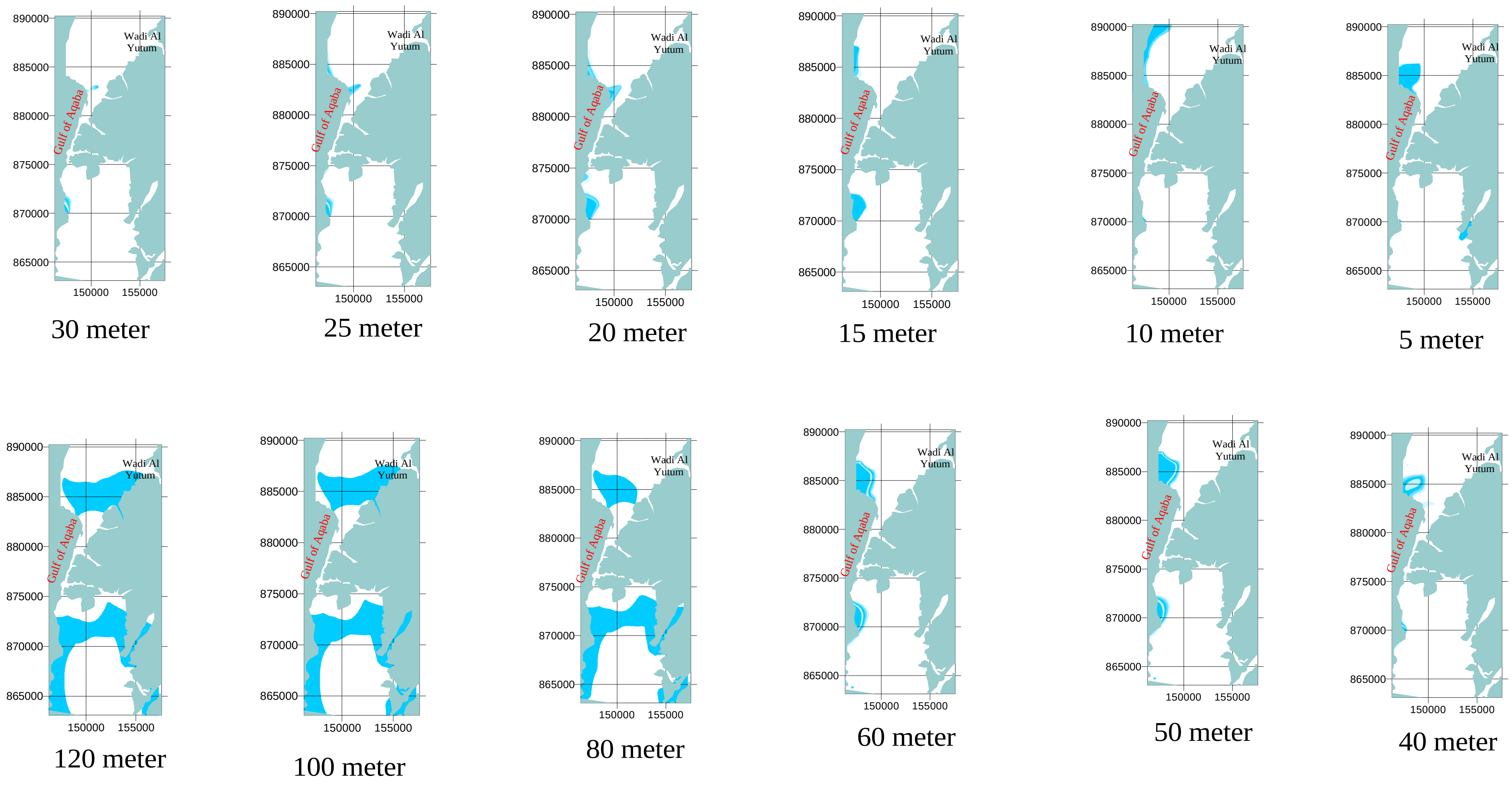


Fig. (67): Spatial distribution of salt and seawater intrusion with resistivity range of 0.8-13 Ohm*m.

2.7.7 Hydrogeochemical Study

The water well of the Southern Aqaba Gas Station has electrical conductivity of 7150 µ S/cm, and it has a distance from the shoreline 820 m, an elevation of 8.7 m, groundwater depth 8 m, and static water level 0.7 m. The well is pumped at a daily rate of 60-100 m^3 for car washing. The well locates at 150371 E and 883164 N, where the groundwater gradient is unable to form a hydrostatic equilibrium to resist the encroachment of seawater, because the main flow lines of groundwater from the northern part –most southern part of Wadi Araba- do not pass through the well's region.
With a head of 0.7 m the depth of the interface under sea level should be as 0.7*40, which equals 28 meters.

Having an EC value of 7150 µ S/cm indicates without any doubt a sea water intrusion to the well area. The recent abstracted water originates partly from sea water (Fig. 68).

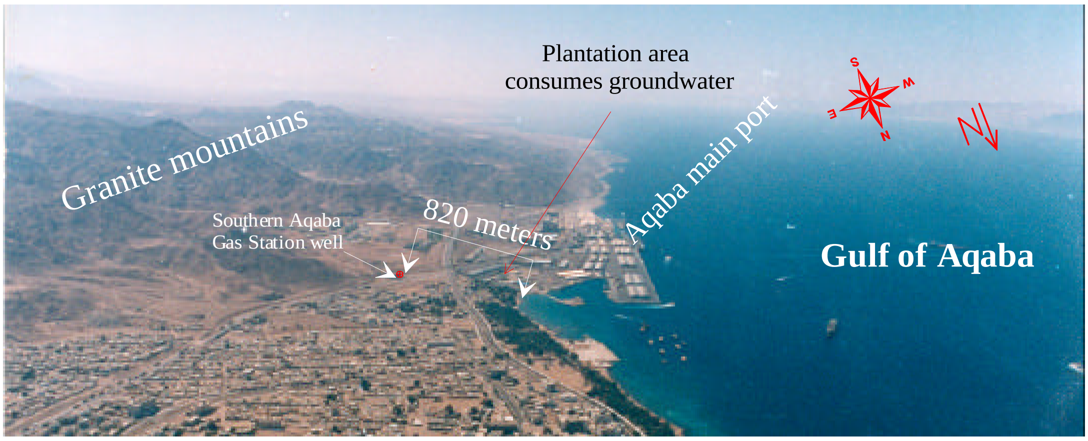


Fig. (68): The old town of Aqaba where lateral seawater intrusions exist.

It was assumed that the groundwater **C** of the Gas Station well is a mixture of seawater **A** and the aquifer's groundwater **B** to calculate the proportions of components **A** and **B** in sample **C**. The mixture is obtained by mixing sample **A** and **B** in 2% steps until the Euclidean distance between the calculated mixture and sample **C** is the smallest. It was found by using Hydrowin that the contribution of seawater to the well is 16 %.

Durov diagram which illustrates the mixing flow paths in terms of the chemistry of the samples **A** and **B** to produce sample **C** was run (Fig. 69)

	Gas Station Well		*Seawater*	
Ratios	mg/l	mmol/l	mg/l	mmol/l
Ca/Mg	13.667	8.29	0.319	0.194
Ca/SO4	2.348	5.627	0.152	0.364
Na/Cl	0.356	0.549	0.556	0.858
Dissolved Minerals				
Halite (NaCl)	3104.393	53.06	26718.14	456.720
Anhydrite (CaSO4)	724.639	5.32	3828.392	28.109

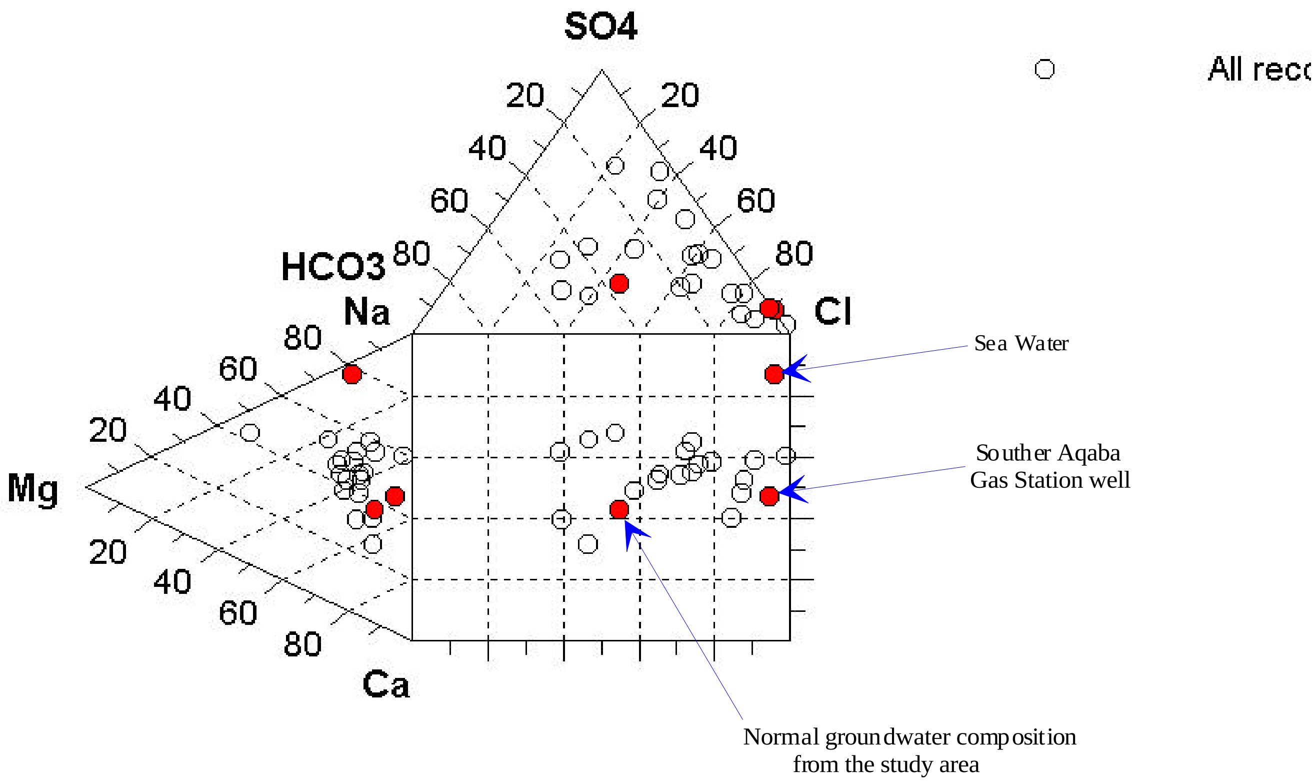


Fig. (69): Durov diagram illustrating the mixing flow paths of seawater and groundwater in the Gas Station's well.

Mixing of seawater with a groundwater to approach the composition of groundwater in the Gas station well gives:

mg/l	***Seawater***	***Normal Groundwater***	***Gas Station***	***Optimized***
K	380	1.2	28.5	61.808
Mg	1350	13.5	87.8	227.34
Ca	400	91.6	1200	140.944
Na	10500	76.4	1220	1744.176
Cl	19000	119.	3424.138	3139.96
SO4	2700	70.5	511.057	491.22
HCO3	142	168.97	112.85	164.655

Generally minor ions such as iodide, strontium and fluoride may appear in greater concentrations in the intruding seawaters, than in the seawater itself due to water-rock interactions (LLOYD & HEATHCOTE, 1985).

The concentration of fluoride in seawater is 1.3 mg/l, in the groundwater of the study area 0.7 mg/l, and 1.5 mg/l in the well of the Gas Station. This enrichment of fluoride in the Gas Station's well can be attributed to the water-rock interactions of the intruding seawater.

The Na^+/Cl^- ratio is a good indicator on salt water intrusions. It is expected that the groundwater affected by seawater intrusion should has a higher ratios of Na^+/Cl^-.
Na^+/Cl^- ratios are illustrated in Figure (70) which also indicates that spatially the ratios are higher near the shorelines than elsewhere in the study area. The area of the upconing phenomena of the interface shows also a circle shape of elevated ratios.

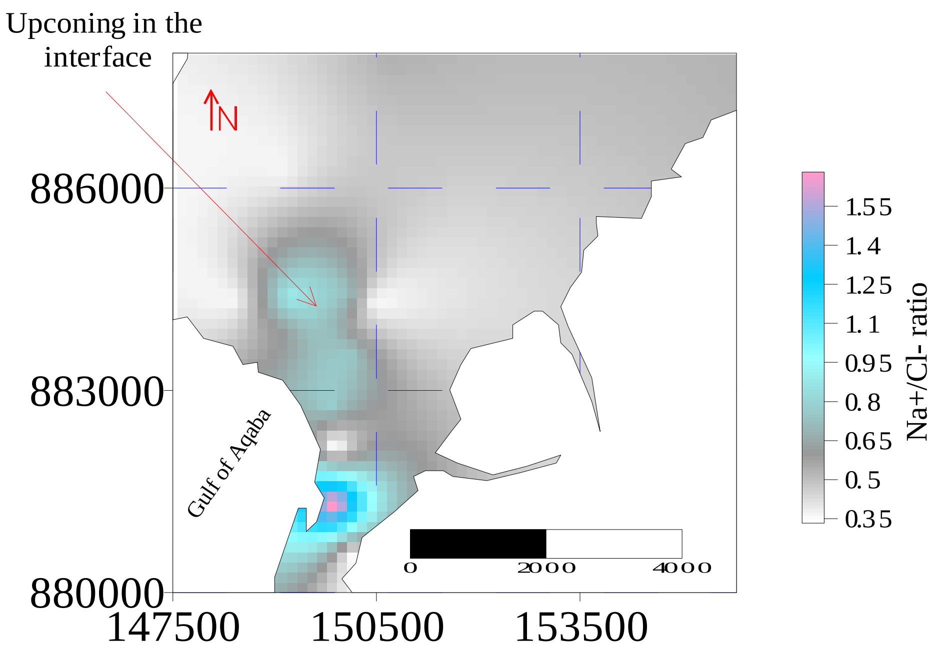
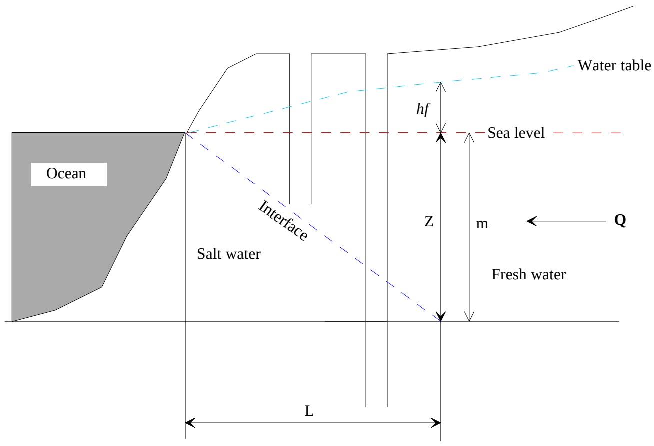


Fig. (70): Spatial raster model of the ratio Na+/Cl- ratios in the groundwater.

2.7.8 Forward Modeling on the Interface Behaviour Under Several Groundwater Flow Scenarios

Refereeing to (Ghyben-Herzberg) the inland position of the salt water wedge can be calculated using the formula:

$$L = \frac{(r_s - r_f)Km^2}{r_{f}Q'}$$



where ;
L *is the intrusion distance of seawater from the shoreline.*
Q' *is the discharge per unit length of shoreline, and it equals* ***Q/y****, where* ***y*** *is the length of the shoreline.*
K *is the permeability of the aquifer.*
m *is the saturation thickness of the aquifer.*

This formula will be applied to the northern part of the Gulf of Aqaba.

The pumping tests carried out in the study area were evaluated here to calculate an average permeability of **0.00005m/s = 4.32 m/day**.

The calculations on the recharge and throughput of the aquifer system in the northern part of the Gulf of Aqaba, gave an amount of **5.5 to 9** million m^3/year with a shoreline length of **8000** meters.
It is possible to model these values to simulate seawater intrusion beneath the city of Aqaba.

Using the previous formula gives:

$$\mathbf{L} = \frac{0.31536 * m^2}{Q}$$

Where Q is the amount of water flowing into the northern part of the Gulf.

The *m* value should remain in a range of a few meters to less than 100 meter. The reason for that is the permeability value which is only valid for this range of alluvium's thickness.

Table (28) illustrates modeled cases of inland seawater intrusion (L) with respect to different flow values out of the aquifer into the gulf with different saturation thickness.

The results with Q = 6 million m^3 /y are more likely here to represent the situation of the intruding seawater. It is the expected condition in the selected study part, where the flow amounts average around 6 million m^3 /y. This gives an intrusion with a saturation thickness of 80 meters, and a distance of 189.21 meters into the land.

When the aquifer is abstracted at higher pumping rates, then seawater will penetrate more into the land. If the flow were 3 million m^3 /y, then with a saturation thickness of 60 m the intrusion would be at a distance of 378 m from the shoreline under the city of Aqaba.

Table (28): Modeled cases of inland seawater intrusion (L) with respect to different flow amounts from the aquifer into the gulf for different saturation thickness.

SATURATION THICKNESS	SEAWATER INTRUSION IN LAND IN METERS (L) FOR DIFFERENT Q VALUES					
	Q 1.5 million m^3 /Y	Q 3 million m^3 /Y	Q 4.5 million m^3 /Y	Q 6 million m^3 /Y	Q 8 million m^3 /Y	Q 12 million m^3 /Y
10 m	21.024m	10.512	7.008m	5.256m	3.942m	2.628m
20 m	84.096m	42.048	28.032m	21.024m	15.768m	10.512m
30 m	189.216m	94.608	63.072m	47.304m	35.478m	23.652m
40 m	336.384m	168.192	112.128m	84.096m	63.072m	42.048m
50 m	525.6m	262.8	175.2m	131.4m	98.55m	65.7m
60 m	756.864m	378.432	252.288m	189.216m	141.912m	94.608m
80 m	1345.536m	672.768	448.512m	336.384m	252.288m	168.192m
100 m	2102.4m	1051.2	700.8m	525.6m	394.2m	262.8m

2.8 Modeling Groundwater Flow and Balance of the Upper Aquifer System (Stream Alluviums)

2.8.1 Introduction

The nature of the spatial distribution of the alluvia creates some differences in their spatial physical hydrogeological parameters. The land use schemes, and the sustainability of the ecological systems require a good understanding of the hydrogeological settings of the aquifer on which these activities exist. The same should be understood about the relationship between the groundwater body and the other natural ecosystems.
In this section the flow model of the study area will be constructed after defining the quantities and qualities of the water, direct abstraction, evaporation from the shallow parts of the aquifer, and the submarine groundwater discharge into the Gulf's water. The hydrogeochemical modeling of the aquifer is of great use in delineating the flow paths of the water end members within the groundwater body.

The safe yield of the aquifer will be worked out in addition to the transport model of chemical constituents.

The flood processes are responsible for the formation of the aquifer's thick alluviums, which proved by pumping tests carried out in the area to have relatively high ranges of permeabilities. These allow transmitting specific groundwater amounts into the Gulf of Aqaba, which is vulnerable ecological system for pollution.

Groundwater heads due to the continues inflow from Wadi Al Yutum and Wadi Araba, and direct and indirect recharge processes are besides the good permeabilities of the alluvium cause appreciable water amounts to flow into the Gulf of Aqaba.

2.8.2 Conceptuality and Quantification of Flow Processes

Two main issues to be discussed here are the input/output of the aquifer in quantitative and qualitative terms. The general formula of quantifying the groundwater balance is:

$$\Delta S = Q_r - Q_d$$

where ΔS *is the change in groundwater storage,* Q_r *is the recharge to groundwater and* Q_d *is the discharge from the groundwater.*

A knowledge of the main components of this equation is essential in assessing the 'safe yield' to the aquifer to enable managing it.

Q_r **of the study area includes:**

- *Lateral flows from other aquifers.*
- *Direct recharge from precipitation.*
- *Indirect recharge from the downward infiltration through the granite joints, and cracks.*
- *Indirect recharge from floods along side wadis and alluvial fans.*
- *Upwards leakage from the deep aquifer (valley fill).*
- *Leakage from the water supply system and direct recharge from Man-made resources.*

While Q_d includes:

- *Abstractions from the aquifer.*
- *Evapotranspiration from the shallow part of the aquifer.*
- *Submarine Groundwater Discharge into the Gulf of Aqaba.*

The study area is hydrogeologically subdivided into two separate subareas with each other; northern and southern part. This requires to deal with each one alone.

The northern subarea measures about 170 km^2, whereas the southern one measures about 100 km^2. In the northern one more data are available and therefore the concentration of the following study is on it.

The different input and output processes are:

Input into the aquifer

1. Lateral flows and seepage from other aquifers

Wadi Al Yutum and Wadi Araba are the main lateral flows into the area supporting the aquifer. Previously it was stated that about 3.5 million m^3/y is the lateral coming flow from Wadi Al Yutum. This water has an electrical conductivity of 1048 µ S/cm.

Wadi Araba in its southern part supports the aquifer with 6.8 million m^3/y with an EC of 1200 µ S/cm in Rahma wells -about 30 km north of Aqaba. That salinity increases southwards especially when the water passes Sabkhat Taba; located about 20 km to the north of Aqaba. The salinity of the water at the end of the path in Aqaba Airport well is 3000 µ S/cm.

Mixing between the two groundwater currents; Wadi Al Yutum and Wadi Araba, takes place in the aquifer under the city of Aqaba.

The southern subarea discharges around **2.2 million m^3/y** as a throughput into the sea.

2. Direct recharge from precipitation

Direct recharge from rainfall in a normal year was calculated to be 0.74 mm/y. This rate gives 0.1258 million m^3/y for the northern subarea, and 0.074 million m^3/y for the southern subarea.

The recharge water joins the groundwater body relatively fast, respecting the low soil field capacities and the high infiltration rates. Accordingly, it reaches the groundwater with an assumed EC-value **350 m S/cm**.

3. Indirect recharge from the downward infiltration of water through the granite joints and cracks

This approach will be neglected in the study area because of the low rain amounts, steep sloped mountains, and high rates of evaporations.

4. Indirect recharge by floods along side wadis and alluvial fans

0.3 million m^3/y indirect recharge were found to support the subarea from Wadi Al Yutum, and 0.35 million m^3/y from the eastern side wadis along the southern part of Wadi Araba. 0.65 million m^3 /y along Wadi Mabruk and the area extending to the southern flank of Wadi Al Yutum.

Additional amounts of indirect recharge are those lost which are from the surface floods before they reach the mouths of the alluvial fans due to the infiltration in the wadis themselves.

5. Upward leakage from the deep aquifer

There are indications that an upward leakage from the deep groundwater joins the upper aquifer. The upper and the lower parts of the aquifer are hydraulically interconnected, but some separating layers of small grain sizes in between lead to a partial confining of the deep groundwater. Occasional recharge to the deep part of the aquifer produces higher heads, allowing water to flow into the areas of low confinement. The possible pathway is towards the Gulf of Aqaba by upward leakage.
To prove that in the study area, age determination methods can be applied because deep groundwater is of older age than that of the shallow water.

The geo-thermometry is also a good indicator on that. The deep circulated water is distinguished by having higher temperatures which increases with increasing circulation depth.

Samples from the study area were taken from shallow wells with temperatures ranging from 20 to 30 C°.

Due to low gradients and permeabilities the amounts of upward leakage must be negligible.

6. Human and land use impacts

The human impacts in recharging the aquifer are discussed in the section of assessing the land use impacts.
These include the leakages from the water supply net work in the northern part of the study area, leakage from the Aqaba waste water treatment plant, and leakages from the septic tanks from houses not connected with to sewerage system of the city.

<u>Output of the aquifer:</u>

1. Abstraction

During the field work information was collected from the well owners to estimate abstractions. It deserves mention here that the groundwater which is pumped from the wells of the study area, is used only for irrigation purposes. Another smaller part is used for construction. Accordingly it is supposed that a part of this abstracted water returns into the groundwater body.

This in turn has a role in increasing the salinity of groundwater when this returned water loses a part as evaporation, and washes some salts present between the soils particles.

The total daily abstraction amounts from the wells of the city are **3000-4000 m^3/day**, about **1.3 million m^3/y.**

Three wells are locating in Wadi Al Yutum, and the total daily abstraction from them is about **600-800 m^3/day**, **0.24 million m^3/y.**

2. Evaporation

The aquifer of the study area is shallow, and the unsaturated zone is composed mainly of alluviums of low field capacities and high infiltration rates. The area is distinguished by high potential-evaporation rates. All that makes it possible for a part of the groundwater to evaporate.

Using the correlation between the EC-values of groundwater and its depth may give estimates on the evaporation rates of the groundwater in the study area.

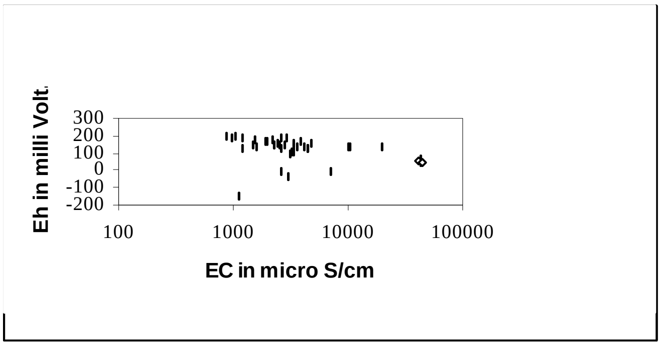


Fig. (71): Plot of groundwater depth and its EC.

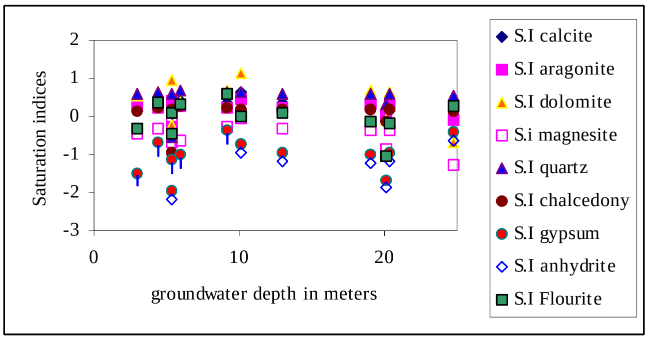


Fig. (71): Plot of groundwater depth and S.I of the minerals.

Regression between the groundwater depths and EC-values (Fig. 71) reveals no clear relationship. Another regression between the groundwater depths and the minerals saturation indices was carried out (Fig. 72) trying to find the impact of the groundwater depths on the saturation states, since by evaporation from groundwater pure water from is taken calling to increase the dissolved minerals in the unit volume of the liquid. It was found also no clear relationship from this regression.
The evaporation from the groundwater is to be considered in this research as 7.5%/y.

3. Groundwater Inputs into the Gulf of Aqaba

To calculate the discharge of groundwater into the sea Glover method was used. Glover (1959) arrived at a simple solution for an unconfined aquifer, making assumptions about the relationship between the thickness of the freshwater lens and the hydraulic head, which gives the relationship between y(x) the thickness of the freshwater lens at any distance (x) from the coast and the flow:

$$Q = \Delta K L y_0$$

where, Δ *is the difference between seawater and freshwater density divided by the freshwater density (~ 0.025), L= the width of the region through which freshwater seeps into the sea floor, and* y_0 *= the depth to the salt wedge at the coast.*

The total amounts of water received by the northern subarea extending until Wadi Al Muhtadi are **11.226 million m^3/y**, and after evaporation losses as **10.38 million m^3/y.**

The seawater intrusion study located the interface near to the shoreline with a distance of about 15 meters below the surface. The total length of the shoreline in the northern part of the study area is 7500 meters. The permeability factor here is considered as ($8*10^{-5}$ m/sec).

Applying the previous formula gives:

$$\mathbf{Q = \Delta K L y_0}$$

$$\mathbf{Q = 0.025*(8*10^{-5}\ m/sec.)*7500\ meter*15\ meter}$$

$$\mathbf{= 7.1\ million\ m^3\ /y}$$

$$\mathbf{= 225.14\ liter/second.}$$

$$\mathbf{= 0.03002\ liter/meter.\ second}$$

The annual discharge of groundwater into the Gulf of Aqaba from the northern region is 7.1 million m^3 /y. Accordingly the excess is 3.28 million m^3 /y.

The southern subarea possesses relatively deeper groundwater levels compared to the northern subarea. Hence evaporation can be neglected.

The total flowing amounts of water in this basin were found in the chapter of “Hydrogeology” not to exceed more than **3 million m^3/y** .

The hydrodynamic interface was estimated under the surface level here by geo-electrical method as 11.1m at 100m from the shoreline, 51.8m at 200m from the shoreline, and less than 4 meters at the shoreline.

Applying the formula of Glover (1959) considering a permeability factor of ($8*10^{-5}$ m/sec) and shoreline length of 11000 meters gives:

$$\mathbf{Q = 0.025*(8*10^{-5}\ m/sec.)*11000\ meter*4\ meter}$$

$$\mathbf{= 2.78\ MCM/y.}$$

$$\mathbf{= 88.153\ liter/second.}$$

$$\mathbf{= 0.008014\ liter/meter.\ second}$$

The flowing amounts of groundwater in the southern basin of the study area are low. The EC-value of **21080 m S/cm** in the Fertilizers Company well (500m from the shore) (Fig. 73) is very high for the groundwater, and indicates without any doubt a mixing process with sea water. A hydrogeological barrier in this aquifer produces high difference in the heads.

The flowing water amounts through the aquifers were quantified, and the actual flow conditions were approached. The quality of flow may confirm on the previous. The procedure is to follow the flowing water as a flux, which mixes when meeting another water flux of other quality. The EC-value of the indirect recharge water coming from floods was considered as 600 µ S/cm (depending on the suspended and dissolved materials they carry).
The EC of groundwater in the northern subarea after all input water types get mixed in the aquifer is calculated as:

Wadi Al Yutum groundwater ***Southern Wadi Araba G.W*** ***Rain water (recharge)***

$$\frac{3.5MCM/y*100\%*1048mS./cm}{11.226MCM/y}+\frac{6.8MCM/y*100\%*3000mS./cm}{11.226MCM/y}+\frac{0.1258MCM/y*100\%*350mS./cm}{11.226MCM/y}$$

Indirect recharge

$$+\frac{(0.3+0.35+0.65)MCM/y*100\%*600mS./cm}{11.226MCM/y} = \mathbf{2217.37\ m\ S/cm.}$$

This is the EC of the groundwater in the mixture in the named aquifer before evaporation loss.

Exposing 7.5% (as evaporation) from the 11.226 **million m^3/y** with a quality of 2217.37 µ S/cm for evaporation will increase the conductivity of this water as 166.30 µ S/cm.
At the end the water in the northern subarea is of EC of 2383.7 µ S/cm.

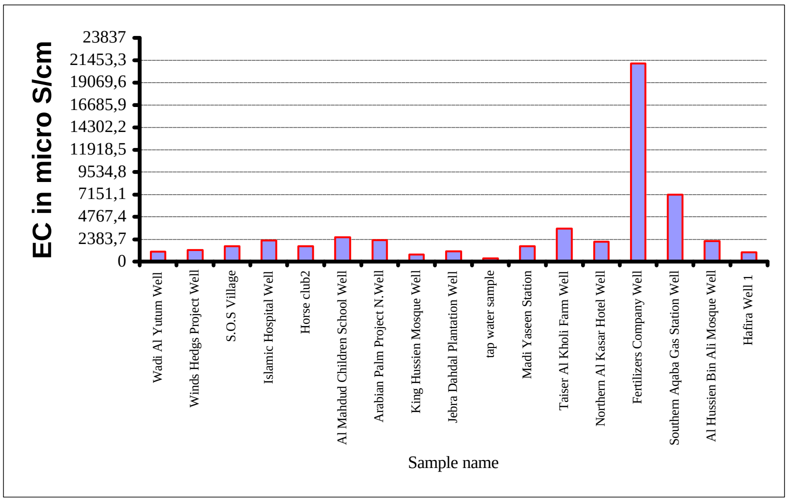


Fig. (73): EC-values of different water samples in the study area.

2.8.3 Hydrogeochemical Modeling

The quality of the groundwater in the study area is a function of several factors; its origin, recharge process, human impacts and mixing processes with the intruded seawater, besides the mixing of the groundwater layers; the shallow with the deep.
The study area has two types of aquifers in general; the shallow aquifer, and the deep one. The shallow groundwater of the aquifer flows faster than the deep one, and possesses lower salinity than the deep groundwater. The unavailability of deep wells in the study area made it difficult to reveal direct information about the deep groundwater quality.

The upper flowing groundwater should be of a younger age than the deep one, because the recharge processes take place in this flowing zone. The deep groundwater passes along the hydrodynamic interface between the fresh and the seawater to join the marine water body, while it is easier for the shallow groundwater, which joins it by flowing through the inlet between the upper limit of the zone of the interface and the sea level. This has an important role in adding the layering mechanism between the upper shallow water body and the deep one. The long residence time of the deep groundwater in the study area in the aquifer exposes it for more solubility reactions with the rock phase, which leads for higher salinity. All besides the segregation of some heavy suspended materials received from the upper aquifer into the lower one, such as organic matters accompanied around some immobile heavy metals in a groundwater of high pH values. If this true, the high EC water comes from the deep aquifer should be of low Eh values according to the presence of the segregated materials, which consumes high amounts of oxygen to attain their reactions.
The correlation between the EC-values and the Eh-values of the groundwater revealed to some extent a negative relationship between them. May a part of this trend is attributed to this expected impact. See Figure (74).

Durov diagram is used to shed light on the hydro-geochemical processes in groundwater aquifers, where end members of the water types are defined. The method is to plot the anions Mg, Ca, and Na in one triangle and the cations Cl, HCO3 and SO4 in another triangle. The resulting points of every sample should be matched to give a third point in a plane with two axes; the base of the anions triangle, and that of the anions.
It was here important to involve the human impacts as another end members which affect the water quality. Accordingly seven embers were found:

- Seawater (intrusion)
- Rain water (recharge)
- Observation well of the waste water treatment plant of Aqaba (processed waste water leakages)
- Waste water from a dug hole (cesspool leakages)
- Wadi Al Yutum water (inflow)
- Wadi Araba water, Rahma well (inflow)
- Drinking water supply (leakages)

The other groundwater samples were given the symbol of the empty black circle and were also plotted in the diagram. Fig. (75).

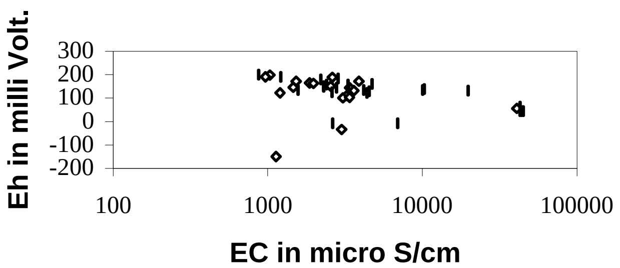


Fig. (74): Correlation between Eh and EC-values of the groundwater.

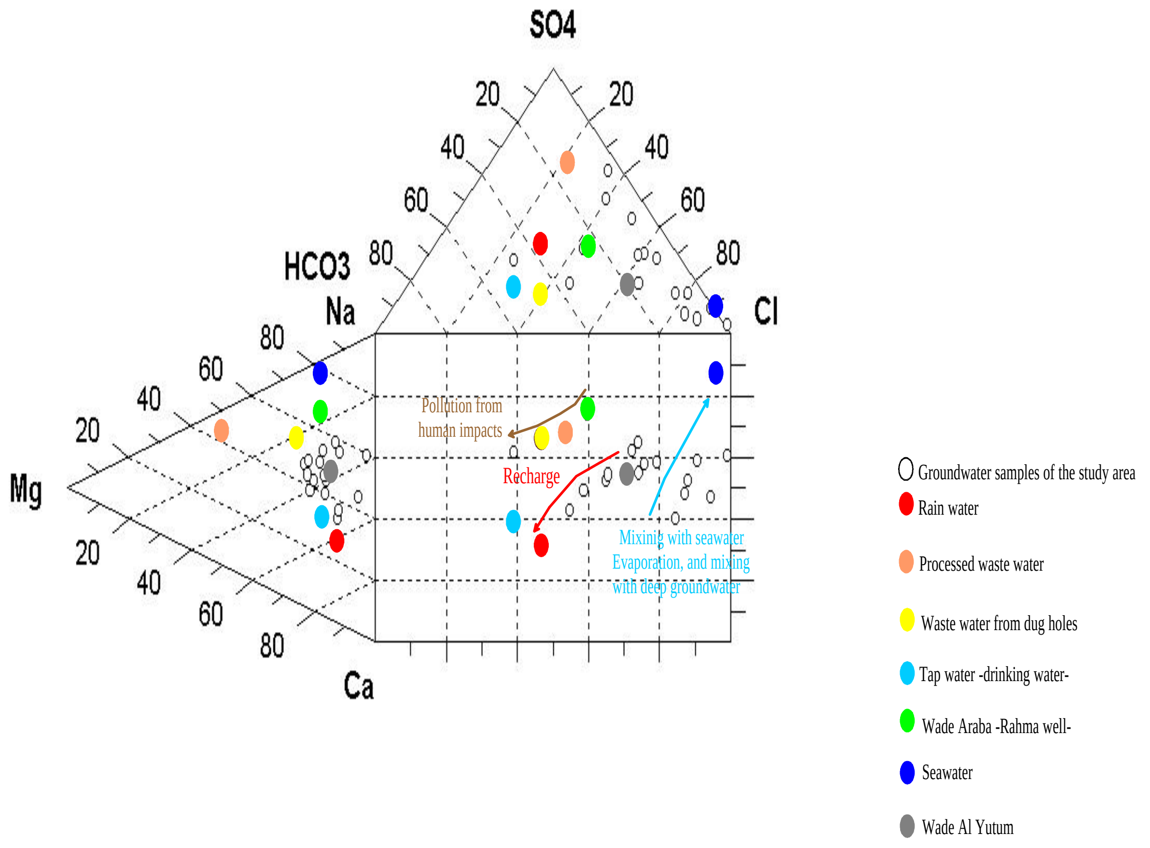


Fig. (75): Durve diagram: plots of groundwater end members.

The first look on the diagram shows that the end members of the water types are surrounding the groundwater samples of the aquifer of the study area.
On the cations triangle it is clear that most samples are clustering around that of Wadi Al Yutum water type, which indicates the strong impact of the water that flows from the wadi into the basin. It seems also that Wadi Al Yutum water is the main source of the groundwater.

The anions triangle shows scattering in the distribution of the samples. But with that it shows that most groundwater samples plot closer to Wadi Al Yutum's groundwater than the other end member.
In the same triangle seawater occupies the corner of the high chloride concentration, and some samples are clustering in this corner which indicates the impact of seawater encroachment on them and the impact of the mixing with the deep groundwater besides the effect of evaporation from the shallow part of the aquifer.
In the former triangle the water samples are generally clustering between the end members; seawater, Wadi Al Yutum, processed waste water and Wadi Araba's water.

In the resulting plane it was possible to distinguish ***three major hydrogeochemical processes*** *in the aquifer:*

- Going towards **rain water** and the **supply water leakages** qualities (red arrow) is an indication on the **recharge processes**. The samples which locate between the rain water type and Wadi Al Yutum water type are those exposed to the impact of the mixing with low salinity water which is the rain in this case. *This process is found in the alluvial fans zones and wadis zones where the recharge is higher.*

- In the aquifer proceeds mixing process between waters of low salinity and other water types of higher salinity. The processes of **over-pumping** from the coastal aquifer lead to attract the seawater interface more towards. This is besides the ability of the **deep groundwater to flow upward** allowing mixing with the upper shallow groundwater. Other process leads the groundwater for more salinity is the **groundwater evaporation**. It clear on the plane that some groundwater samples are going in the direction of seawater quality (blue arrow). Accordingly, this behavior is attributed to the previously mentioned three processes. The general trend here is to increase the salinity and degrade the quality of the groundwater. *This process is more likely to be found in the coastal zones and in the zones where the groundwater is shallow, and the zones where many pumping wells are present with high abstraction.*

- Going in the direction of the polluted water types due to the human impacts (brown arrow) is another general trend of groundwater chemistry. Aqaba waste water treatment plant locates on the southern Wadi Araba mouth, the groundwater around it is derived from Wadi Araba (see the green point in the plain). Along the arrow locates the sample of the observation well of the plant (represents leakages of processed waste water) and then locates the untreated waste water. This process degrades the groundwater quality.

<u>The main trend of the upper groundwater aquifer in the study area is to show three hydrogeochemical processes</u>; *recharge from rain water, mixing with seawater and deep groundwater, and evaporation from the shallow groundwater, and pollution leads for degradation of the water quality.*

Cluster analyses on the same samples was used in revealing the trends of the chemical processes in the groundwater and to put the samples in groups. After that the Piper diagram was used to plot the different produced groups to confirm the method. Accordingly, three dominant trends were deduced; recharge, mixing with seawater and/or deep groundwater, and pollution. In addition to that the flowing groundwater comes from Wadi Al Yutum and Wadi Araba was clustered in one group, where three samples from the northern subarea of the aquifer joined this group. Figures (76) and (77) show the different produced groundwater groups.

The Euclidic distance which is the geometrical distance in many dimensional space,

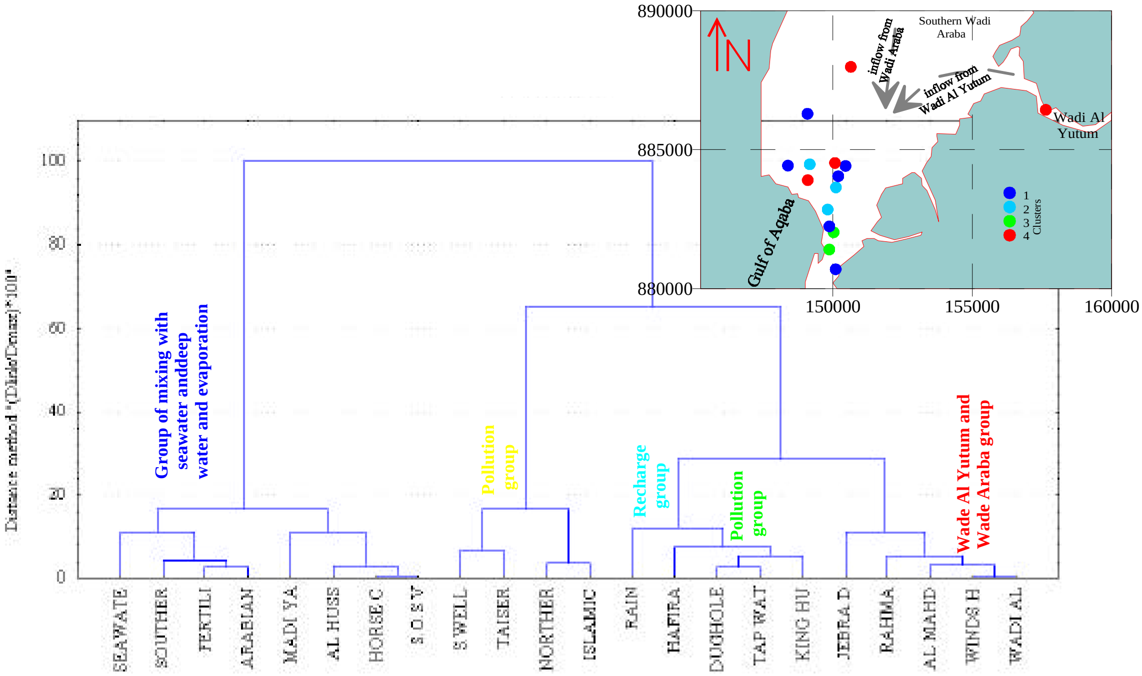
$$\textbf{Distance (x,y)} = \left\{ \sum_i (\mathbf{x}_i - \mathbf{y}_i)^2 \right\}^{\frac{1}{2}}$$

Was used to calculate the distances between the different samples (Table 29).

From the produced Piper diagram the cations triangle represents perfectly the different water groups i.e. it separates between them in a clear boarders. It leads to use the triangle's components (SO4, Cl, HCO3+CO3) to build the transport model due to them.

Table (29): The results of the calculated distances (Euclidic distance) between the different groundwater samples.

	WADI AL	WINDS H	S.O.S V	ISLAMIC	HORSE C	AL MAHD	ARABIAN	KING HU	JEBRA D	TAP WAT	MADI YA	TAISER	NORTHER	FERTILI	SOUTHER	AL HUSS	HAFIRA	RAIN	S.WELL	RAHMA	DUGHOLE	SEAWATE
Wadi Al		167	656	1387	649	1636	1448	323	215	736	785	2837	1232	21756	7098	1270	246	890	2065	122	1807	51713
Winds H	167		494	1229	490	1470	1287	487	231	902	631	2682	1078	21590	6935	1106	338	1055	1918	188	1657	51548
S.O.S V	656	494		870	72	1034	821	973	653	1384	339	2312	762	21103	6453	629	793	1534	1599	667	1273	51069
Islamic	1387	1229	870		891	469	566	1684	1287	2092	650	1482	266	20500	5861	528	1452	2235	848	1343	969	50434
Horse c	649	490	72	891		1054	837	969	659	1374	357	2334	791	21114	6469	656	797	1523	1618	660	1296	51075
Al Mahd	1636	1470	1034	469	1054		551	1948	1569	2369	943	1369	578	20168	5563	519	1703	2520	816	1605	653	50119
Arabian	1448	1287	821	566	837	551		1756	1394	2162	713	1730	711	20339	5658	284	1561	2306	1247	1447	1007	50297
King Hu	323	487	973	1684	969	1948	1756		416	428	1086	3125	1523	22071	7403	1582	304	585	2344	363	2093	52029
Jebra D	215	231	653	1287	659	1569	1394	416		826	708	2728	1129	21705	7038	1221	232	980	1951	178	1732	51657
tap wat	736	902	1384	2092	1374	2369	2162	428	826		1491	3526	1933	22485	7812	1998	710	163	2741	770	2510	52439
Madi Ya	785	631	339	650	357	943	713	1086	708	1491		2128	588	21028	6353	588	890	1634	1439	768	1281	50975
Taiser	2837	2682	2312	1482	2334	1369	1730	3125	2728	3526	2128		1606	19318	4856	1792	2880	3666	896	2784	1597	49223
Norther	1232	1078	762	266	791	578	711	1523	1129	1933	588	1606		20680	6059	563	1282	2079	880	1182	953	50625
Fertili	21756	21590	21103	20500	21114	20168	20339	22071	21705	22485	21028	19318	20680		14782	20498	21846	22631	20078	21745	20150	30161
Souther	7098	6935	6453	5861	6469	5563	5658	7403	7038	7812	6353	4856	6059	14782		5839	7191	7952	5590	7096	5643	44774
Al Huss	1270	1106	629	528	656	519	284	1582	1221	1998	588	1792	563	20498	5839		1376	2147	1212	1268	902	50470
Hafira	246	338	793	1452	797	1703	1561	304	232	710	890	2880	1282	21846	7191	1376		867	2086	213	1825	51798
Rain	890	1055	1534	2235	1523	2520	2306	585	980	163	1634	3666	2079	22631	7952	2147	867		2886	924	2672	52584
S.Well	2065	1918	1599	848	1618	816	1247	2344	1951	2741	1439	896	880	20078	5590	1212	2086	2886		1999	976	49986
Rahma	122	188	667	1343	660	1605	1447	363	178	770	768	2784	1182	21745	7096	1268	213	924	1999		1770	51695
Dughole	1807	1657	1273	969	1296	653	1007	2093	1732	2510	1281	1597	953	20150	5643	902	1825	2672	976	1770		50106
Seawater	51713	51548	51069	50434	51075	50119	50297	52029	51657	52439	50975	49223	50625	30161	44774	50470	51798	52584	49986	51695	50106	



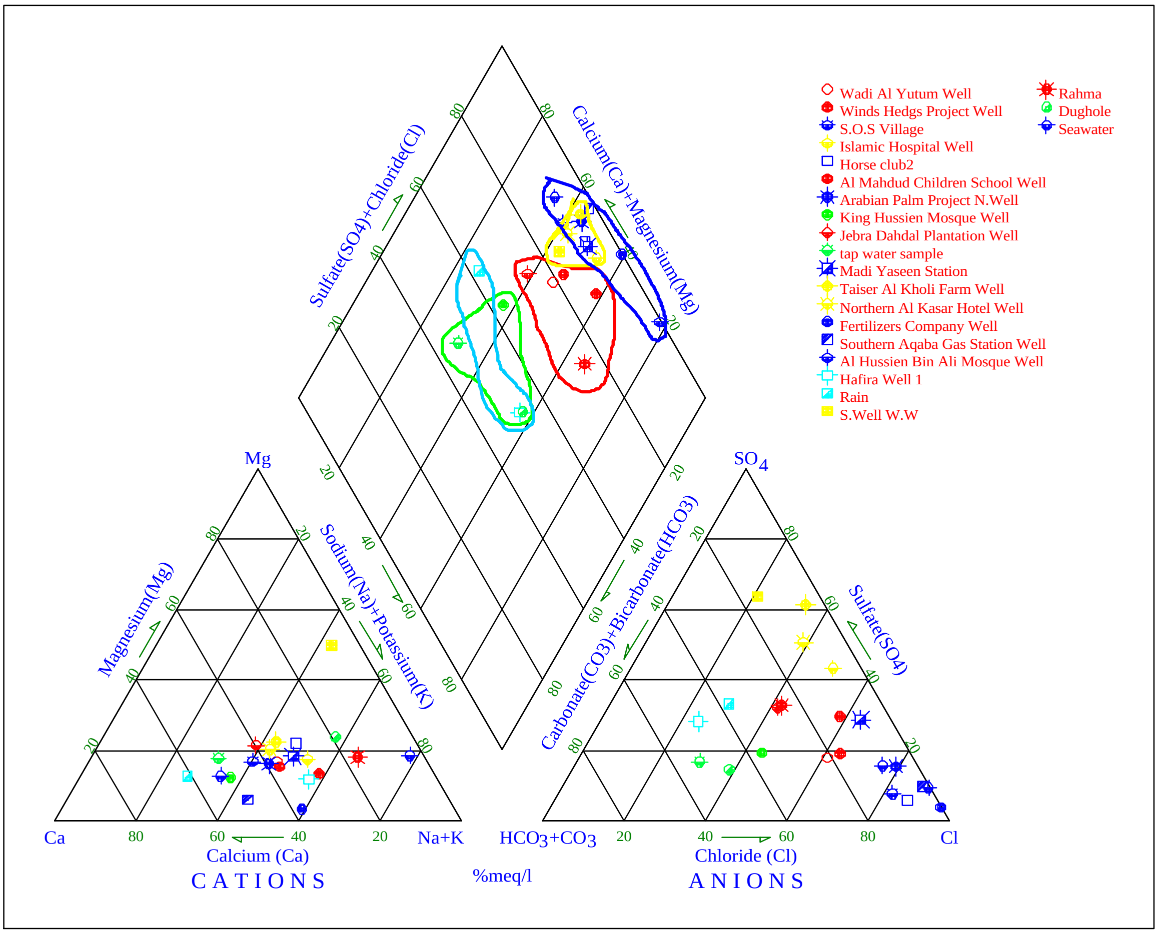


Fig.(76, 77): Clusters of groundwater types and their plots on Piper diagram.

The spatial distribution of Chloride in the northern part of the study area gives indications on the mixing process with the groundwater that comes from Wadi Al Yutum, mixing process with deep groundwater and with seawater. The irrigation process of the private gardens was clear also. Chloride proved to be conservative in the aquifer giving well distinguished clustering boarders on the cations triangle of Piper diagram.

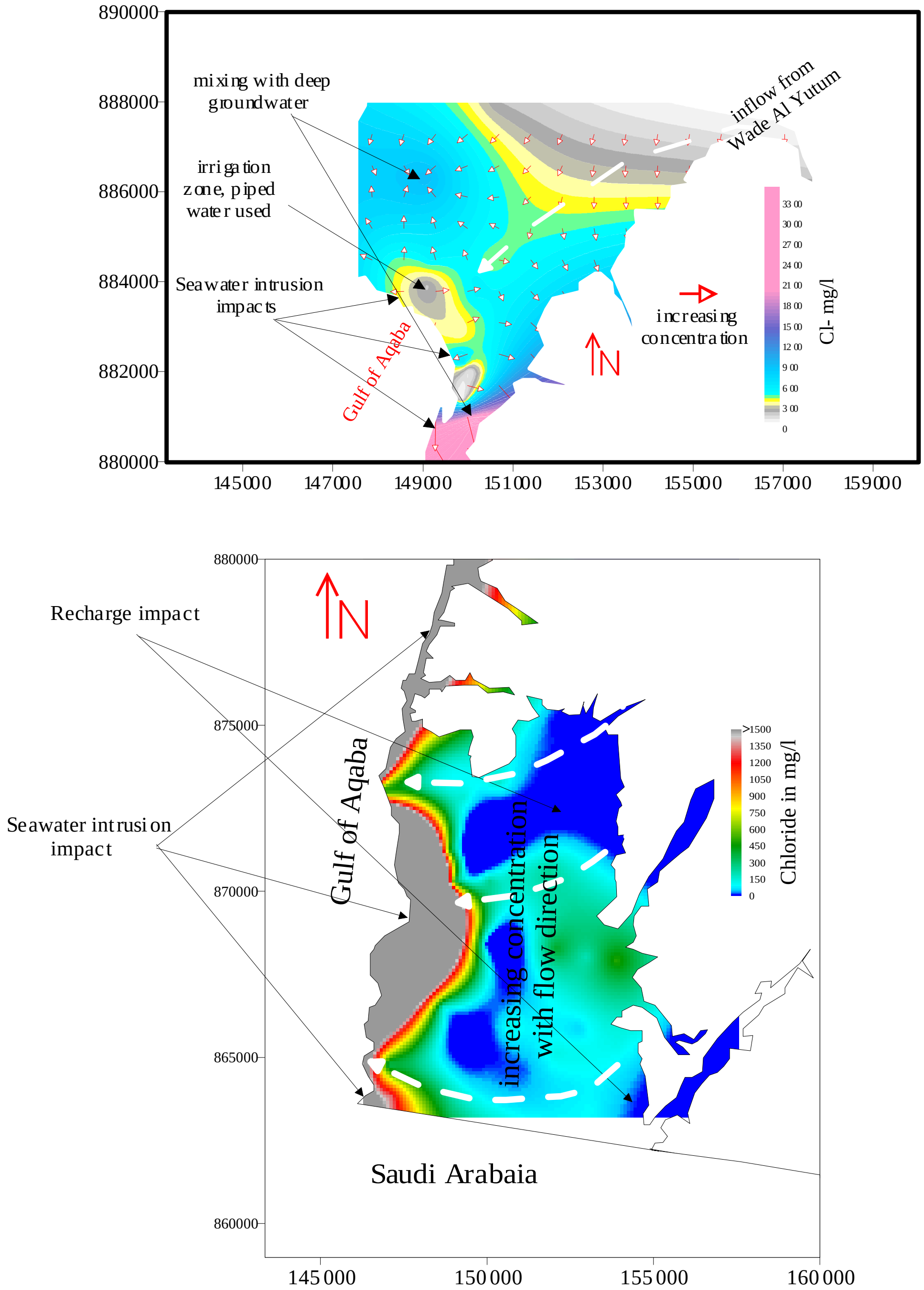


Fig. (78): Raster models of chloride concentration; upper one is from the water hydrochemistry measurements, and lower one is from the geoelectric measurements.

The modeled geoelectrical-hydrochemical results of chloride concentrations in the southern subarea were mapped with a spacing of 100 meters. The general trend of the resulted map is an increase of the concentration towards the Gulf of Aqaba and with the direction of the groundwater flow. It was also the major trend in the northern subarea. Some indications on the recharge zones could be seen having chloride concentrations lower than 40 mg/l (Fig. 78).

2.8.4 Hydrogeological Modeling on the Groundwater:

Use is made of groundwater head data and hydrogeological parameters to build a simple flow model, which is expected to reveal the spatial groundwater velocity and flow amounts in the upper part of the aquifer.
The model supposes that the flow of groundwater in the study area occurs mainly within the first saturated 10 meters. Going downward in the aquifer, the factor of permeability becomes lower. The cause behind that is the compaction which increases with increasing depth, and the short flow path that should the water cross into the sink. The shallow groundwater flows directly into the Gulf of Aqaba, while the deep groundwater should flow along the existing seawater-fresh water interface.
The general flow formula to be applied here is:

$$Q = K*g*A$$

Where Q *is the amount of flowing groundwater (* m^3*/s) (throughput).*
K *is the permeability (m/s).*
g *is the groundwater gradient.*
A *is the cross sectional area, through which the groundwater flows.*
*The value **K*g** represents the groundwater flow velocity.*

The pumping tests that have been carried out in the study area revealed that the permeability factor in the northern subarea for the upper part of the aquifer has an average of ($3*10^{-4}$ m/s).

For the aquifer of the southern subarea the whole permeability should be theoretically lower than that of the northern subarea. The low recharge it is not possible with a permeability of $3*10^{-4}$ m/s to keep the groundwater levels high as were found, which indicate low flow. Accordingly, the theoretical value of permeability for was assumed as $0.1*10^{-4}$ m/s.

The occurrence of a barrier conditions in the southern subarea of the aquifer as was confirmed by geoelectrical soundings, although they were not able to reveal the spatial extension of this barrier, and faulting processes reduce the permeability of the aquifer, when they uplift or down lift impermeable zones and layers.

The direct field measurements located the groundwater level in the northern subarea of the aquifer at an elevation range of zero to about 40 meters. The geoelectrical surveys carried out in the southern subarea used to estimate the groundwater level found it to range from zero near the shorelines to more than 130 meters in the east (Fig. 79).

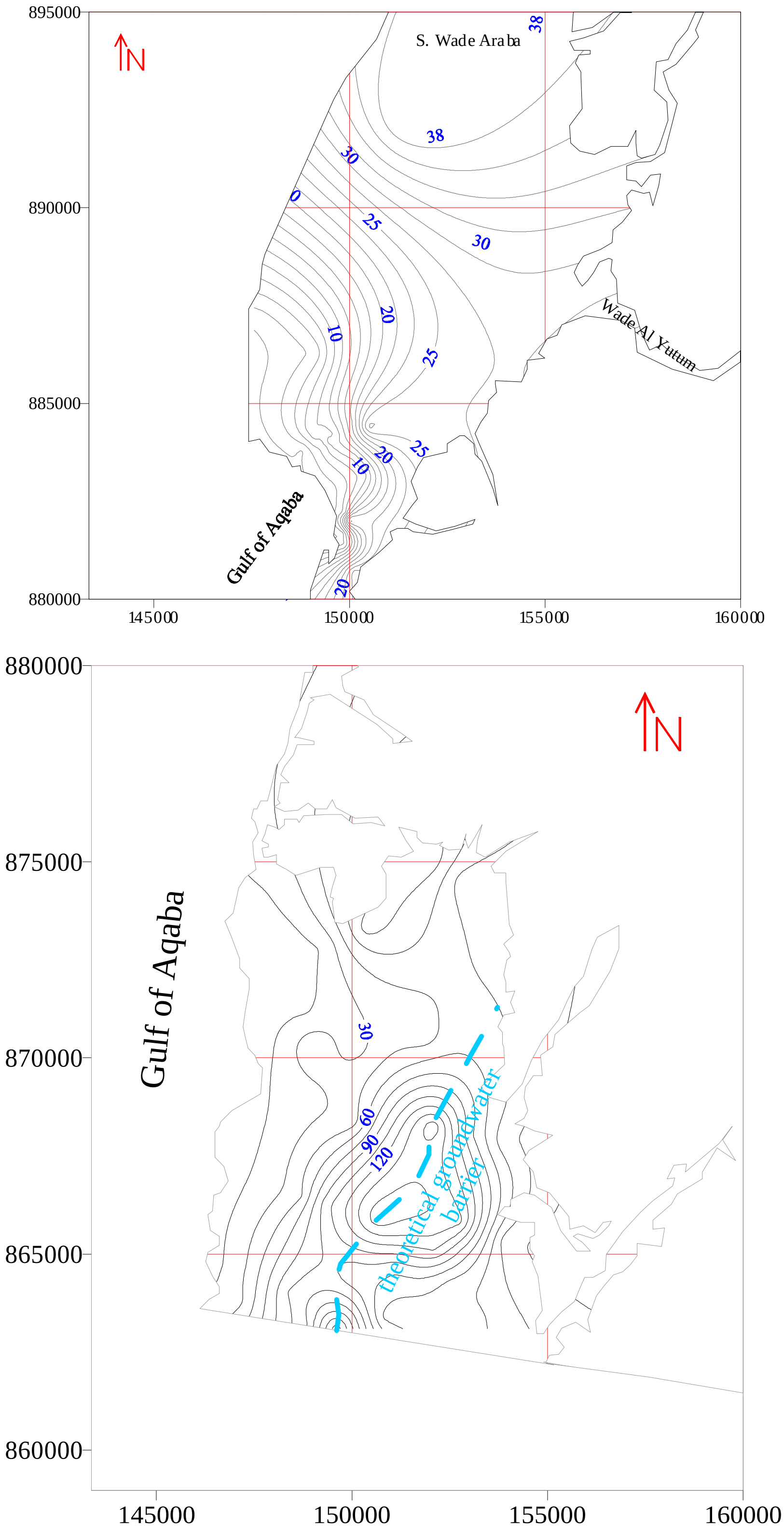


Fig. (79): Groundwater levels; the northern and the southern subareas.

The measured groundwater levels in the northern part, and those estimated by the vertical geoelectric method (Schlumberger) were subtracted from the topography using DEM of 100 meters resolution. Accordingly the static water levels and flow directions were constructed (Fig. 80).

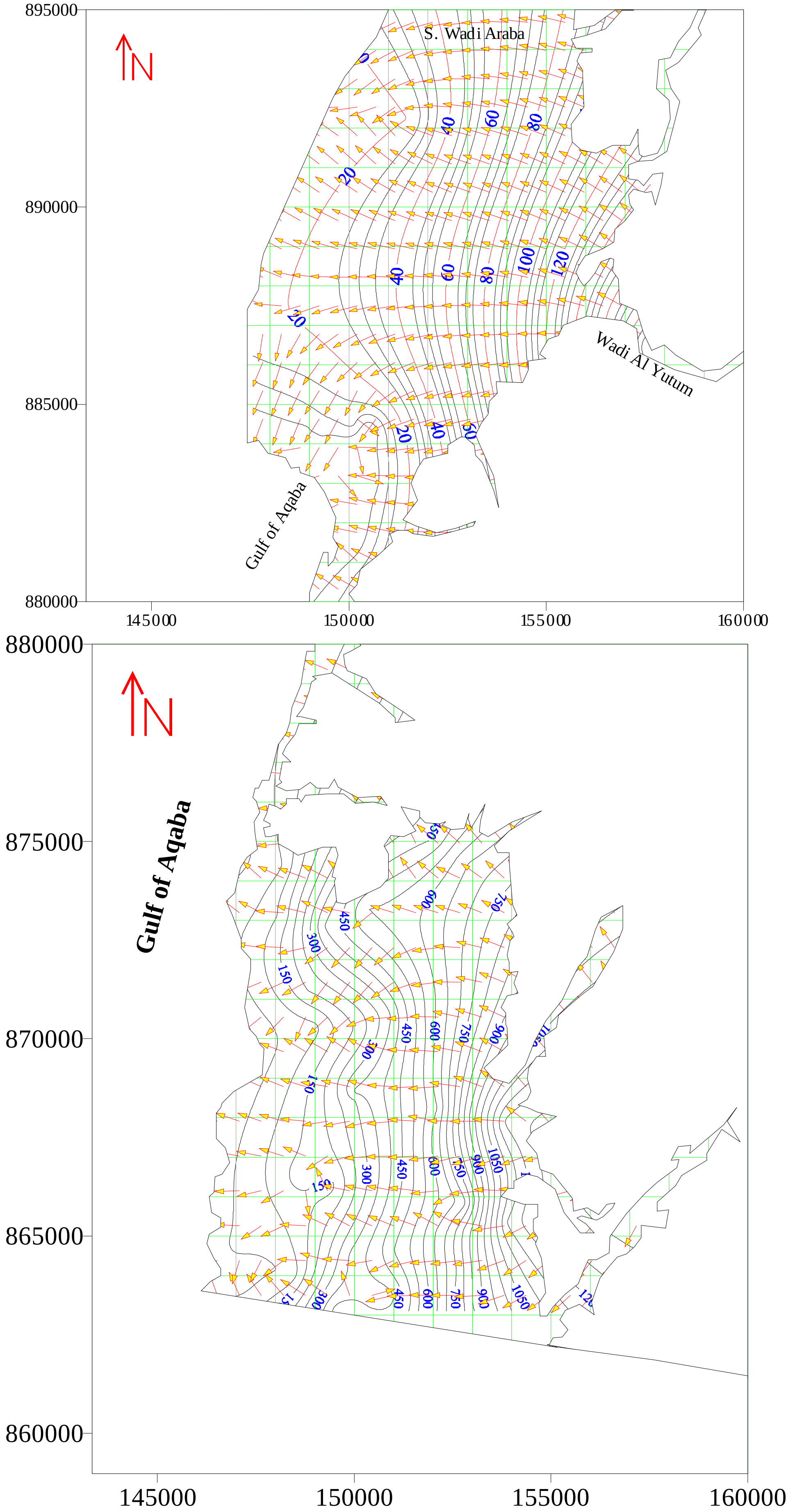


Fig. (80): Static groundwater levels and flow lines.

Wadi Al Yutum inherited the aquifer high head contrast, which in turn was reflected on the flow directions directed to the west. The major trend in the directions of flow is towards the Gulf of Aqaba.

The groundwater levels in the northern subarea range from about 190 m asl in Wadi Al Yutum to zero m in the Gulf of Aqaba area. In the southern subarea they range from about 1050 m asl in the east, nearer to the periphery of the granite basements to zero m in the Gulf of Aqaba area.
The theoretical analyses of the flow pattern in the northern subarea indicates that the groundwater flow from Wadi Al Yutum is forced by the groundwater flows from the southern Wadi Araba to follow in the general flowing pattern towards the Gulf of Aqaba. The groundwater from here flows towards the centre of Wadi Araba and then it joins the major flow direction.

Having a saturated thickness all over the aquifer of 10 meters and a permeability factors as $3*10^{-4}$ m/s and $0.1*10^{-4}$ m/s for the northern and the southern upper aquifers respectively, the average flow velocities and amounts of flow were calculated to:

Flow velocity (V) = gradient * permeability

Flow amount (Q) = V * Cross sectional area of the flow path

Area of the flow path = Saturation thickness * Width of the flow path

The northern upper aquifer with 7500 meters flow path width and 4000 meters flow path length:

Average flow velocity = (40m/4000m)*$3*10^{-4}$ m/s
= 0.000003 m/second
Average flow amount = [0.000003 m/s*(7500m*10m)*3600sec.*24hour*365day/1000,000]
= 7.09 million m^3/year
= 224.8 litter/second
= 0.03 litter/m.second

The southern upper aquifer, with 11000 meters flow path width, and 7000 meters length:

Average flow velocity = (800m/8500m)*$0.1*10^{-4}$ m/s
= $9.4*10^{-7}$ m/second
Average flow amount = [$9.4*10^{-7}$ m/s*(11000m*10m)*3600sec.*24hour*365day/1000,000]
= 3.26 million m^3/year
= 103.53 litter/second
= 0.0094 litter/m.second

These values are in a good agreement with those, calculated by submarine groundwater flow calculated using the interface between the fresh and seawaters.

2.8.5 Confirmation by a Comparison Study Between Groundwater Levels of Two Successive Years; An Indication on the Groundwater Flow

Through the filed work the groundwater levels were measured twice; in April/1999, and in May/2000. The general trend is a lower level of May 2000 measurements than those of April/1999 by about 0.3 meter in the city of Aqaba and about 4 meter in Wadi Al Yutum. From these measurements it is possible to derive a relative indications on the spatial flow rates in the study area, *namely the part of Wadi Al Yutum and beneath the city of Aqaba*. It deserves mention here that the year 2000 was considered as a dry year all over Jordan. The study area received in this year no direct recharge. Also due to the low rain amounts a very small amounts of indirect recharge were expected. Depending on that, the water level dropped by 0.3 meter under the city of Aqaba. Fig. (81).

It is considered that nothing changed in the prevailing conditions of the aquifer except the absence of direct and indirect recharge.

Accordingly, the amount of recharge over all the study area (250 km^2) for one year was:

One year recharge = Change in groundwater level storage coefficient * area of the aquifer*

$$= 0.3\ m * 0.13 * 250\ km^2 * 1000{,}000$$

$$= 9.75\ \text{million}\ m^3/\text{year}.$$

This value can well fit with that calculated due to the **normal recharge** in the study area of ***5.76 million m^3/year***. The excess water can be attributed to the recharge of the dry year 2000.

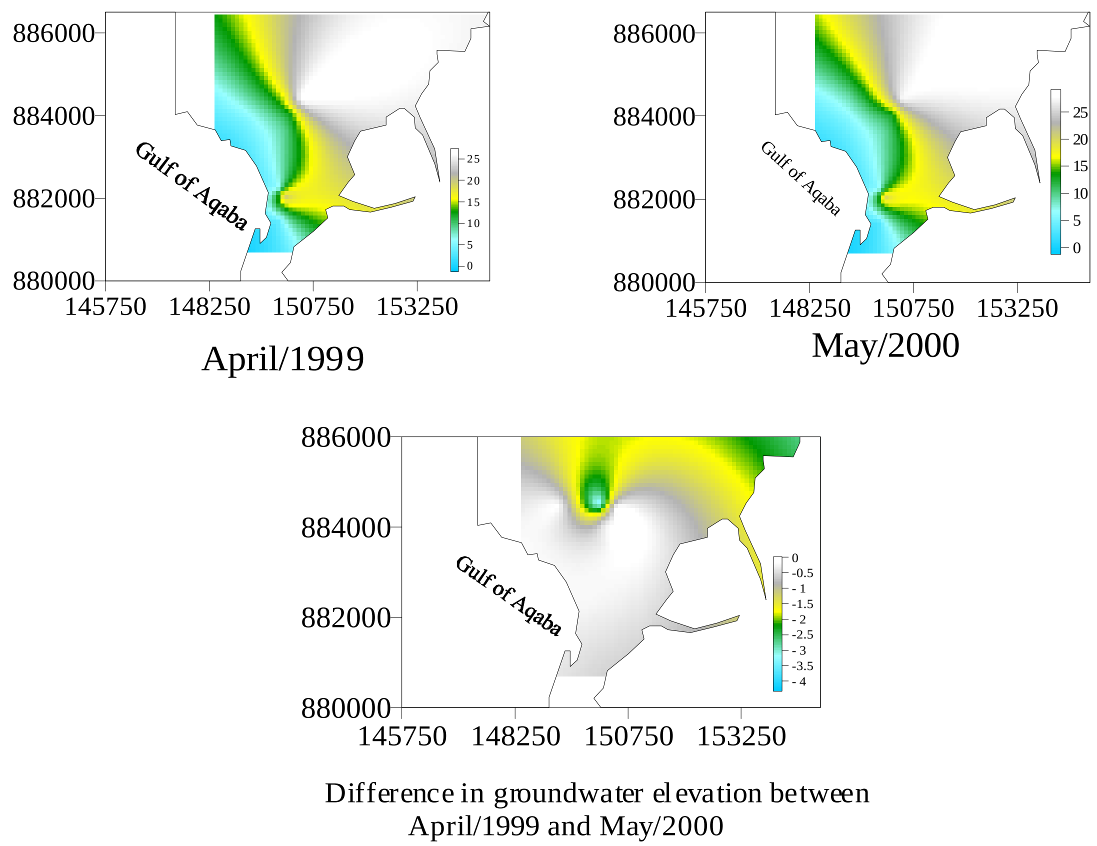


Fig. (81): Groundwater levels changes in meters in the year 1999/2000.

2.8.6 Safe Yield from the Aquifer

The safe yield from the aquifer can be approached applying the general formula:

Draw down = (total abstraction – total recharge) / (area of the aquifer * aquifer's storativity)

The draw down has a bad impact on the aquifer, when it allows the mixing of the upper fresh groundwater layers with the deep salt water. Another impact concerns the coastal aquifers, when it allows more encroachment of the seawater into the land. The draw down may produce problems to constructions, especially foundations of the buildings.

The excess of water found in the northern subarea of the aquifer was estimated at 3.28 million m^3/year.
This excess stays in the aquifer, and causes an increase in the water head as:

(3.28 million m^3/y)/ [(170 km^2 *which is Area of the aquifer*)*(0.13 assumed *storage coefficient* of *the aquifer*)]
=14.84 cm/year.

In other words, this is the safe yield per annum of the aquifer under the city of Aqaba. This value represents the rise in the water head per a year from the excess from the flowing groundwater. This approach is the natural one i.e. without human impacts.

The southern part of the aquifer produces no excess. Accordingly it shouldn't been touched due to the groundwater as for any abstraction activity. ***More studies should be done to investigate the role of the revealed barrier in this subarea in capturing the groundwater.***

2.8.7 Geoelectrical Modeling on Fresh Water Availability:

The geoelectric surveys carried out in the study area, have been used to slice the subsurface of the aquifer, to show the availability and the spatial distribution of the fresh water.

The previously discussed Archie's law was used to reveal the low electrical conductivity parts of layers bearing water.

Previously it was stated that the groundwater EC-values can be expressed as:

$$\mathbf{EC} = \frac{22583}{r}$$

*Where r is the resistivity of the geoelectrical layers (**Ohm.m**).*

The resistivites of the layers containing fresh groundwater ranges from 20 to 65 Ohm.m. Accordingly, the EC-values for the different depths (Fig. 82) range from **1129.15 to 347.40** m **S/cm.**

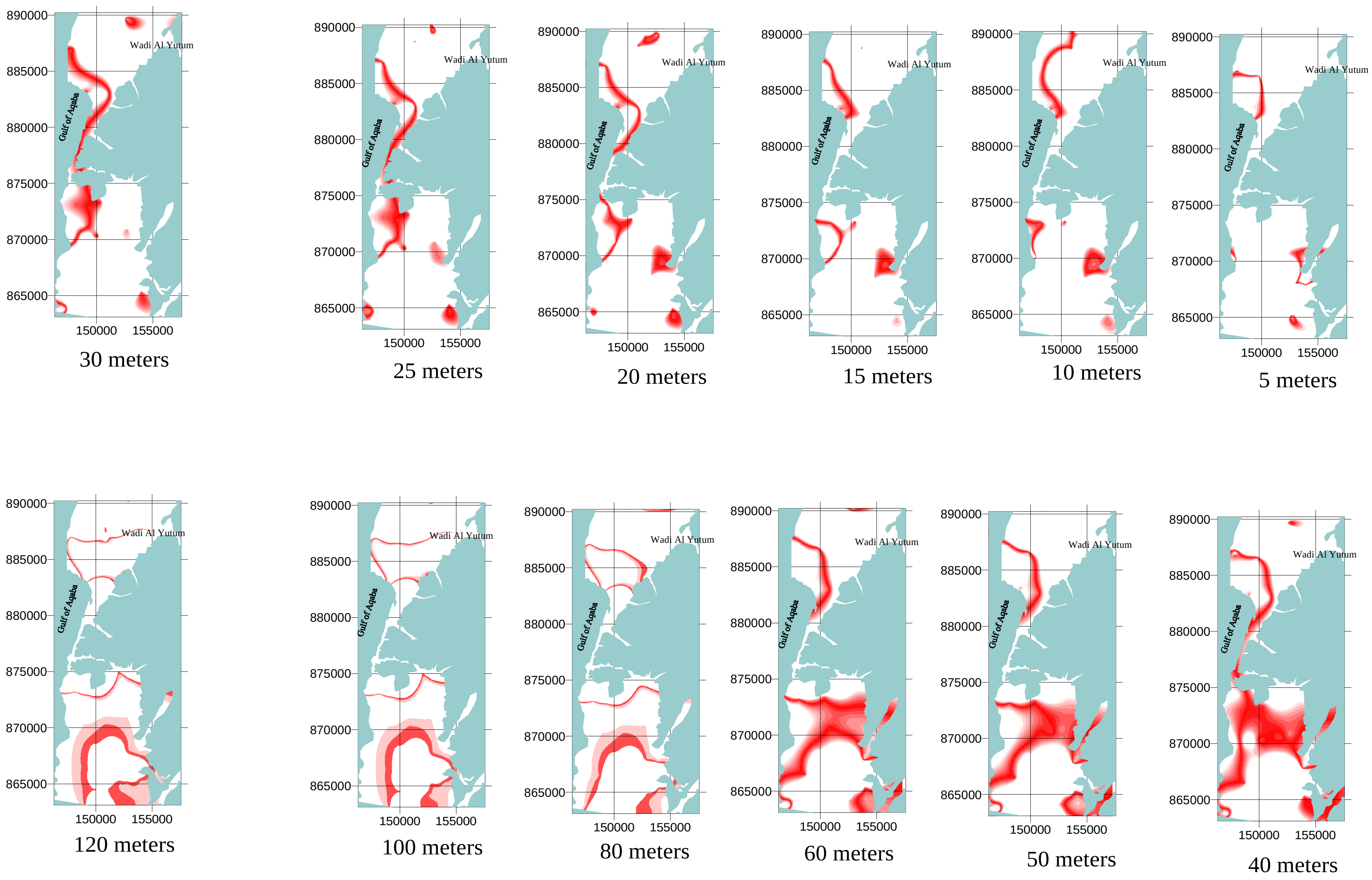


Fig. (82): Spatial abundance of fresh groundwater, modeled using the geoelectric survey results with resistivities range of 20-65 Ohm*m.

2.8.8 Modeling Transport of Groundwater

In coastal aquifers it is important to know the discharge of water directly into the sea (Submarine Groundwater Discharges) because it may be an important volume. It is also necessary to assess the biogeochemical impact of that water on the gulf's water quantitatively and qualitatively.
Contaminants, including nutrients and industrial wastes may be introduced into the coastal marine environments by SGD. In order to understand the impacts of these solute inputs the magnitude and chemistry of the groundwater discharge should be quantified.

The subsurface groundwater discharge into the Gulf of Aqaba is:

- *0.03(l/m.s) and 7.09 million (m^3/y) from the northern subarea along a shoreline of 7500 m with an average flow velocity of $3*10^{-6}$ (m/s). (See page 147)*
- *0.0049(l/m.s) and 3.26 million (m^3/y) from the southern subarea along a shoreline of 11000 m with an average flow velocity of $9.4*10^{-7}$ (m/s). (See page 147)*

Different chemical constituents join the Gulf water with the discharged water. Some of these constituents are conservative. The different **hydrobiogeochemical** processes taking place in the aquifer lead to increases reduction of these constituents.
Transport of dissolved chemical constituents in groundwater is attributed to two major mechanisms; **advection, and diffusion**. Advection means that the chemical solute possesses the same groundwater flow velocity to be transported. Accordingly, there exists no transport of the solute when the hydraulic gradient of the groundwater is zero. The diffusion process takes place even if the groundwater is not flowing. Here the solute moves from the high concentration area to the lower one. Generally diffusion process takes for reactive constituents.

The triangle representation of the cations namely of Cl^-, $HCO3^-$ and $SO4^{2-}$ (Fig. 76,77) revealed contrast in the borders between the different previously specified clusters of the groundwater. Accordingly, it emphasises on that they are conservative within the aquifer, so they can be used here to build a simple model for their input amounts into the Gulf of Aqaba, regarding their average concentrations, and the submarine groundwater flow rates. The used average values of concentrations, will enable us to approach the actual situations.

Table (30) shows the received amounts per year of Cl^-, $HCO3^-$ and $SO4^{2-}$ by the Gulf of Aqaba from the groundwater discharge.

Table (30): Amounts of Cl^-, $HCO3^-$ and $SO4^{2-}$ discharged into the Gulf of Aqaba.

CHEMICAL CONSTITUENT	NORTHERN AQUIFER (7500 METER CONTACT WITH THE GULF OF AQABA)		SOUTHERN AQUIFER (11000 METER CONTACT WITH THE GULF OF AQABA)	
	Average concentration in the aquifer (mg/l)	Received Amounts by the Gulf of Aqaba (kg/year)	Average concentration in the aquifer (mg/l)	Received Amounts by the Gulf of Aqaba (kg/year)
Cl^-	*300*	*2126788*	*700*	*2285445*
$HCO3^-$	*130*	*921608*	*28*	*91418*
$SO4^{2-}$	*100*	*708929*	*428*	*1397387*

One recent approach to model the transport of pollutants in aquifer media is to use the pollutants themselves as traces. Ortlam (1996) used the method in Bremen-Germany, to measure the groundwater flow velocity. The target was the potassium wastes, which came from pottasmines in the drainage area of the river Weser.

Quantifying the impacts of the different types of pollutants in the study area, on the aquifer and marine ecology requires modeling of potential source, attenuation factors, reactivity with the aquifer’s matrices and the spatial concentration and release history of the pollutants under study.

Chapter 3

ASSESSING HUMAN IMPACTS ON THE ECO-SYSTEMS IN AQABA

3.1 Introduction

Munn (1979) defined the environmental impact assessment as *an activity designed to identify and predict the impact on the biogeophysical environment and on man's health and well-being of legislative proposals, policies, programs, projects, and operational procedures, and to interpret and communicate information about the impacts.*
Coastal aquifers are more vulnerable for pollution than other types of groundwater aquifers since they are normally shallow and in direct contact with the marine ecology. Discharges of groundwater and impacts of conservative chemical constituents into vulnerable marine ecology of the Gulf of Aqaba were previously quantified.
In the following, pollution processes, their impacts on the soil and groundwater and on the marine ecology are quantified.

3.2 Conceptuality of Pollution Processes and Quantification of their Potential Sources

The human, industrial and agricultural activities have their impacts on the hydroecology. The groundwater is shallow, and the aquifer possesses good yielding rates with permeable soil cover, high infiltration rates and weak matrices buffering capacity. High rates of groundwater discharge into the Gulf of Aqaba (relatively due to the groundwater balance) do not allow long residence time to attenuate pollutants. Accordingly, it is expected that disturbances within the natural marine cycles may take place. One feature is the eutrophication process manifested as algae growth along the shores.

Pollution potential sources of soil and groundwater refer to:

- **Sea porting processes**
- **Liquid wastes disposal**
- **Small scale agricultural activities, specifically fertilizing process**
- **Solid and liquid wastes and dust particles emission from industrial activities**
- **Overpumping of groundwater bodies**

Details on these potential sources, the affected zones, and the types of impacts are shown in Table (31).

POLLUTION POTENTIAL	*EMITTED POLLUTANTS*	*QUANTITY OF EMISSION*	*AFFECTED ECOLOGICAL RESOURCES*	*AFFECTED ZONES*	*TYPE OF IMPACT, AND POLLUTION*	*NOTICES*
Aqaba Sea Port	Phosphate and cement dust particles, oils, liquid wastes of ships	(4011960 Ton/year) is the ported amount of phosphate through Aqaba Seaport.	Soil cover, groundwater, marine ecology	All the study area. (depends on wind direction and dust particles distribution).	Eutrophication along shores, chemical pollution of the groundwater, increasing salinity of soils.	-
Aqaba Waste Water Treatment Plant (WWTP)	Organic phosphate, $NO3^-$, K^+, F^-, Cl^-, $SO4^{2-}$, Na^+, organic components, Fecal Coliform and total Coliform	(1.5 million m^3 /year) leak into the aquifer from the treated waste water.	Groundwater, marine ecology	The zones around the plant, and along the flow direction of the groundwater	Eutrophication along shores, chemical and organic pollution of groundwater, raising water tables which affect basements of buildings.	Overloaded plant, inefficient treatment
Houses Dug Holes Waste Water direct Disposal	Organic phosphate, $NO3^-$, K^+, F^-, Cl^-, $SO4^{2-}$, organic components, Fecal Choliform and Total Choliform	(About 0.5 million m^3 /year) total leakages.	Groundwater, marine ecology	Aqaba city zones which are still not connected to the (WWTP) and the gulf water.	Eutrophication along shores, chemical and organic pollution of groundwater	Raw waste water into the aquifer.
Plantation Activities	Organic and chemical fertilizers, irrigation by treated waste water	One million m^3 /year is irrigation by treated waste water for public, and governmental plantation projects. Use of fertilizers is irregular, but it exists.	Soil, groundwater, marine ecology	Mostly in the northern part of the study area.	Eutrophication along shores, chemical and organic pollution of groundwater, increasing soil cover salinity.	-
Industry and transport	Heavy metals, gypsum and sulfur (mineral phases)	Irregular, but impacts can be observed especially near the Fertilizers Factory.	Soil, groundwater, marine ecology	Southern subarea.	Toxicity of sea and groundwater. Lowering pH values.	Gypsum is a solid phase residual of the fertilizers industry, and the sulfur is attributed to trucking process
Over pumping of aquifers	No emissions.	Depends on the abstraction amounts.	Groundwater	Northern subarea	Encroachment of seawater into the land, and increasing salinity of groundwater	-

Table (31): Details on pollutants potential sources, the affected zones, and the types of impacts.

3.3 Impacts on Soil Cover

The sea porting processes of phosphate and cement, the trucking process of raw materials and the industrial solid wastes disposal are the main processes that impact the soil cover. Fertilizing of private and governmental gardens and plantations impact also the soil.

The chemical analyses of soil water from different locations and depths show a trend of increasing salinity in a south ward direction. This is in correlation with the spatial locations of industrial, porting and trucking processes, which are located in the southern part of the study area. The wind speed and direction has major role in exposing all the study area for dust particles resulting from loading processes in the sea port. The granite mountains overlook the sea port retard wind transportation. This allows depositing of dust particles on the mountains' surfaces. Here accumulation of particles takes place until precipitation events come, wash and carry particles with floods into the seawater. A part of the particles joins the soil cover (Fig. 83). Here the process is attributed to the coastal wadis.

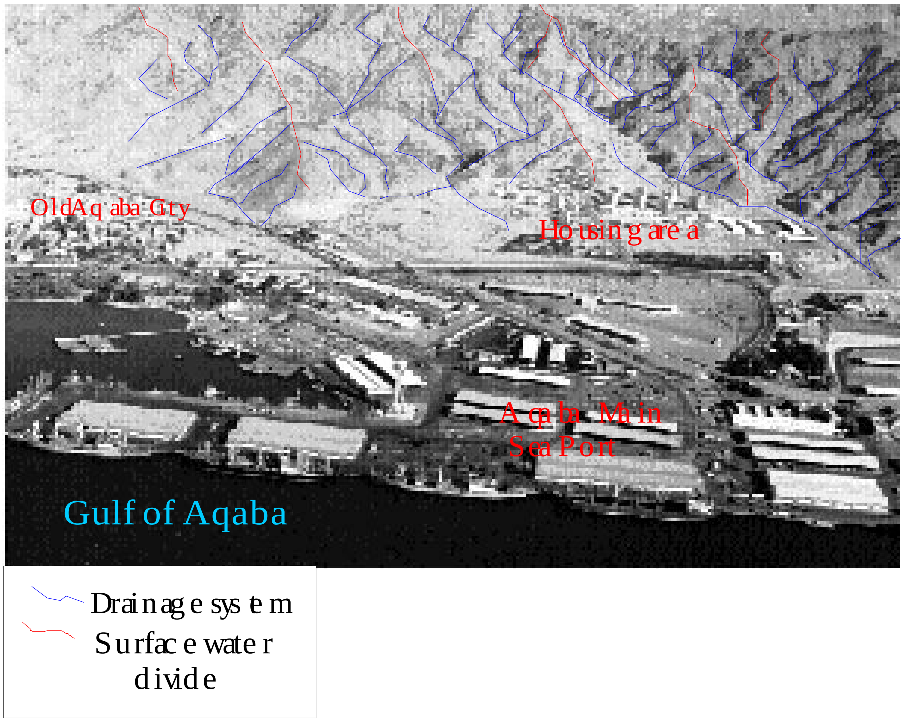


Fig. (83): Aqaba main sea port -conceptuality of the dust particles wash into the seawater-.

Processes of dust deposition in sea have sever impact on the marine ecology, since these particles disturb the natural continuity of the nutrition cycles, and klog the pulbs of coral reefs and retard their growth. (Katyal & Satake,1996)

If the thermodynamics of seawater allows the dissolution of the solid phases of the phosphate mineral, then the produced dissolved phosphate will contribute in increasing the eutrophication –algae growth- in the shore waters.

Five locations in the study area were investigated on their soil water chemistry. It was found that the highest phosphate concentration is in main sea port of Aqaba, where porting and loading operation take place (Fig. 84). The sampling method, locations and chemistry were discussed in the section on soil.

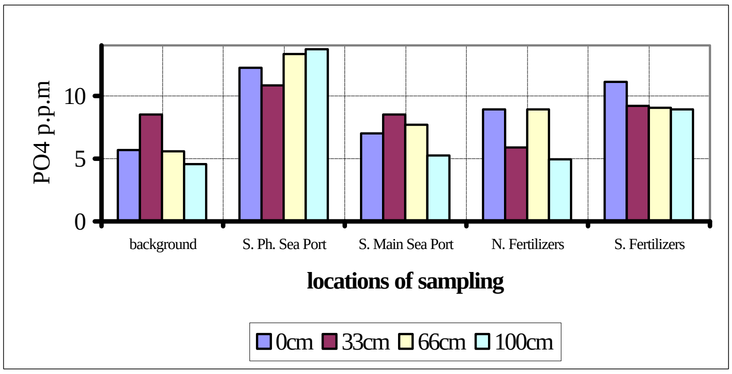


Fig. (84): Concentration of $PO4^{3-}$ in the soil water of different locations (ppm).

The Fertilizers Company in the southern part of the study area produces several types of agricultural fertilizers. During the manufacturing stages a solid phase of Gypsum ($CaSO_4.2H_2O$) is produced and disposed in the southern part of the factory (Fig. 85).

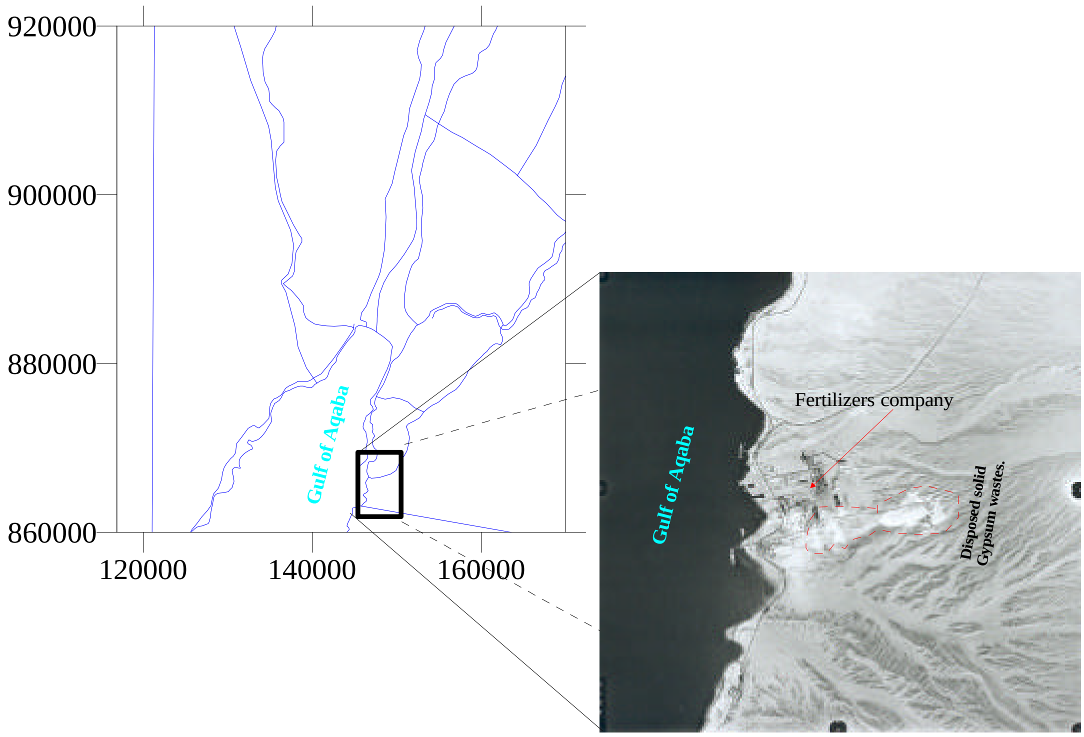


Fig. (85): Industrial Gypsum disposed in the southern part of the Fertilizers Factory.

Gypsum is known to possess high solubility in water, and acts as lowering factor of the pH value in the soil –***acidification of soil***-. In the company of this process with the presence of some released heavy metals, this will produce a medium which can increase their mobility, where in advanced stages they join the marine ecology with the discharged groundwater and floods, which strike the shores from the side coastal wadis. The impacts of the presence of high doses of heavy metals in the marine ecology lead to the disturbance of the marine life.

From the other point of view lowering of the soil pH lead to a conditions under which the precipitated phosphate mineral particles within the soil can get dissolved. Accordingly it may enhance the mobility of the phosphate with the flowing groundwater into the sea and make available additional source of algae’s growth.

In Table 23 it is clear that the wells locating in plantations are having higher concentrations (several times) of $SO4^{2-}$, compared to that of Wadi Al Yutum which is 83.8 mg/l and out of human impacts and land use units. The cause behind that is the use of the superphosphate as a fertilizer, which is a chemical fertilzer made by treating powdered phosphate with sulpheric acid. But in the well of the fertilzers factory, the concentration of $SO4^{2-}$ was found also high (428 mg/l) with the fact that no plantation exist in the surrounding. Also in the soil water chemistry (Table 13) the concentrations of $SO4^{2-}$ in the surrounding of the Fertilizers Factory were very high compared to other locations.

3.4 Impacts on Groundwater

The safe yield of groundwater cannot cover municipal uses. Some small scale agricultural and industrial activities in the region may make use of that water. Quality may be a limiting factor for use.

Before the construction of the **waste water treatment plant in Aqaba** –before 1987-, septic systems were used to dispose the waste water into the ground. After that year the residential areas were connected with the plant in several stages. Some houses are still not connected and use cesspools in disposing waste water.
Figure (86) shows the treatment stages. The waste water has to stay 2 weeks of the sedimentation pond, and 2 weeks in every stage in the maturation ponds. Due to the overload it stays 10 day in the sedimentation pond, and 5 days in every stage of the maturation. The infiltrated treated water into the groundwater body is of suspected quality.

In a study for the Water Research and Study Center of the University of Jordan in winter of 1988, the Aqaba waste water treatment plant was evaluated for its efficiency and impacts on the surrounding environment.
Table (32) illustrates the results of study as chemical analysis on the inlet water, facultative ponds, maturation ponds, effluent water and on the groundwater represented by the well of the Palm Plantation Project locating directly south of the plant.

Table (32): Results of evaluation study on the water chemistry of the Aqaba W.W.T.P and the groundwater of the surroundings.

Parameter	Inlet	Facultative pond	Maturation pond	Effluent	Palm Project well
EC (µ S/cm)	1420	1620	1680	1680	1980
pH	7.37	7.48	8.19	8.28	8.05
Temp. C degree	18.9	17.8	18.0	18.1	28.4
BOD5	461.6	199.8	161.8	145.7	86.8
COD	600	550	-	500	25
TOC mg/l	28.4	247	-	183.67	29.29
NH4 meq/l	-	3.15	2.98	2.38	0.021
NO3 meq/l	-	0.70	0.63	0.55	0.77
HCO3 meq/l	-	6.8	7.52	7.72	2.67
Cl meq/l	-	8.56	8.20	8.40	12.95
Ca meq/l	-	2.80	3.30	3.50	3.60
Mg meq/l	-	2.26	2.20	2.30	2.70
Na meq/l	-	10.39	10.84	10.74	13.14
K meq/l	-	0.6	0.702	0.702	0.14
SO4 meq/l	-	3.10	3.70	2.91	2.97

* *Water Research and Study Center of the University of Jordan in winter of 1988.*

The study ended to that the plant does not treat the waste water as required, and the leakages of the different treatment ponds form negative impacts on the groundwater quality. The evaporation process from the ponds increased the EC-value of the water from 1420 to 1680 µ S/cm even the study took place in winter.

Impacts of the plant and the dug holes can be summarized as follows:

- Raising the groundwater table. This can cause leakage of groundwater into the surrounding houses basements. The water table was measured in observation wells around the plant and found to be less than 2 meters where as the normal groundwater table is more than 9 meters in depth (Fig. 87).
- Polluting the groundwater by adding high concentrations of some chemical constituents accompanied with the waste water.
- Pollution may reach the Gulf water and affect the marine ecology "eutrophication process".

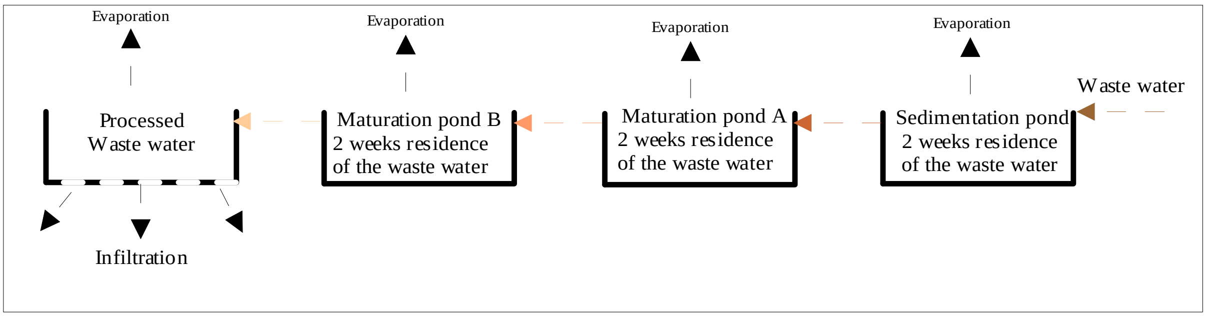


Fig. (86): Waste water treatment plant in Aqaba.

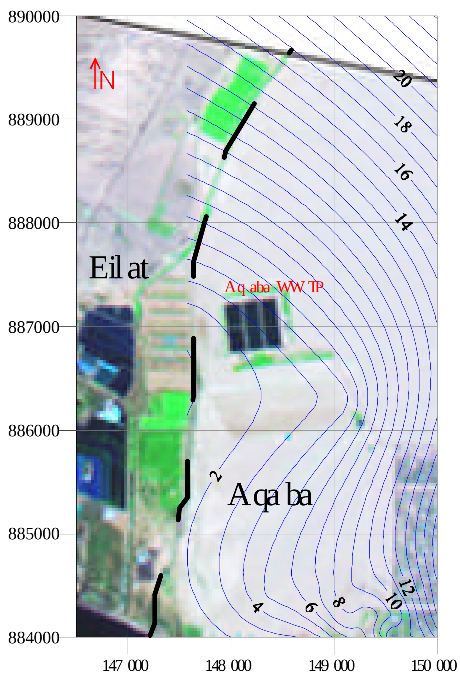


Fig. (87): Groundwater level raising near the Aqaba waste water treatment plant.

In sand and gravel aquifers like the alluvial aquifer in Aqaba, plumes of degraded groundwater develop when the effluent is discharged into the groundwater. This occurs even in well-constructed properly functioning dug holes. These plumes are typically characterized by elevated concentrations of **potassium, chloride, phosphate**, **nitrate, ammonia** and **dissolved organic carbon (DOC)** (mainly derived from municipal effluent), and can also contain elevated levels of **fluoride** (from toothpaste) and total and Faecal Coliforms. Some parameters such as chloride are not degraded or attenuated in groundwater. Once they reach the water table, they flow along with the groundwater developing long plumes (sometimes kilometers long). Some parameters are slowed or degraded in groundwater. For example phosphorus transport is slowed because it tends to stick or 'sorb' onto aquifer sediments. Also, Coliform bacteria do not usually survive for long time periods in groundwater.

In order to define the most factors which have impact on the groundwater quality, **factor analysis** was performed on some good distributed wells in the study area due to their water quality. Many parameters were given for every sample including **major chemical constituents, heavy metals, saturation states of minerals, human impacts indicators and the depth to the groundwater table (unsaturation zone thickness).**
This analysis was carried out using statistical software (SPSS for windows). Here we applied the R-Mode and Varimax Rotation in calculating the factors. Table (33) shows the different factors with their components.

Table (33): The different dominant factors in the chemistry of the groundwater with their components. Every color indicates different factor.

ROTATED COMPONENTS MATRIX	COMPONENTS				
	1	2	3	4	5
$NO3^-$	0.949	-	-	-	-
K^+	0.943	-	-	-	-
pH	-0.943	-	-	-	-
Cu	0.908	0.262	-	-	-
Ca^{2+}	0.898	-	0.208	0.324	-
SI Magnesite	-0.888	0.338	-	-	-
Cl^-	0.876	-	-	0.436	-
SI Dolomite	-0.871	0.375	-	-	0.215
Cd	0.867	0.333	-	-	-
EC	0.816	-	0.375	0.381	-
Na^+	0.815	-	0.394	0.374	-
$NO2^-$	0.814	-	-	-	0.332
SI Calcite	-0.767	0.420	-	0.206	0.388
SI Aragonite	-0.767	0.420	-	0.205	0.389
OH^-	-0.686	-	-0.223	0.446	0.399
SiO2	-	0.972	-	-	-
SI Chalcedony	-	0.967	0.200	-	-
SI Quartz	-	0.967	0.200	-	-
SI Fluorite	0.244	0.812	0.433	-	-
F-	-	0.665	0.590	-0.215	-
Well elev.	-	-0.521	-	0.257	-
$SO4^{2-}$	-	0.288	0.938	-	-
$NH4^+$	-	-	0.871	-	-
Mg^{2+}	0.216	0.369	0.848	0.233	-
Cr	-	0.225	0.741	0.427	-
SI Anhydrite	0.438	0.517	0.696	-	-
SI Gypsum	0.438	0.517	0.695	-	-
DOC	-	0.378	0.566	-0.418	0.455
Zn	-	0.439	-0.514	-	0.201
Water depth	-	-0.621	-	0.718	-
$HCO3^-$	-	-	-	-0.714	-
Ni	-	-	0.395	0.673	0.202
BOD	-	0.493	-	-0.648	0.302
As	-	-0.348	-	-0.532	-
Fe	-0.308	-	-0.282	0.206	0.7081
Pb	0.280	-	-	-	0.704
$PO4^{2-}$	-	-	-	-	-0.574

5 factors were derived and the relation between the different components of each factor was used to identify them:

- Factor 1 "**mixing process between the groundwater types in the aquifer themselves and/or other water types from the surface**" here this refers to recharge; direct and indirect types, leakage process from water supply net works and leakage from irrigation return flows. On the other hand mixing process between the groundwater types leads to this factor. The effects of this factor are:

- *Increasing the solubility of the carbonate minerals.*
- *Increases in the concentrations of chemical constituents resulting in salinity impacts.*
- *Decreases in the pH values since mixing of two different waters leads to that.*
- *Increases in the dissolved oxygen and CO2 gas concentrations.*
- *Increases in the mobility of heavy metals, especially copper, lead and cadmium.*
- *Enhancing nitrification reactions to produce NO3-; the stable form of nitrates. This normally occurs in well oxygenated waters.*

- Factor 2 " **Impacts of the unsaturation zone on the groundwater quality, and the aquifer's matrices-groundwater interactions**", here the deeper the groundwater table, the less the human impacts. There was a negative correlation between the groundwater depth, and the biological oxygen demand (BOD), and the dissolved organic carbon (DOC) which are good indicators on the human impacts. On the other hand the interaction between the aquifer's matrices, which are derived from igneous rocks and the groundwater leads to raising concentrations of SiO2- - and F-, and to decrease the solubility of the silicate minerals –or to precipitate them- as the Quartz and Chalcedony and Fluorite. Some heavy metals from igneous origin were concentrated here such as Cr, Zn, and Cu. The impact of the unsaturated zone in reducing the pollution of the groundwater emphasizes their great role in the coastal water table aquifers.

- Factor 3 "**Human impacts on the aquifer**" parameters of human impacts correlate positively with each other. These are NH4-, DOC, EC, F-, SO4- - and Na+, besides lowering the pH value (liberation of the CO2 gas, organic matter decay). Some heavy metals have also shown increases in concentration such as Ni and Cr.

- Factor 4 "**Impacts of the unsaturation zone**" here a negative correlation was found between the depth to the groundwater and the DOC, BOD and HCO3- concentrations.

- Factor 5 " **Deficiency in oxygen and precipitation of carbonate minerals**" this factor gave indications on reactions related to the deficiency of oxygen such as the process of denitrification with increases in the concentration of NO2 and DOC. The precipitation of carbonate minerals such as Calcite, Dolomite and Aragonite were combined with the consumption of PO_4^{3-} .

Table (34) shows the natural concentration levels of some pollution indicators in the groundwater. Dissolved organic carbon correlates with ammonia concentration. This indicates that the source of the organic matters in the aquifer is from human wastes (Fig. 88).

Table (34): Concentrations of some pollution indicators in the groundwater.

POLLUTION INDICATOR	NATURAL LEVEL IN GROUNDWATER	MAXIMUM VALUE IN THE AQUIFER	MINIMUM VALUE IN THE AQUIFER	AVERAGE	SOURCE
BOD	0 mg/l	10 mg/l	0 mg/l	3.5 mg/l	Decay of organic matter, present in water
DOC	0.5 mg/l	4.8 mg/l	1.3 mg/l	2.95 mg/l	Organic matter in groundwater
$NH4^+$	<0.2 mg/l	26.468 mg/l	0 mg/l	2.808 mg/l	Sewage, animal manure, fertilizers, and other contamination
$NO3^-$	<15 mg/l	419 mg/l	10.8 mg/l	82.1 mg/l	Human and animals wastes
$PO4^{3-}$	0.005-0.1 mg/l	0.09 mg/l	0.05 mg/l	0.0545 mg/l	Sewage, animal manure, fertilizers, and other contamination
F^-	<10 mg/l	3.6 mg/l	0.3 mg/l	1.74 mg/l	Depends mostly on the rock type. Teeth pastes released into waste water are good source.

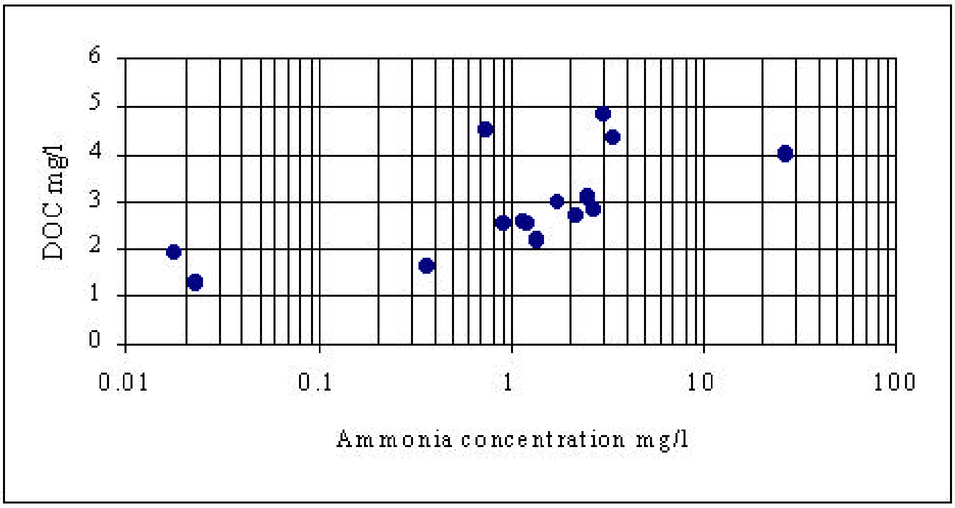
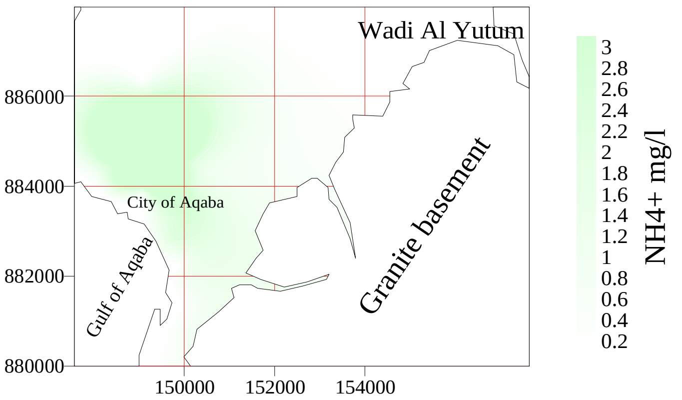


Fig. (88): Correlation between ammonia and dissolved organic carbon in the groundwater.

The spatial distribution of these two human pollution indicators; DOC and NH_4^+ is in accordance. This allows distinguishing areas having point sources of pollution releasing human wastes into the groundwater.

From the two maps; DOC and NH_4^+ (Fig. 89), it is clear that the area which locates between 148000-150000 E and 884000-886000 N possesses a human pollution potentials. It is also clear here that these potential sources of pollution are close to the marine water body. This is emphasizes on the importance of land use plans in coastal cities. The flow pattern indicates that the Gulf of Aqaba is the base where mobile pollutants end.



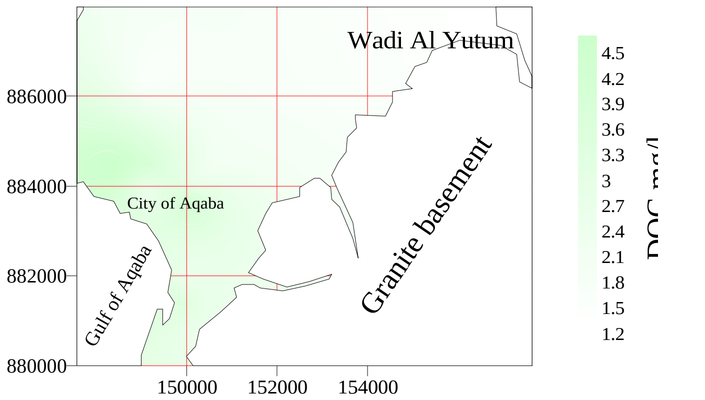


Fig. (89): Raster models of spatial distribution of pollution indicators DOC and NH_4^+.

In July/1987 a **hydrogeoelectrical study** was performed by Lafi (1987) to evaluate the most southern part of Wadi Araba in term of its groundwater potentials. The survey was applied in the area of the Aqaba waste water treatment plant before its operation. In the year 1998 a VES survey was applied with the same method in the same location to predict the difference in the formation's resistivities trying to detect the impact of treated waste water leakage on the aquifer. Figure (90,a,b) shows the curves of the two surveys.

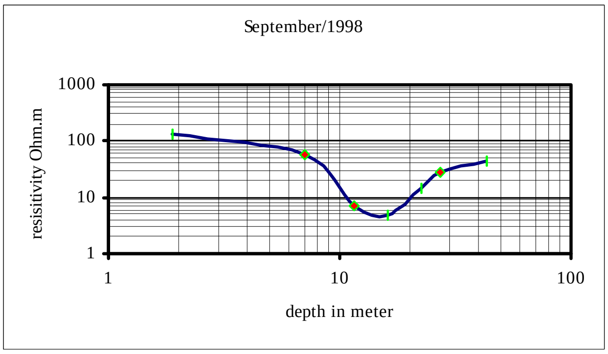


Fig. (90,a): VES curve (1998).

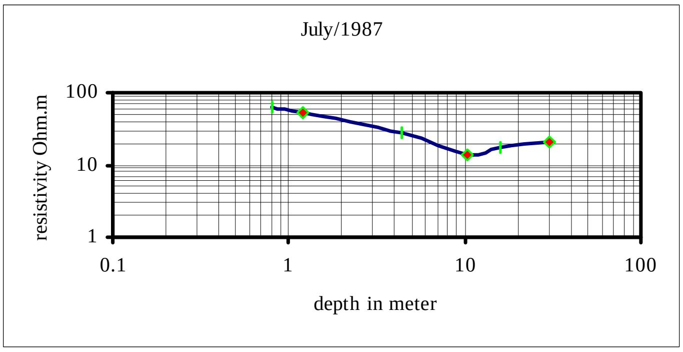


Fig. (90,b): VES curve (1987).

The impact of waste water on the groundwater resistivity are not similar every where. The type of material in the waste water and the concentrations are the main factors which effect the resistivity.

The electrical conductivity of the treated waste water joining the aquifer is 2010 µ S/cm. The salinity of the groundwater in the area of the leakage is about 3000 µ S/cm. Accordingly, it is supposed that the leaking water should cause a decrease in the groundwater EC. But as the grain size of the aquifer matrices here is small, the accumulation of some suspended materials from the treated waste water takes place, and they get filtered within these matrices. These act as good conductors if they are polarized molecules.

The general trend in the difference between the two curves is that the resistivity got lower in 1998 than that of 1987.

Another impact of this plant is that it causes a rise in the groundwater level of the surrounding. Basements of the nearby houses, underground utilities, storage tanks may suffer flooding. *It also threatens local groundwater quality. Areas endangered by earthquakes are* *vulnerable to damage caused by liquefaction of cohesionless silty and sandy deposits saturated at shallow depths.*

A **positive impact** of the waste water treatment plant of Aqaba is the increase of vegetation growth because of the shallow water level. This also attracted some birds kinds into this area, especially because it is not allowed for the civil people to enter the area. Accordingly, the area of the plant is now considered as a **life protection zone**.

Over-pumping processes from the groundwater in the study area causes mixing between the deep saline groundwater and that shallow one, which is of less salinity. This is besides that it had impacts on the hydrodynamic interface between the seawater and fresh groundwater as was discussed previously. The main **impacts combined with land use** in the study area which affects the groundwater quality is due to the leakage of the waste water and the processed waste water. Besides that the private gardening and plantation processes combined with fertilizing process add pressures on the groundwater quality indicated as increases in the concentrations of SO4 and PO4 in the wells of plantations.
High concentration of ammonia were found in wells located in the zones where fertilizing process take place. It was 26.468 mg/l in one plantation well co-ordinates (149171 E, 884471 N).

The distribution of dissolved organic carbon in the groundwater as an indicator on the human impacts was put to a grid. The different **land use** units were overlain on the produced map (Fig. 91). This figure shows that the area of Wadi Al Yutum suffers no human impacts, but going to the city zone the concentration of DOC starts to increase. The worst situations are found to the south of the waste water treatment plant and to the west of the housing units, which are partly connected to the sewage system where the DOC concentration is more than the natural by a level of about 3.3 mg/l.

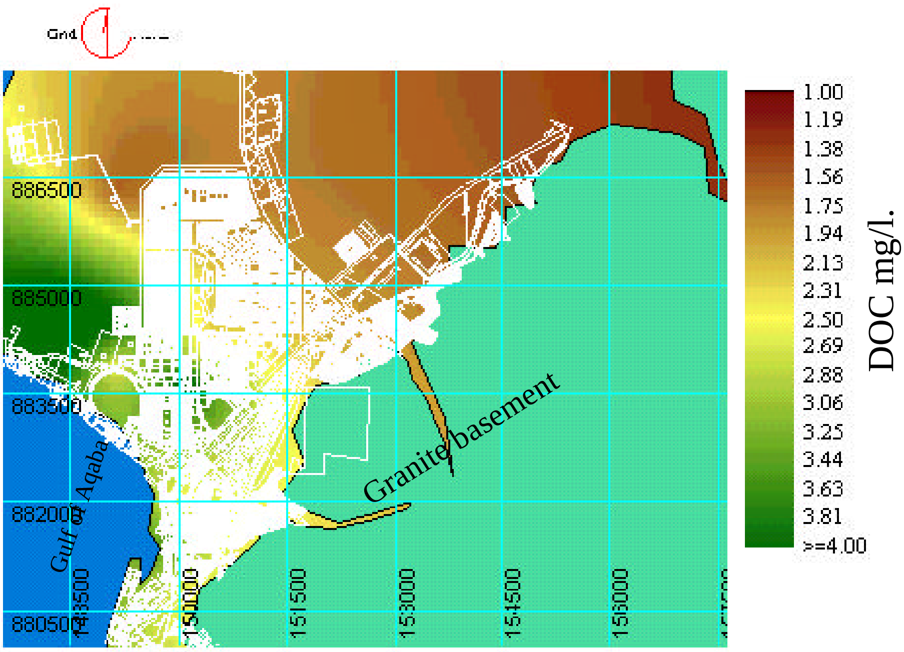


Fig. (91): Impacts of the land use supplying the aquifer with DOC.

The housing areas (Ash Shalalah) and the old town of Aqaba located between co-ordinates *150500-151500 E and 880500-882000 N* possess no sewage systems. The groundwater flows to the west to join the marine water body as submarine groundwater discharge. One water

well located in the middle of this zone (in King Hussein mosque) has an ammonia concentration of 1.20 mg/l, nitrate 57.3 mg/l, nitrate 0.052 mg/l, fluoride 0.7 mg/l, DOC 2.5 mg/l, and EC of 745 µ S/cm. About 500 meters to the west from the former well, another well was measured (Hafera well). The concentrations were found as; ammonia concentration 0 mg/l, nitrate 104 mg/l, nitrate 0.11, fluoride 1.8 mg/l, DOC 3.5 mg/l and EC 990 µ S/cm.
In these two wells which locate along the same flow line, the groundwater possesses well oxygenated conditions because the ammonia became zero at the end, and the nitrite and nitrate concentrations increased. This process takes place in the oxygenated mediums. The only expected source for oxygen along this path way is the leakage of well oxygenated drinking water pipes diluting the groundwater.

This discussion confirms the ability of the groundwater aquifer in the study area to transport the different pollutants for long distances. This indicates an inefficient self-purification process of the aquifers matrices.

3.5 Impacts on the Marine Ecology of the Gulf of Aqaba

The International Oceanographic Commission (IOC) for the United Nations Educational and Scientific Commission (UNESCO) defines marine pollution as: *"Introduction by man directly or indirectly of substances into the marine environment (including estuaries) resulting in such deleterious effects as harm to living reduction of amenities."*. Katayal & Satake (1996).

The groundwater flow into the Gulf of Aqaba is a fact which was quantified in this study. In addition land use impacts and low self-purification capacity of aquifer's matrices render the discharged water to be of a doubtful quality.
The principal known impact of land use on the marine ecology is attributed to the release of high concentrations of heavy metals into the marine water body. The process may take place through the runoff when it washes the land surface and then joins the sea carrying the settled heavy metals of different natural and pollution sources. Another possibility is through the aquifer due to the transportation process.

The groundwater's of the study area have low concentration of heavy metals. Some wells possess high concentration of Iron is attributed to the corrosion of casing material.

Recently, **eutrophication** became an alarming fact. It takes place in the marine environment of the Gulf of Aqaba.
The characteristics of eutrophication processes in reservoir and lakes, are quite specific in the semi-arid areas. Not only do the problems derived from eutrophication affect both the quality of water, but they also have an adverse effect on the fauna.
An increase in nutrients (nitrogen and phosphorus) resulting in eutrophication is enhanced in semi-arid areas by temperature and light, which are the two predominant factors in biological production. Phosphorus is usually the main nutrient responsible for freshwater eutrophication, whereas nitrogen is the primary nutrient causing eutrophication of coastal areas and seas.
Municipal and industrial waste waters, and fertilizer use in agriculture provide watercourses with nutrients causing eutrophication. Growth and decay of algae and other water plants is enhanced causing changes in the balance of water ecosystems and creating favorable

conditions for the development of pathogenic microorganisms. The term “eutrophication stands for:

1. A change towards a more nutrient rich state in-water; streams, lakes and seas
2. An increase in production and biomass
3. A decrease in vision and access to lightin water
4. An increase in oxygen consumption
5. A change in the combination of species, usually a reduction in the number of species
6. Eutrophication can be both natural and cultural.

http://www1.1de.1u.se/iiiee/IMPACTS/WATERPOLLUTION/WATER_HOME:HTML

The growth of algae in the marine water body can be represented as:

$$\mathbf{106\ CO_2 \ +16\ NO_3^- + HPO_4^{2-} + 122\ H_2O + 18\ H^+}$$
$$\mathbf{+ \text{(trace elements, energy)} = C_{106} H_{263} O_{110} N_{16} P_1 + 138\ O_2\ =} \ \textbf{\textit{algae}}$$

the process will go on, until the available phosphate or nitrate is used up. The reverse of this reaction takes place to enable the decay of algae. (Drever, 1997)

Now taking the part of the reactants from the previous equation, the requirements for the reaction to go forward producing the algae are available. The CO_2 and H^+ gases can get dissolved in seawater from the atmosphere, the water (H_2O) is available, while sun energy is well abundant around the year.

Lioyd & Heathcote (1985) mentioned that the average seawater composition includes the concentration of NO_3^- and HPO_4^{2-} of 0.5 and 0.07 mg/l respectively. These two nutrients are considered as the limiting factor for eutrophication.

Under these conditions the algae in the marine environments grows and decomposes in a balanced cycle, forming no negative impacts on this environment.

Total phosphorous levels higher than 0.03 mg/L contribute to increased plant growth, while total phosphorous levels above 0.1 mg/L may stimulate plant growth sufficiently to surpass natural eutrophication rates.
http://www.leo.lehigh.edu/envirosci/watershed/wq/wqbackground/phosphatesbg.html

In a study carried out for the Aqaba Region Authority in 1993 “Aqaba Coastal Resources Environmental Management Study in Jordan” the phenomena of eutrophication was attributed to the phosphate dust particles deposition in the sea water (from porting process).

In a long term records study (14 months) for the Marine Science Station in Aqaba in 1998, the environmental quality of the Gulf of Aqaba in the coastal areas at four locations and one meter depth was defined. Natural and anthropomorphic factors resulted in positively modifying the chlorophyll concentration. Values of NO3 and PO4 were also positively modified and found sometimes to exceed 0.5 mg/l and 40 μg/l respectively.

The previous measured concentrations are approaching the specified threshold values to start eutrophication.

In eutrophication process microscopic floating plants, known as algae, multiply rapidly when fertilized by phosphorus. These algae cloud the water making it difficult for larger submerged aquatic vegetation (SAV) to get enough light. The SAV may dieback reducing available habitat of aquatic animals. When the algae themselves eventually die they decompose. During decomposition dissolved oxygen is removed from the water. Lowered oxygen levels make it difficult for other aquatic organisms to survive.

http://www.agnr.umd.edu/users/agron/nutrient/Factshee/Phosphorus/Eutrop.html

CHAPTER 4

VULNERABILITY ANALYSIS OF THE ECO-SYSTEMS FOR CONTAMINATION RISK

4.1 Introduction

The study area is in general vulnerable for pollution. Governmental plans to develop the region of Aqaba, increasing industrial activities, population, sea porting processes and tourism activities will grow accordingly. The susceptibility of the groundwater quality and quantity to be negatively impacted is possible.
Therefore it was important to subdivide the area with respect to its aquifer vulnerability for pollution risk.
The modern vulnerability studies of the Eco-systems for the risk of contamination consider that the ecological systems are related to each other, and accordingly try to involve all of them in analyzing the spatial vulnerability of a specific area. At the end factors of economy, social aspects, and policy are being added by the decision makers to produce the best choices in the land use plans.
The vulnerability studies of the Eco-systems may be categorized in terms of a specific effect, such as the vulnerability of soils for insecticide.

4.2 Using DRASTIC Index (General Groundwater Pollution Risk Evaluation)

DRASTIC is one of the mapping systems which provide a systematic way for planners, administrators, and managers to address the relative vulnerability of an area's water table aquifer to contamination when making decisions that may impact the groundwater resource. DRASTIC was developed by the U.S. EPA and the National Water Well Association. Interest has been growing in Virginia since DRASTIC map training workshops were initiated by the Virginia (Ground Water Protection Steering Committee).
http://www.deq.state.va.us/gwpsc/drastic.html

The name DRASTIC is derived from the seven factors that go into the maps, these are:

Depth to water
Recharge
Aquifer Media
Soils
Topography
Impact of Vadose Zones
(Hydraulic) Conductivity

The system consists of two major components; the mapping of hydrogeologic settings and the assignment of an index number which helps the user evaluate the relative ground water pollution potential of these settings. *This information can be used for preventative purposes through the* ***prioritization*** *of areas where ground water protection is critical and can identify areas where special attention is warranted.*

The methodology was developed around a set of basic assumptions concerning a generic contaminant. They are: 1) material introduced at the land surface as a soluble solid or liquid travels to the aquifer with recharge waters derived from precipitation; 2) the mobility of the contaminant is assumed to be equal to that of the groundwater; and, 3) attenuation processes are assumed to go on in the soil, Vadose zone and aquifer. DRASTIC was not specifically designed to deal with pollutants introduced in the shallow or deep subsurface, such as leaking underground storage tanks or deep mine wastes.

Ratings for each parameter are assigned depending on the impact of the factor on contamination potential. Ratings vary from 1 to 10 with higher values describing greater pollution potential. These ratings and ranges are used for all evaluations, but the weighting of each parameter changes to account for differences between general land use and agricultural use.

Weights vary from 1 to 5 with higher weights representing greater pollution potential. The DRASTIC index number is the sum of the products of each set of rates and weights for each parameter.
Tables (35, a, b, c, d, e, f, g, h, i) illustrate the ratings and weights of the different Drastic index components, and its qualitative categories.

Table (35,a): Ratings of water table depth.

WATER TABLE DEPTH METER	DRASTIC RATING
0.00-1.23	10
1.23-4.58	9
4.58-9.15	7
9.15-15.25	5
15.25-22.88	3
22.88-30.50	2
>30.50	1

Table (35,b): Ratings of groundwater recharge.

RECHARGE (MILLI METER/YEAR)	DRASTIC RATING
00.0-50-8	1
50.8-101.6	3
101.6-177.8	6
177.8-254	8
>254	9

Table (35,c): Ratings of the aquifer material.

AQUIFER MATERIAL	DRASTIC RATING	TYPICAL RATING
Massive shale	1-3	2
Metamorphic/igneous	2-5	3
Weathered metamorphic/igneous	3-5	4
Glacial till	4-6	5
Bedded sandstone, limestone, shale sequences	5-9	6
Massive sandstone	4-9	6
Massive limestone	4-9	6
Sand and gravel	4-9	8
Basalt	2-10	9
Karst limestone	9-10	10

Table (35,d): Ratings of soil material.

SOIL MATERIAL	DRASTIC RATING
Thin or absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and / or aggregated clay	7
Sandy loam	6
Loam	5
Silty loam	4
Clay loam	3
Muck	2
Nonshrinking and non aggregated clay	1

Table (35,e): Ratings of slope percent.

SLOPE (%)	DRASTIC RATING
0-2	10
2-6	9
6-12	5
12-18	3
>18	1

Table (35,f): Ratings of hydraulic conductivity.

HYDRAULIC CONDUCTIVITY (meter/s)	DRASTIC RATING
$0.50*10^{-6}$ - $0.50*10^{-4}$	1
$0.50*10^{-4}$ – $0.15*10^{-3}$	2
$0.15*10^{-3}$- $0.36*10^{-3}$	4
$0.36*10^{-3}$- $0.51*10^{-3}$	6
$0.51*10^{-3}$ – $0.10*10^{-2}$	8
> $0.10*10^{-2}$	10

Table (35,g): Ratings of the unsaturated zone material.

UNSATURATED ZONE MATERIAL	DRASTIC RATING	TYPICAL RATING
Confining layer	1	1
Silt/clay	2-6	3
Shale	2-5	3
Limestone	2-7	6
Sandstone	4-8	6
Bedded limestone, sandstone shale	4-8	6
Sand and gravel with significant silt & clay	4-8	6
Metamorphic / igneous	2-8	4
Sand and gravel	6-9	8
Basalt	2-10	9
Karst limestone	8-10	10

Table (35,h): Weights of the different components.

COMPONENT	WEIGHT
Depth to water	5
Net recharge	4
Aquifer media	3
Soil media	2
Topography	1
Unsaturated zone media	5
Hydraulic conductivity	3

Table (35,i): Drastic Qualitative Categories.

DRASTIC QUALITATIVE CATEGORY ***(Drastic Index)***			
Low	***Moderate***	***High***	***Very High***
1-100	101-140	141-200	>200

The final result for the one position is obtained from the following simple equation:

DRASTIC Index = D r D w + R r R w + A r A w + S r S w + T r T w + I r I w + C r C w

Where

Dr = Ratings to the depth to water table
Dw = Weights assigned to the depth to water table.
Rr = Ratings for ranges of aquifer recharge
Rw = Weights for the aquifer recharge
Ar = Ratings assigned to aquifer media
Aw = Weights assigned to aquifer media
Sr = Ratings for the soil media
Sw = Weights for soil media
Tr = Ratings for topography (slope)
Tw = Weights assigned to topography
Ir = Ratings assigned to vadose zone
Iw = Weights assigned to vadose zone
Cr = Ratings for rates of hydraulic conductivity
Cw = Weights given to hydraulic conductivity

The procedure for mapping the study area according to drastic index was clarified for every component. Dealing with a big data set called us to use the GIS Arcview technique.

Water Table Depth

The top of the saturated zone is called the water table. The water table rises and falls according to the season of the year and the amount of rain and snowmelt that occurs. It is typically higher in early Spring and lower in late Summer. Heavy rainfall or drought conditions may cause changes in the typical pattern.

Water table depth determines the depth of material through which a contaminant must travel before reaching the aquifer.

The direct measurements for water levels in boreholes, besides the results of the geoelectric sounding formed the data source in building the grid. Additional interpolations were carried out to cover the areas where data were not available.

The produced *Z* values were put in an ascending form using Surfer 7, and the rates were given. The grid was built using a spacing of 50 meters. Figure (92) shows the produced map for the groundwater levels rating. Ten rates were found ranging from 1 to 10.

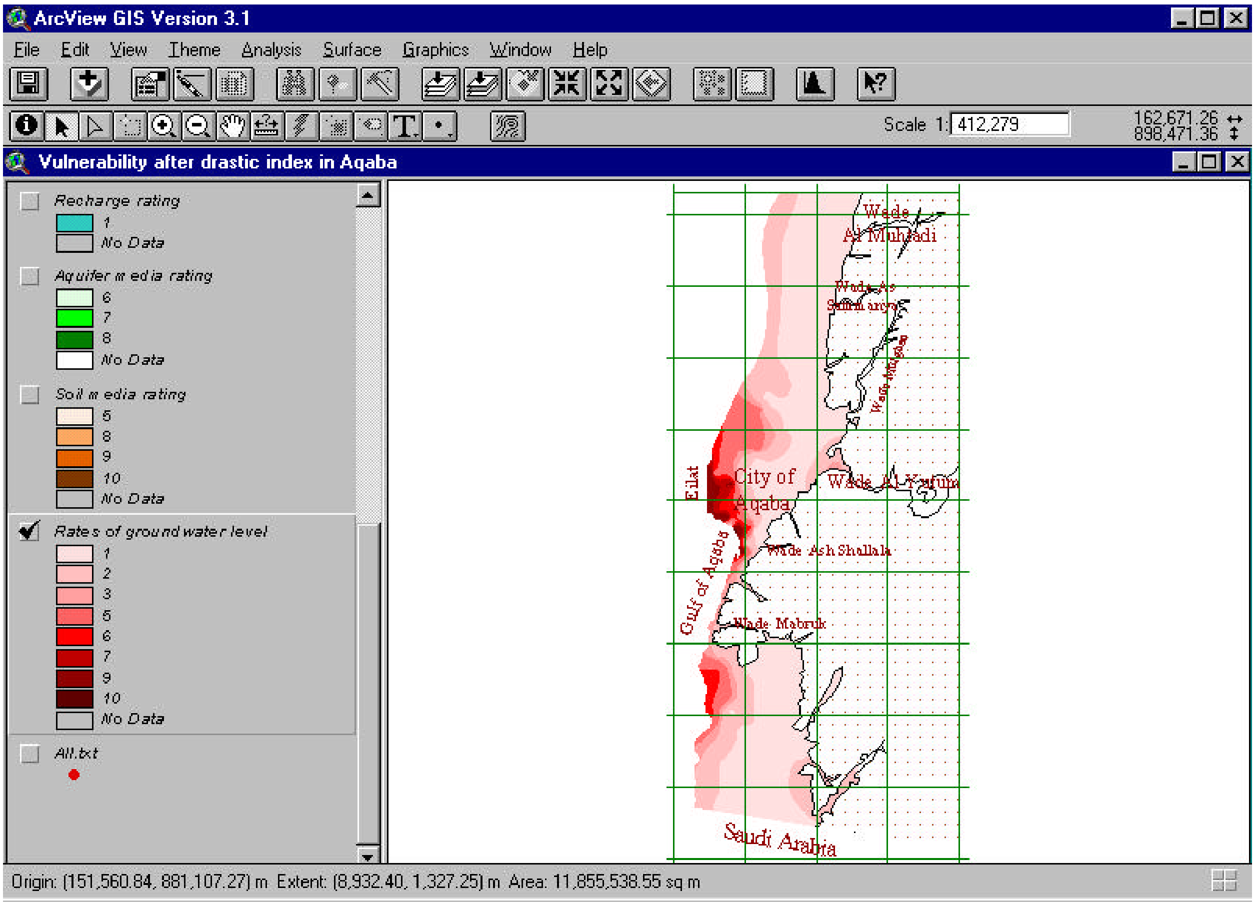


Fig. (92): Groundwater levels rating.

Vadose Zone

This is the zone above the water table which is unsaturated or discontinuously saturated. It determines the attenuation characteristics of the material below the typical soil horizon and above the water table. It is the region above the water table where pores and fractures are partially filled with water and partly by air. The pressure in the unsaturated zone is atmospheric. Conditions are usually highly oxidizing due to the presence of free oxygen in the air and highly reactive due to the presence of water.

The unsaturated zone forms an important buffer between hazardous wastes and the water table. Understanding the mechanisms and rates of movement of pollutants in sedimentary rocks is an important step in the process of groundwater protection.

It plays an important role in many modeling applications, e.g. for recharge estimation, surface-groundwater interaction and agricultural pollution. The unsaturated zone refers here to the mostly-unsaturated soil profile extending from the land surface down to the groundwater table. The profile is usually heterogeneous, consisting of horizons with distinct differences in the physical properties of the soil.

The unsaturated zone is characterized by cyclic fluctuations in the soil moisture as water is replenished by rainfall and removed from the soil profile by evapotranspiration and percolation.

The geological map of the study area, and the well's data were used in defining this zone. Digitizing the different sub-zones and giving them the special rates were carried out. Accordingly the grid was built. Figure (93) shows the map of the Vadose zone rating.
Four rates were found ranging from 3 to 9.

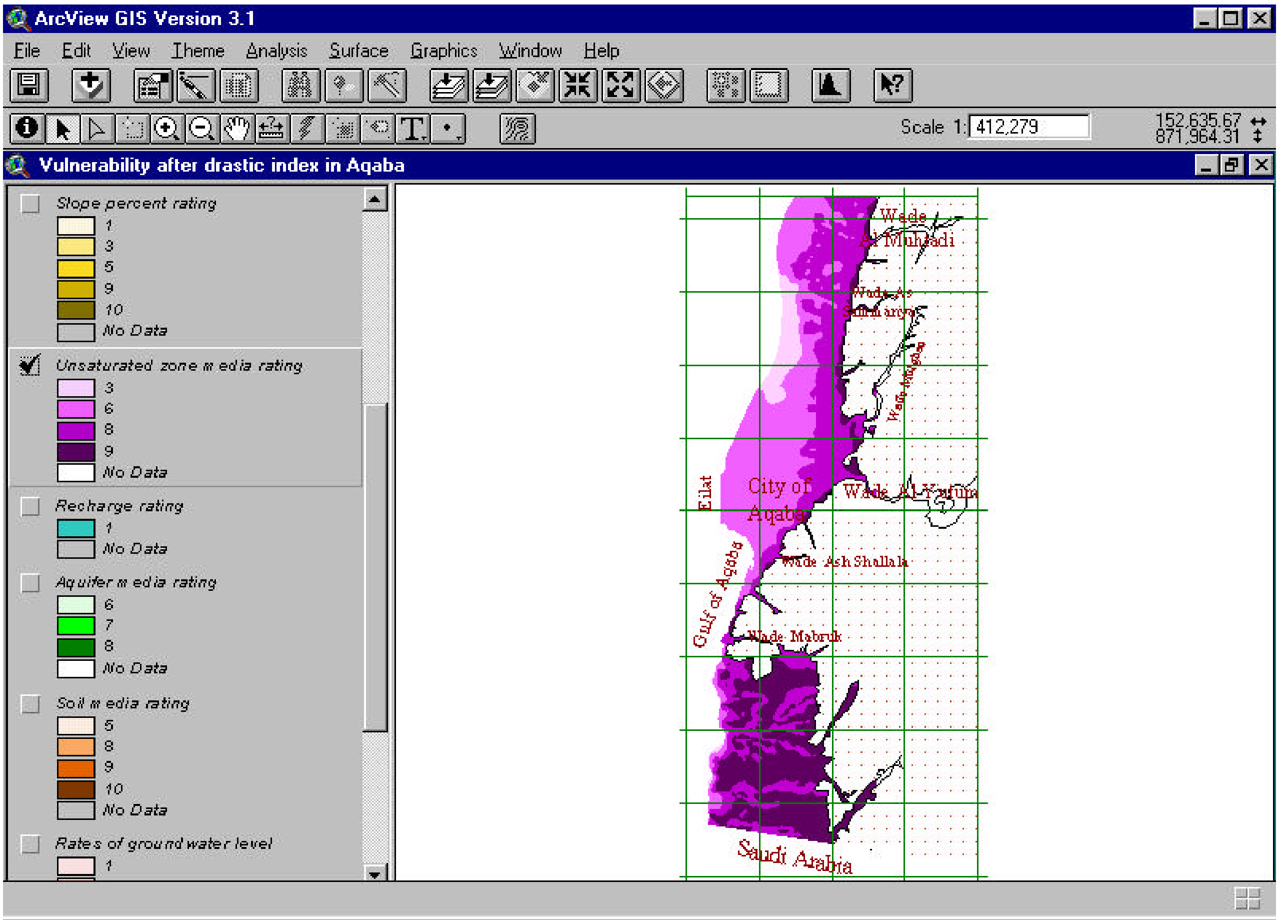


Fig. (93): Unsaturated zone rating.

Aquifer Media

This refers to the consolidated or unconsolidated rocks serving as aquifers (sand and gravel or limestone). The route and path length which a contaminant must follow are governed by the flow system within the aquifer. The aquifer medium also influences the amount of effective surface area materials which contaminants may come into contact with. The larger the grain size and the more fractures or openings within the aquifer, the higher the permeability and the lower the attenuation capacity of the aquifer media, for example, massive shale (low) or sand and gravel (very high).

The geological map of the study area, the wells data besides the results of the geoelectrical sounding interpretation of the layers bearing groundwater were used as the data source in specifying the media of the aquifer all over the study area. The rates were given for every media type. Figure (94) shows the produced map of the aquifer media rating.
Three rates were found ranging from 6 to 8.

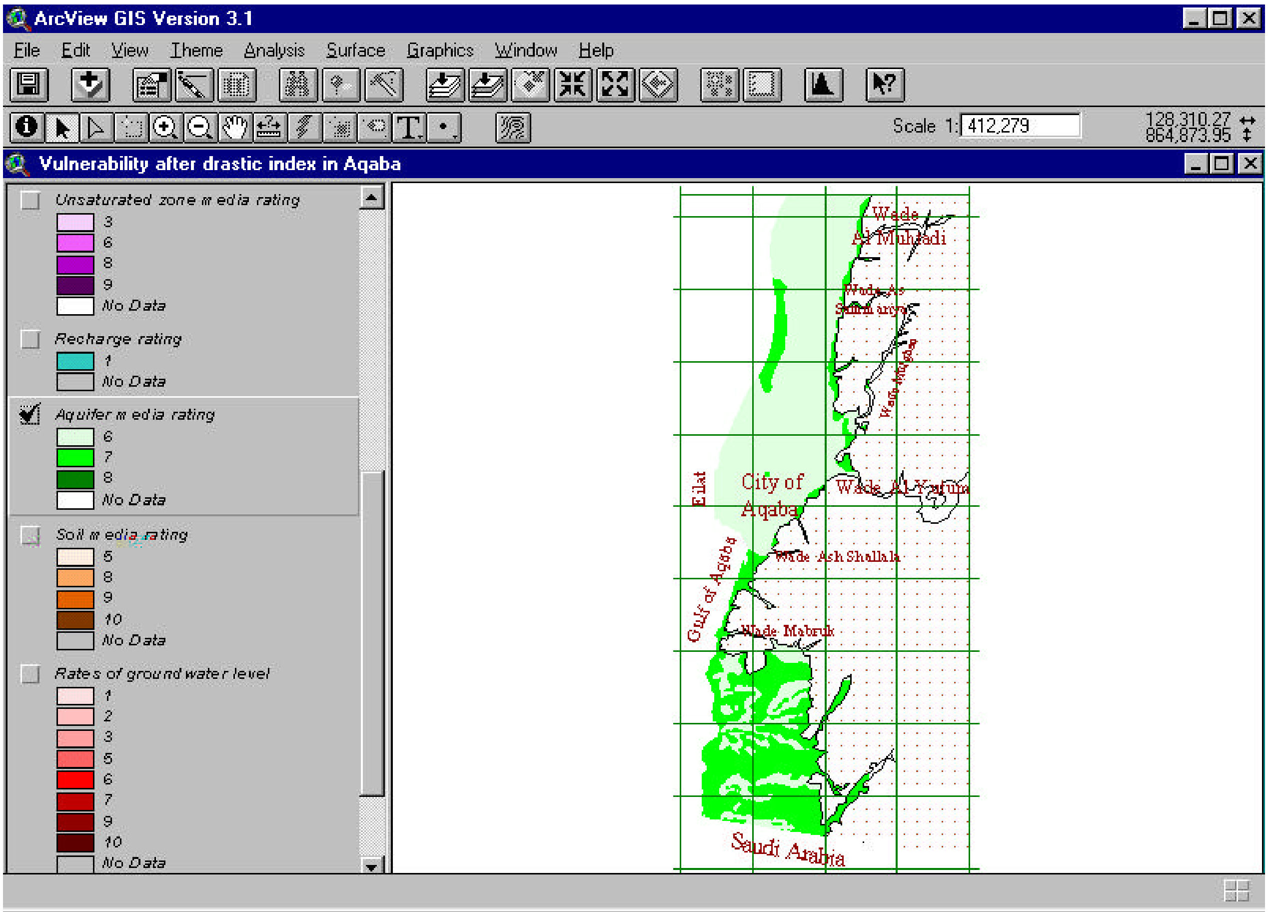


Fig. (94): Aquifer media rating.

Topography

This refers to the slope and slope variability of the land surface. It controls the likelihood that a pollutant will run off or remain on the surface long enough to infiltrate. Topography also influences soil development and has an effect on pollutant attenuation. *Zero-two percent slope provides the greatest opportunity for a pollutant to infiltrate.* Neither the pollutant nor precipitation exits the area as runoff. On the other hand, *18+ percent slope provides a high runoff capacity and a lesser probability of contaminant infiltration* (high erosion and contamination of surface water).

The high resolution elevation model of the study area –100 meter spacing- have been used in generating the slope. IDRISI 32 (GIS) for windows was used in modeling the percent slope of the study area, and in converting the produced raster model into (x,y,z) type of data. The produced data was put in an ascending order, and the rates were given. Figure (95) shows the produced map of the percent slope rating. Five rates were found ranging from 1 to 10.

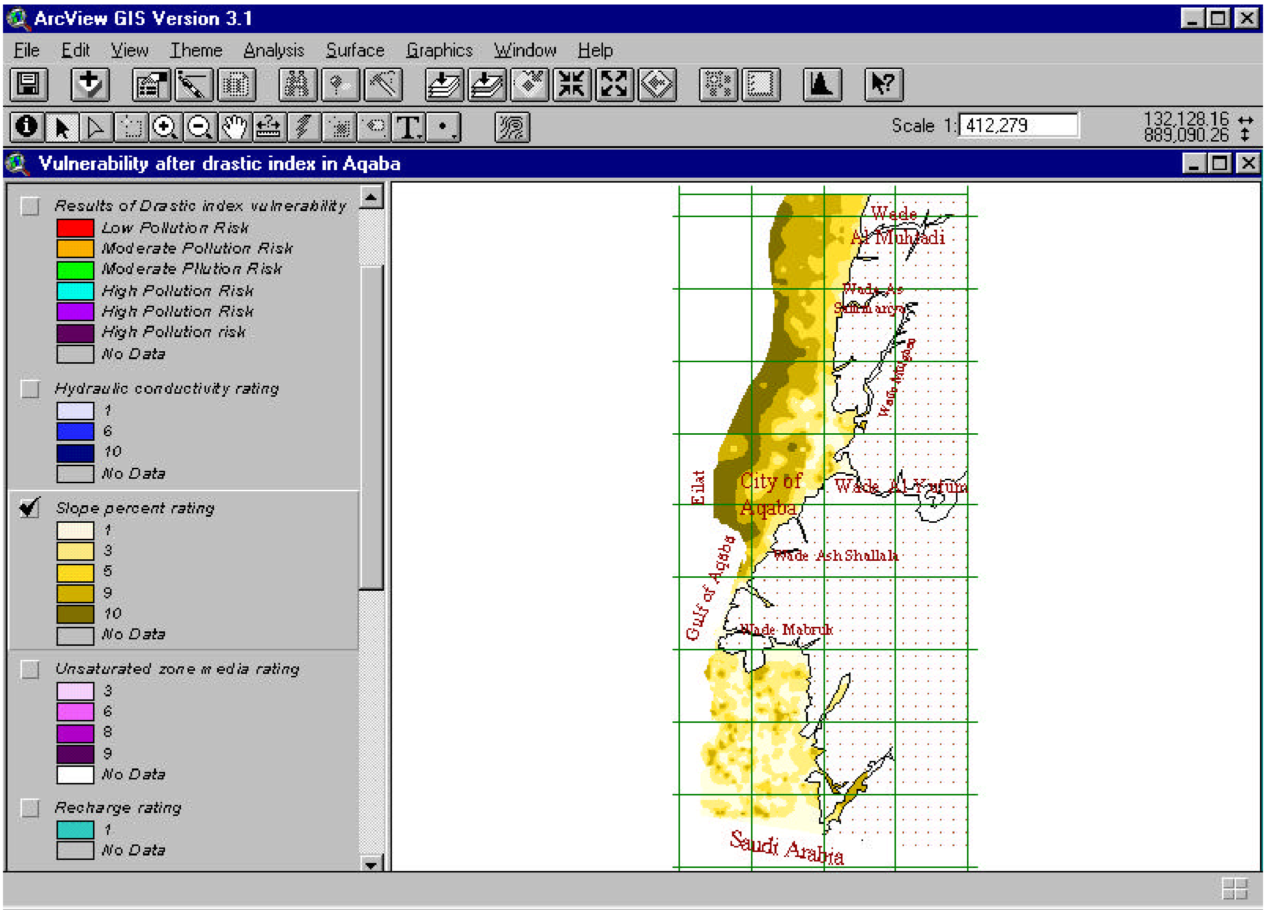


Fig. (95): Topography rating.

Soil Media

This refers to the uppermost portion of the vadose zone characterized by significant biological activity. Soil has a significant impact on the amount of recharge which infiltrates into the ground. The presence of fine-textured material such as silts and clays can decrease soil permeabilities and restrict contaminant movement. The pollution potential of a soil is largely affected by: the type of clay present, the shrink/swell potential of that clay and the grain size of the soil. The less clay shrinks and swells and the smaller the grain size, the less pollution potential.

Soils of the study area were found to be of low field capacities, low contents of clay and organic matters and classified in terms of size as sand. These approaches could give primary indications on the weakness of these soils in protecting the groundwater.

The geological map of the study area, besides the sieve analyses results that were carried out in this research were used as the data source for the soil media in the study area. The produced different zones were grouped after the special rates, and the grid was built. Figure (96) shows the produced map of the soil media rating. Four rates were found ranging from 5 to 10.

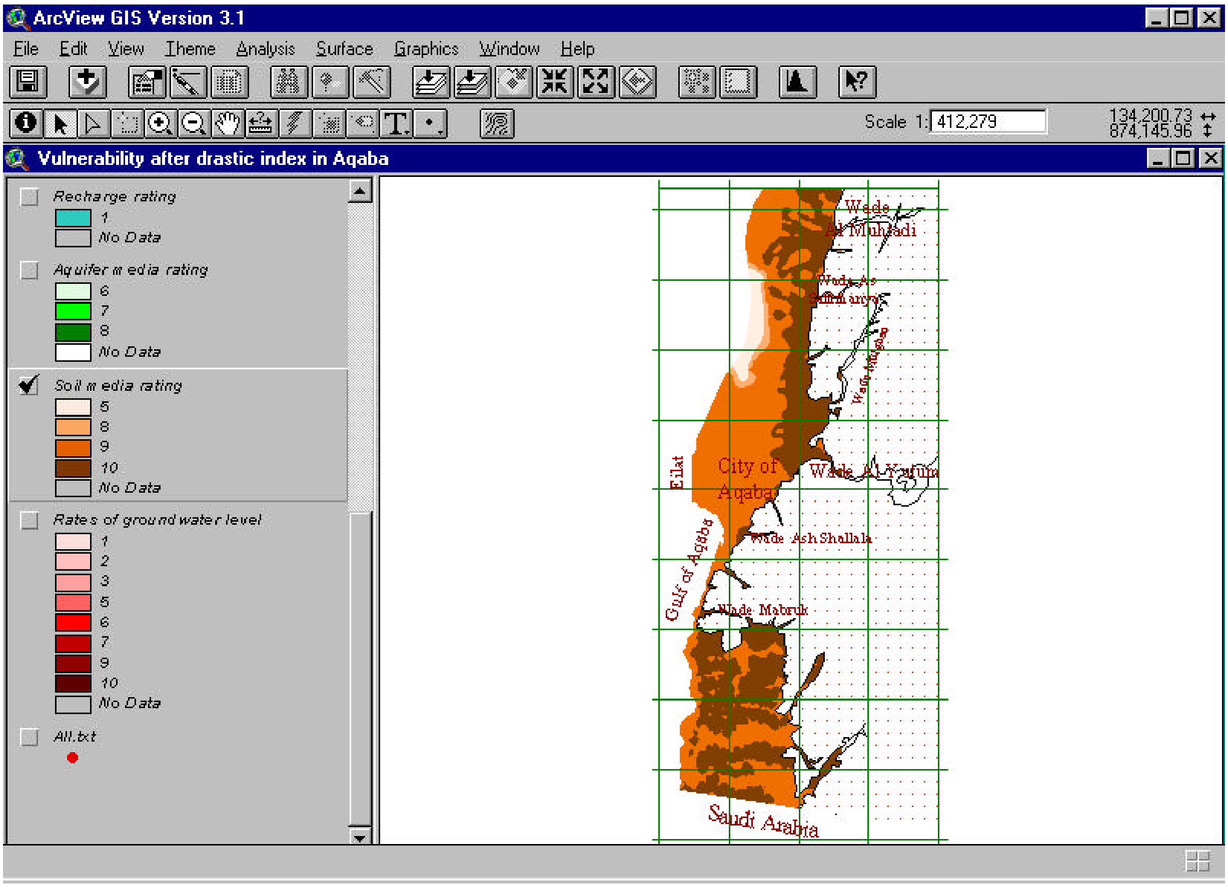


Fig. (96): Soil media rating.

Hydraulic Conductivity

This is the ability of the aquifer materials to transmit water. It controls the rate at which ground water will flow under a given hydraulic gradient. The rate at which the groundwater flows also controls the rate at which a contaminant moves away from the point it entered the aquifer. Values for hydraulic conductivity are calculated and modeled from aquifer pumping tests. *High conductivities are associated with higher pollution potential.*

Pumping tests in the study area enabled defining the extreme values of hydraulic conductivity in term of each aquifer media. Zones of hydraulic conductivity were defined and accordingly the special rates were given. Figure (97) shows the produced map of the hydraulic conductivity rating. Three rates were found ranging from 1 to 10.

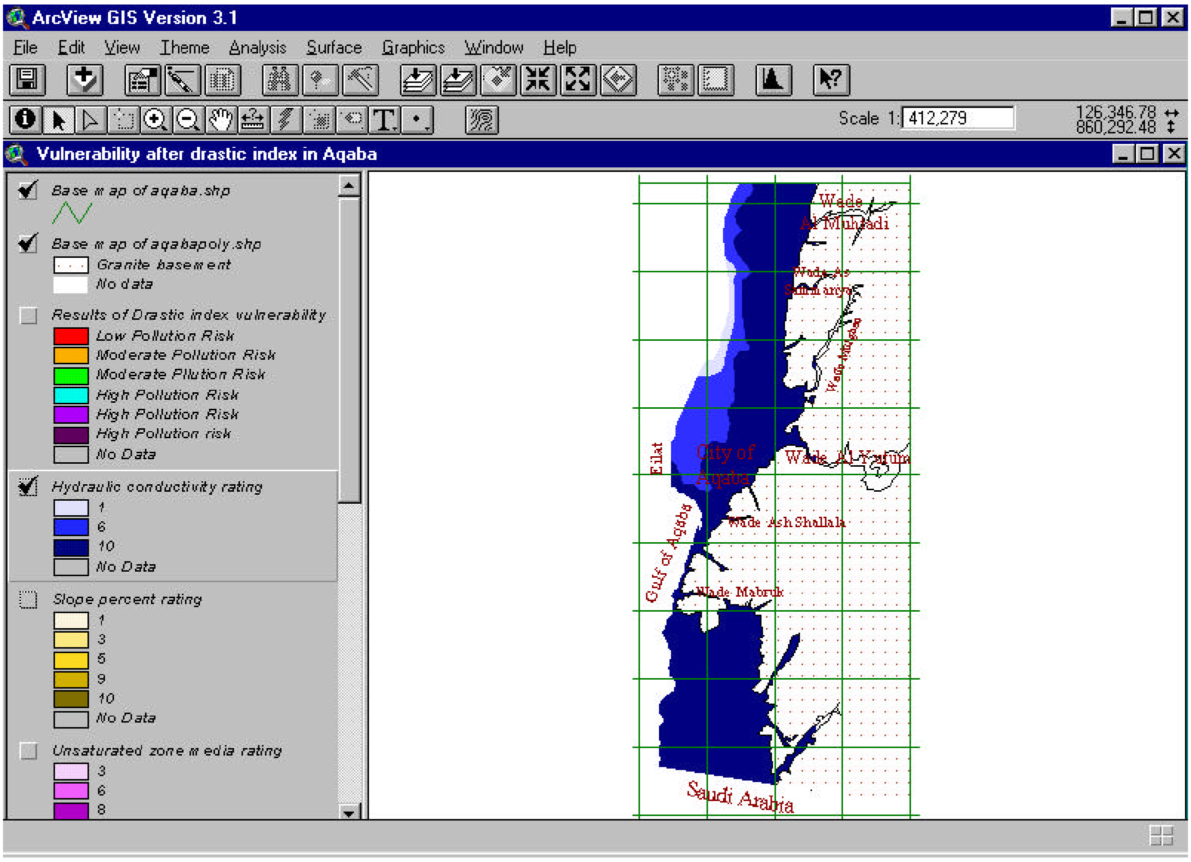


Fig. (97): Hydraulic conductivity rating.

Aquifer Recharge

Precipitation is the primary source of ground water because it infiltrates through the surface of the ground and percolates to the water table. Net recharge represents the amount of water per unit area of land which penetrates the land and reaches the water table. Recharge water is the principle vehicle for leaching and transporting contaminants vertically to the water table and horizontally within the aquifer. The greater the recharge, the greater the potential for ground water pollution (measured in inches/year). Other sources include irrigation, artificial recharge and wastewater application.

The nature of the drastic index rating for the net recharge allows the whole study area to possess only one rating. It is because that the spatial distribution of recharge in the study area with its extreme values do not exceed the first category in the recharge rating. Figure (98) shows the produced map of the recharge rating. One rate was found and attributed to the rate 1.

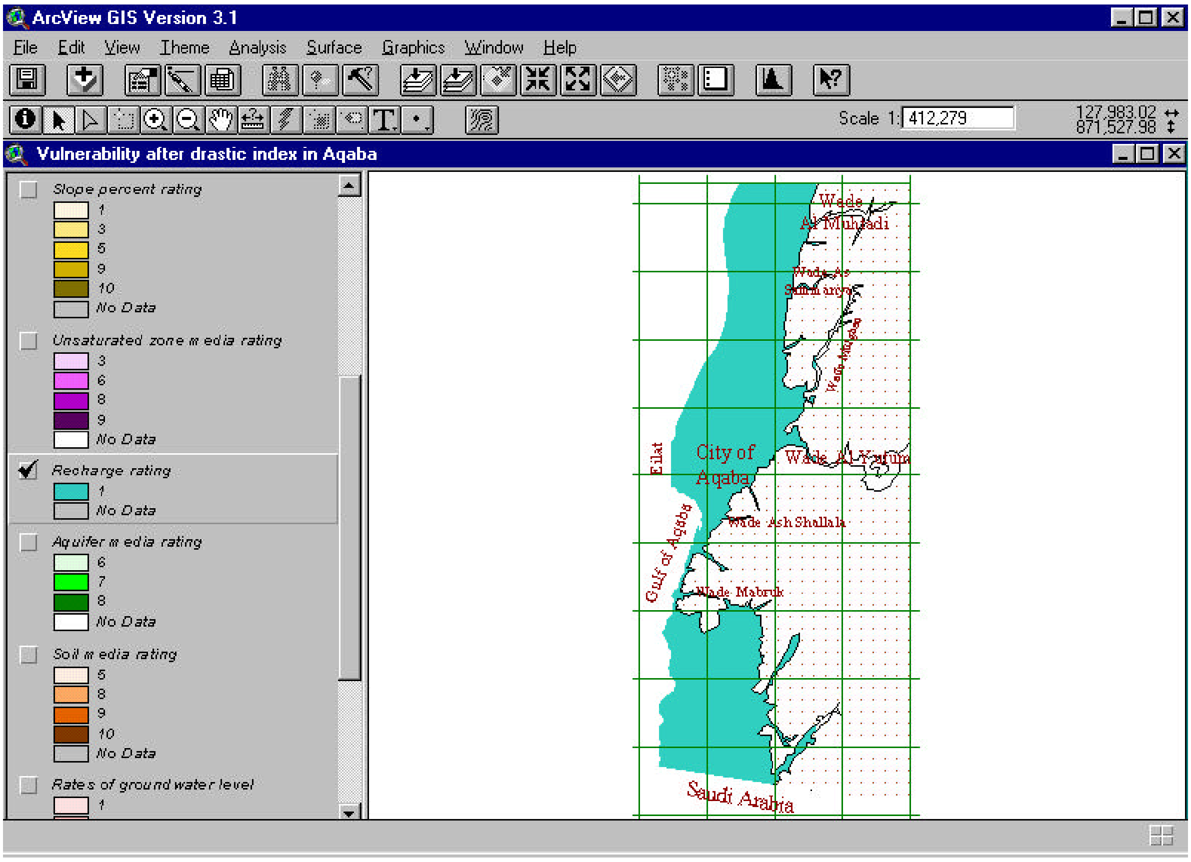


Fig. (98): Aquifer recharge rating.

The produced grids of the Drastic components were used in calculating the Drastic index equation.
The spatial statistics of the distribution of the different Drastic risk quantitative categories shows that the minimum value of the risk in the study area is 67.84 located within the low risk zone. The maximum value of pollution risk was found as 166.93 located in the category of high risk. The mean value of the distribution is 120.50 located in the middle of the moderate class of the risk is between 101-140.

The areas along the shorelines of Aqaba have a high vulnerability risk, while the areas of the side wadis and the alluvial fans occupy a high grade of the moderate class of pollution risk. The flood plains or the areas which follow the alluvial fans possess low grade of moderate class of risk. The mud zones occupied the low class of risk.

The map calculator was used to apply the equation. Figure (99) shows the produced Drastic index map of the study area.

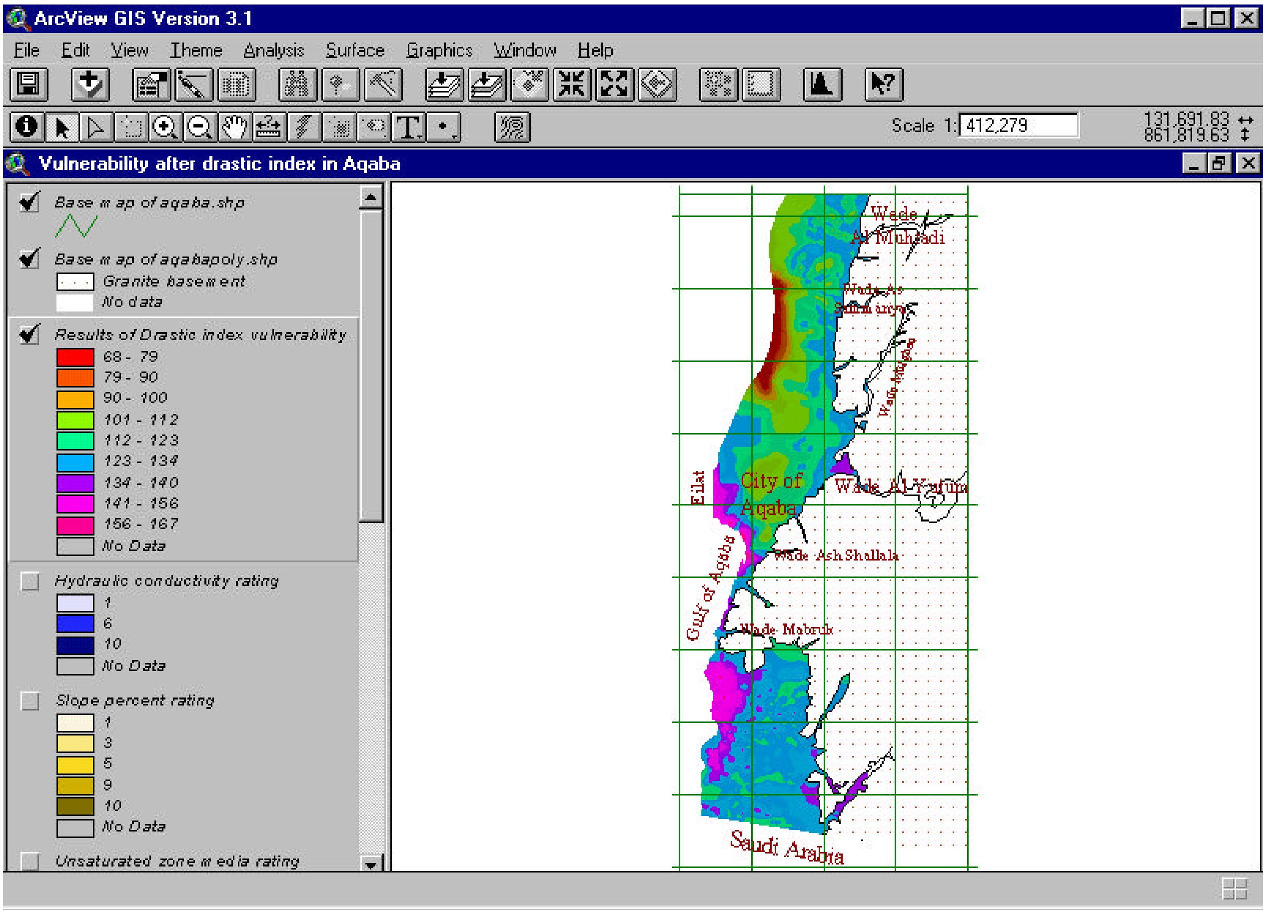


Figure (99): Drastic index map of the study area.

The map of the risk for pollution of the aquifer in the study area was exposed to a reclassification process according to the categories of the Drastic index to produce the end map of the risk classes. Figure (100) shows the map.

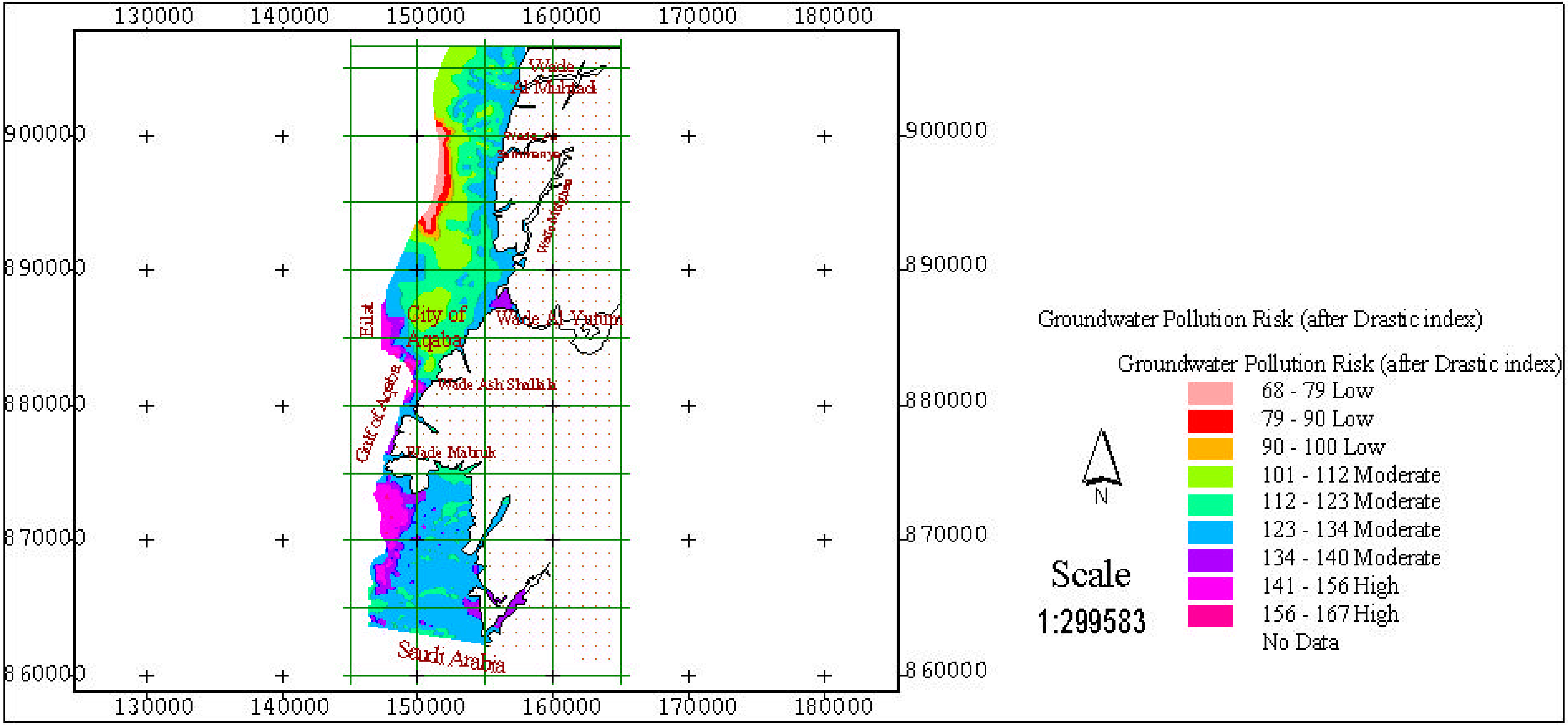


Fig. (100): Groundwater pollution risk map of the study area, reclassified according to the Drastic index.

The results of vulnerability analysis using Drastic index were correlated with the dominant land use units and land forms (Fig. 101).
In general the vulnerability of the Aqaba aquifer for pollution increases going to the west and to the Gulf of Aqaba, where the groundwater depth decreases.
The Aqaba Waste Water Treatment Plant and its surround were found to locate in a high vulnerability zone.
The northern sub-area locates in general in a moderate vulnerable zone, and here the most residential areas are locating. While the southern sub-area (industrial complex) locates in moderate to high vulnerable zone.
The zones locate directly along the Gulf of Aqaba were found to be high vulnerable, where the hotels and the public beaches locate in them.
The side wadis locate in zones of moderate to high vulnerability. The low vulnerable zones were not available in the normal case in Aqaba, but only within the area which includes mud flats according to its geology (see the geological map of the study area page 34).

4.3 Using a Special Developed Vulnerability Index for Aqaba; (SALUFT Index)

The Drastic index is a general evaluating tool for the pollution risk of the different aquifer types. Several geological and hydrogeological conditions of the aquifer could not be included in the this index. These are of a paramount importance and should not be out of concern when the vulnerability of the aquifer for pollution to be evaluated in the region of Aqaba.
These parameters include; the tectonic setting that confirmed the presence of some active faults by the aid of the aerial photography analyses. Another parameter is the self purification criteria of the aquifer matrices depending on the aquifer matrices texture, mineralogy, dissolved oxygen amount in the groundwater, thickness of the vadose zone and the aquifer's permeability.

The hydrological settings are other factors. Here the surface water sheds areas and their inter-connection conditions with the side wadis are important to be included because of their importance in recharging the aquifer. In the next section this new index will be discussed.

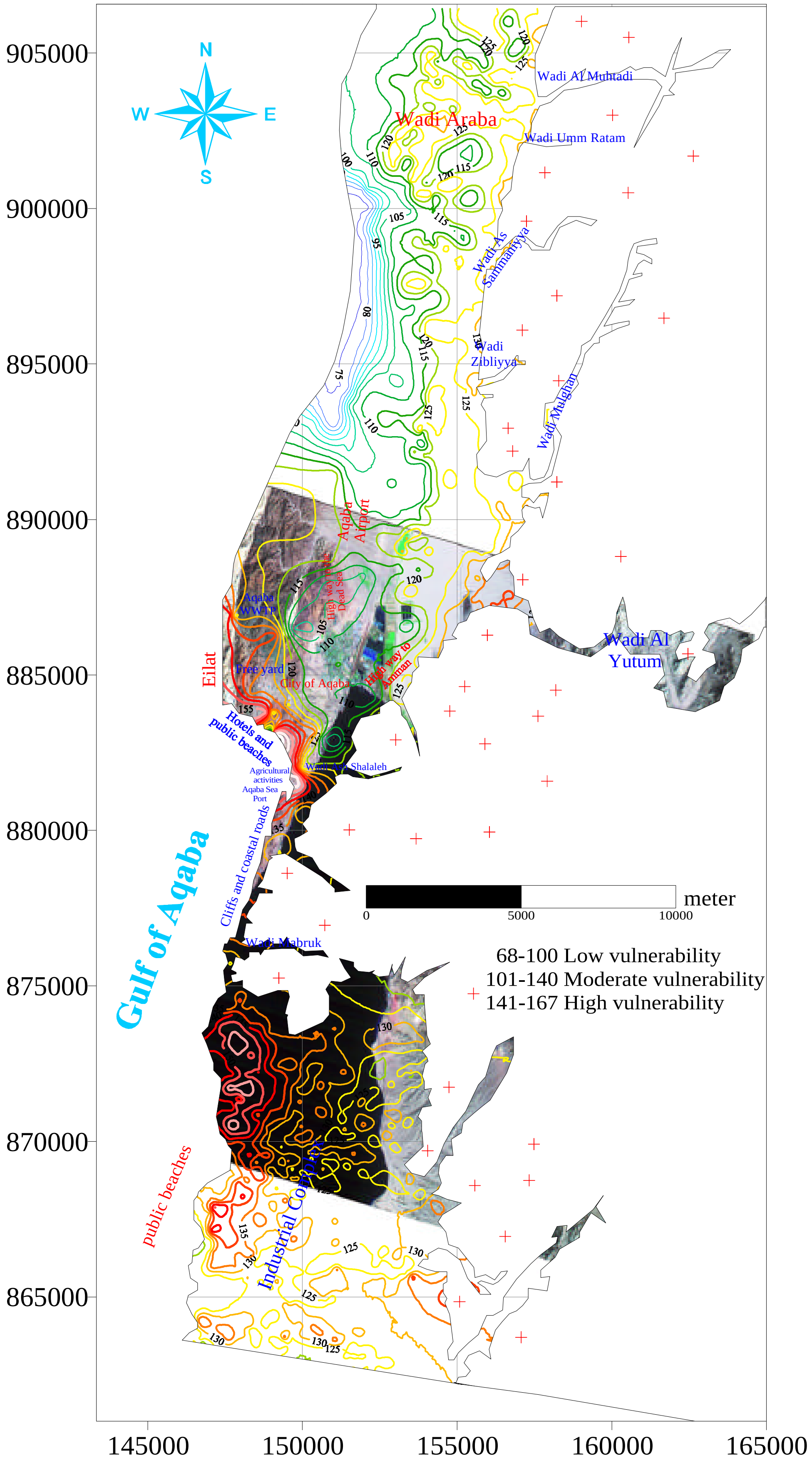


Fig. (101): Spatial correlation between the existing land use units and land forms in Aqaba with the vulnerability of the aquifer for pollution, using Drastic index.

CHAPTER 5

SUSTAINABLE MANAGEMENT OF THE ECO-SYSTEMS IN AQABA

5.1 Introduction

The random use of lands makes the cities less able to face the human's need, while the method of use governs to a big manner the quality of the environment. (Lowe ,1991).
The concept of degradation is inseparable from that of sustainability. Expressed simply, a sustainable land use is one that is able to continue without degrading the land it is using. In this case the sustainability of a particular land use depends both on the properties of the resource and the way it is managed. The feature of a resource that determines its sustainability under a particular use is its resilience, and it is important to note that the resilience of a resource system will according to different land uses and indeed may vary from time to time, depending largely on seasonal and inter-annual variability and management practices and technologies.
A good way to measure the resilience of a particular unit land is to look at its ability to recover after a disturbance. Such a disturbance may be climatic, for example a drought, or human induced, such as vegetation clearance or soil tillage. The greater the disturbance the area can recover from, the greater its resilience. In essence, land degradation is the weakening of an area's resilience. One measure of land degradation is the cost of rehabilitation.

The sustainable management allows utilizing and using the available natural resources but with due to all ramifications that respect the whole diversity and partners in the ecosystem, the rights of the coming generations and the global surround at small and big scales.

Managing the Aqaba region's natural resources with guaranteeing the sustainability requires not to solve the troubles or problems of today forgetting the impacts on the future.

5.2 Developing New Index to Evaluate The Vulnerability of the Eco-Systems for Pollution in Aqaba

The direct relationship between the Aqaba aquifer and marine water body was clarified in this study. Human activities are reflected on the marine ecology. Therefore the quality of groundwater should be given a big priority, otherwise disturbances in the natural cycles of the marine life may take place. This is besides the pollution of soil cover and groundwater.
To include some geo-spatial factors which proved to have significant impact on vulnerability of Aqaba for groundwater pollution that the DRASTIC index couldn't cover, a more comprehensive index was put to examine the suitability of the sub-zones for the different land use choices, aiming at protecting the groundwater.

The index was introduced in this research by depending on the outputs of the detailed studies of the different hydrogeoecological units. It is called **SALUFT** ***respecting for the efforts of Prof. Salameh E. and Prof. Udluft P. in supporting this work.***

The different geo-spatial conditions of the SALUFT were given weights depending on their importance as 1,2 and 3. The higher the weight, the more important the condition, while each condition was classified into 3 classes; vulnerable, moderately vulnerable and less vulnerable, these were given rates as 3, 2 and 1 respectively.

The geo-spatial conditions of SALUFT are:

Surface watershed and connection state to side wadis

Surface watersheds were given the weight 1. Supposing that pollution sources are dominant all over the study area, then large surface watersheds and areas connected to side wadis expose the groundwater for pollution more than small watersheds. Table (36) shows the different rated categories of surface watersheds.

Table (36): The different rated categories of the surface watershed.

GEO-SPATIAL CONDITION **Surface watershed**	STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS	RATES
• Connected to a long side wadi (relatively). • Has the capability to discharge surface runoff into the Gulf of Aqaba. • Possesses big surface area (relatively).	Vulnerable	3
• Connected to a short side wadi (relatively). • Possesses medium surface area (relatively).	Moderate vulnerable	2
• Disconnected from a side wadi. • Possesses small surface area.	Less vulnerable	1

Toposhapes

The G.I.S toposhape classification of the study area due to the topological model (DEM), allows avoiding the flat areas where at the time of precipitation events occurs the recharge to groundwater takes place in fast rates. They are considered as the areas where the surface run off ends and/or reduces its flow velocity. Table (37) shows the different rated categories of the toposhapes. This condition was given a weight of 2.

Table (37): The different rated categories of the toposhapes.

GEO-SPATIAL CONDITION **Toposhapes**	STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS	RATES
Flat area	Vulnerable	3
Semi flat area	Moderate vulnerable	2
Other shapes	Less vulnerable	1

Slope percent

Slope percent can be modeled using G.I.S depending on the digital elevation model of the study area, it was given weight of 1. The importance of this condition is the same as that of the toposhapes, but here the evaluation is at small scale because the toposhape modeling divides the area due to the main dominant geomorphological shape, while slope modeling gives the real slope of every unit pixel in term of the resolution of the model. Table (38) shows the different categories of the slope percent.

Table (38): The different rated categories of the slope percent.

GEO-SPATIAL CONDITION **Slope percent (%)**	STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS	RATES
0-6	Vulnerable	3
6-18	Moderate vulnerable	2
>18	Less vulnerable	1

Because the soil in the study area allows high rates of infiltration, the vulnerable state was given a wide range 0 to 6%.

Distance from the Gulf shorelines

The distance from the shorelines is an important condition. The farther the released pollutants from these shorelines, the better the situation against marine pollution. The resident time given for the pollutants to be decomposed and/or absorbed by the aquifers matrices before they strike the marine body is controlled by this condition. This condition was given the highest grade of importance as weight 3. Table (39) illustrates the different rated distances

Table (39): The different categories of distances from the shorelines.

GEO-SPATIAL CONDITION **Distance from the shorelines of the Gulf of Aqaba (Kilometer)**	STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS	RATES
0-1	Vulnerable	3
1-3	Moderate vulnerable	2
>3	Less vulnerable	1

The groundwater flow rate in the study area is relatively high. Accordingly it was considered that the less vulnerable state is a distance 3 km from the shorelines, the distance which prove to have good attenuation of some pollutant of human activities.

Hydrogeological potentials for recharge

The recharge calculated for the study area for 20 years doesn't exceed a very few millimetre's per a year. But sometimes thunderstorms raise this value for higher than that. The mouths of side wadis are more exposed for recharge than the fluvial plains, while mud flats receive lower amounts of recharge.

This factor deals with the depositional settings. Table (40) shows the different categories for this factor and their rates.

Table (40): Different rated categories of recharge potentials.

GEO-SPATIAL CONDITION **Hydrogeologic potentials for recharge**	STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS	RATES
• Mouths of side wadis. • Alluvial fans. • Recent active tectonic faults.	Vulnerable	3
• Fluvial plains.	Moderate vulnerable	2
• Mud.	Less vulnerable	1

This condition was given the weight 1 regarding the low recharge amounts in the study area.

Structural faulting conditions

The study area was defined in terms of its structures depending on the aerial photography analyses. It was found and proved that the area still active tectonically. Major faults intersect the study area from north to south. Some other places may be affected by the extensions of these faults, while some other areas are not. The faults in semi lithified deposits enhance the flow rates of groundwater and do not allow self purification processes to take place. This condition is very important and was given the weight 3. Table (41) shows the different rated categories for this factor.

Table (41): The different rated categories of faulting condition.

GEO-SPATIAL CONDITION **Structural faulting conditions**	STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS	RATES
• Presence of recent active faults (as indicated from the aerial photography study).	Vulnerable	3
• Expected extension of faults within the alluvial sediments.	Moderate vulnerable	2
• No faulting processes.	Less vulnerable	1

Groundwater flow velocities

The groundwater flow rate is an important condition, it is related to self purification rates of groundwater for different types of pollutants. The faster the flow, the lower the rates of self purification. This depends on the residence time of the groundwater in the aquifer; the longer it stays, the higher the pollutants decomposition or absorption. Because its importance, this condition was given the weight 3. Table (42) shows the different flow rates of groundwater in the aquifer, and the given rates.

Table (42): The different flow rates of groundwater in the aquifer, and the given rates.

GEO-SPATIAL CONDITION **Groundwater flow VELOCITY (m/s)** (depending on the map of groundwater above sea level, by calculating the water gradient of the wanted position with 1000 meters distance from it along the flow path line, considering a constant hydraulic conductivity ($1*10^{-4}$ m/s).	STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS	RATES
$> 0.5*10^{-5}$	Vulnerable	3
$0.5*10^{-5}$ - $0.15*10^{-5}$	Moderate vulnerable	2
$< 0.15*10^{-5}$	Less vulnerable	1

The states of vulnerability in term of flow rate of groundwater were assigned due to the extreme values.

Thickness of the unsaturated zone

The unsaturated zone protects the aquifer against pollution. It is the zone which receives the recharge water before it reaches the groundwater. The thicker the zone, the more protected is the groundwater against pollution of all types. This important condition was given the weight 3.

Table (43) shows the different thickness categories, and their rates.

Table (43): The different thickness categories, and their rates.

GEO-SPATIAL CONDITION **Thickness of unsaturated zone (m)**	STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS	RATES
0-6	Vulnerable	3
6-15	Moderate vulnerable	2
> 15	Less vulnerable	1

Spatial textural conditions of the soil, unsaturated zone and aquifer materials

The finer the grains sizes of the soil cover, the unsaturated zone and the aquifer materials, the higher the rates of self purification against the different pollutants. The pollutants are retarded and face capturing. They may not spread far away. The dominant size of the soil cover of the study area was found as sand size. Some gravel and silt sizes were found to occur in some other places. The clay and/or silt lenses were noticed in the floods paths, this indicates their presence also in the subsurface.

The different sizes were given the rates in Table (44). This condition was given the weight of 2.

Table (44): The different sizes categories and their rates.

GEO-SPATIAL CONDITION **Spatial Textural conditions of the soil, unsaturated zone and aquifer materials**	**STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS**	**RATES**
• Gravel sizes.	Vulnerable	3
• Sand sizes.	Moderate vulnerable	2
• Sand sizes with some silt and/or clay sizes. • Presence of mud flats on the surface.	Less vulnerable	1

General groundwater chemistry as EC-values

The groundwater chemistry differs from one place to another. The salinity ranged from less than 1000 to more than 3000 μ S/cm.
Side wadis and alluvial fans have water of low salinity than other places in the study area such as the Wadi Araba. This condition was given the weight of 2. Table (45) shows the different water salinities and their rates.

Table (45): The different water salinities (EC-values) and their rates.

GEO-SPATIAL CONDITION **General Groundwater Salainities as EC-value (m S/cm)**	**STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS**	**RATES**
• 0-1500	Vulnerable	3
• 1500-3000	Moderate vulnerable	2
• > 3000	Less vulnerable	1

After translating the different geo-spatial conditions into rates, their combination with each other for the one pixel (unit cell) leads to the judgement weather it is vulnerable, moderate vulnerable or less vulnerable. Table (46) shows the different conditions with their weights.

The combination of the conditions with each other to produce the SALUFT Index is obtained by applying the formula;

$$\textbf{SALUFT Index} = \frac{\langle \Sigma(\text{condition category rate}) * (\text{condition weight}) \rangle}{21}$$

Table (46): The different conditions with their weights.

GEO-SPATIAL CONDITION	WEIGHT ACCORDING TO THE IMPORTANCE
Surface watershed (GIS classification of DEM)	1
Land topological shapes (GIS classification of DEM)	2
Slope percent (GIS classification of DEM)	1
Distance from the shorelines of the Gulf of Aqaba	3
Hydrogeological possibility for recharge	1
Structural faulting conditions	3
Groundwater flow rate	3
Thickness of unsaturated zone	3
Spatial conditions of soil, unsaturated zone and aquifer materials texture	2
General groundwater quality as EC value	2

The pollution states according to the different SALUFT index quantitative classes, and the land use suitability are shown in the last column of Table (47).
The SALUFT classes allow suggesting the suitable land use units for every class. The vulnerable class should be carefully handled, where free areas, parking places or recreation areas may be built accordingly allowing minimum pollution releases. The moderate vulnerable areas can include housing and governmental service units. The areas which are less vulnerable can be used for the industrial and irrigation uses.

Table (47): The states of SALUFT index (pollution and the land use suitability units).

SALUFT Index classes	STATE AGAINST POLLUTION IN AQABA, AND/OR SUITABLITY FOR POLLUTANTS RELEASING LANDUSE UNITS	Land use suitability in Aqaba
2.5-3.0	**Vulnerable**	• Free yards. • Recreation areas. • Parking sites.
1.85-2.5	**Moderate vulnerable**	• Housing areas. • Governmental service units.
1.0-1.85	**Less vulnerable**	• Liquid and solid wastes processing and managing stations. • Industrial activities. • Public gardening and plantation activities.

To confirm the validity of the index the vulnerable class was given a range of 0.5 more than the lower limit of the index. While the moderate vulnerable class was given a range of 0.65 more than the upper limit of the vulnerable class. The less vulnerable class was given a range of 0.85 more than the upper limit of the moderate vulnerable class.

This index ***suggests*** *the suitable land use units for every vulnerability's grade zone in Aqaba, but* ***only from the protection of the hydroeco-systems point of view and aiming at protecting the groundwater****. Several factors are also important to be included in this index such as the dimensions of socio-economic settings, political settings, engineering settings, and the other environmental issues. In very advanced stages, the output of all factors can interact with each* *other to choose the most suitable land use plan for a specific zone. These factors may be given weights also.*

At more introduced stages several additional substances may be added and given weight due to their importance in the city and region of Aqaba, (Table 48).

Table (48): Natural factors and their substances to control the vulnerability studies for the Eco-Systems.

TOPOGRAPHY	Elevation, slope variability of land surface; surface runoff paths, stream network density.
VEGETATIVE COVER	Land use, subsurface water pathways, recharge and discharge areas, fracture traces and lineaments, contaminant potential.
CLIMATOLOGY	Long records of precipitation, average temperature, humidity, solar radiation, evaporation, evapotranspiration; effective precipitation assessment.
SOILS	Thickness, structure, texture, mineralogy, chemical and physical properties, porosity, permeability, moisture, infiltration capacity.
HYDROLOGY	Streamflow discharge, hydrograph analysis, baseflow, flow ratio, water exchanges with underlying ground water systems.
HYDROGEOLOGY (Unsaturated zone)	Depth to water; thickness, lithostratigraphy, mineralogy, geometry, fracture index, karst index, effective porosity, and saturation ratio of surficial deposits; vertical effective permeability, effective flow velocity, infiltration rate index, net recharge.
HYDROGEOLOGY (Saturated zone)	Lithostratigraphy, geological structure, geometry, effective porosity, permeability type (primary or secondary), transmissivity, storativity, and hydraulic conductivity of an aquifer; aquifer type (unconfined, semiconfined, confined); water level fluctuations, hydraulic gradient, flow directions, effective flow velocity and discharge, ground water divides, exchanges with surface water bodies or/and adjacent aquifers.
WATER USE	Water-discharge points (spring, wells) and location of ground water extraction works; surface and ground water sources, distribution, and usage; yield and drawdown of pumping/dewatering plants, location and inflow rate of recharge systems.
HYDRO-CHEMISTRY	Physical and chemical properties of surface and ground water, chemical markers, isotope content, age and residence time of water, characteristic ratios; natural surface and ground water quality distribution.
CONTAMINANT FEATURES	Changes in water quality; contaminants present and their physical and chemical characteristics, concentration, half-life, persistence, mobility, dispersivity, cation exchange capacity, biodegradability, etc.
HUMAN IMPACT ON ENVIRONMENT	Extent of urban areas, location and type of industrial complexes, existing and potential contamination sources, potential contamination entries, main objects of protection.

5.3 Coastal Zones Management and Environmental Restoration and Protection In Aqaba:

Coastal zones are composed of the coastal plain, the continental shelf, the waters that cover this shelf and includes features such as bays, estuaries, lagoons, small islets and reefs. It is also the region where marine and continental processes of erosion and deposition interact giving rise to different types of land forms. They are highly productive natural environments, combining forestry and farming opportunities on fertile coastal lands, with a range of capture and culture fisheries in the rich coastal waters. In addition they are also greatly in demand for economic and industrial development. Coastal areas have always provided foci for trade and settlement, and have given easy routes for population movement by land and water. More recently they have become highly attractive venues for tourism.

Managing coastal zones in Aqaba is a complex task because of the multiplicity of economic activities which take place within them. In addition to the complexity of the natural systems which make up the land/water interface, social, institutional, administrative, political and legal issues are added (Fig. 102).

Information management is becoming ever more important to assist decision-making, and multi-disciplinary understanding by senior managers is vital. While management is facilitated through the use of integrated planning techniques that recognise the inter-relationships between the activities in different sectors and the needs of the different stakeholders at many levels.

Aqaba was a small village consisting from the old town encountering no industries or reflections of urbanization. The relatively fast periodical development of the area and uses of the coastal zone with the sustainability look being absent increased pressure on the natural resources that support the associated social and economic systems such as groundwater, soils, air and marine life. This pressure on the environment is both cumulative and complex, and grows as the natural resources become depleted, where there are already indications that the coastal areas are approaching the point where natural productivity falls and ecological systems collapse, that may decline future plans outputs such as tourism outputs.

There are several important environmental and management issues thrown upon the decision makers in Aqaba which are directly related to the socio-economic development:

Environmental issues

- Periodic cumulative pressures on the Eco-systems through the city development stages
- Sea water encroachment into land due to irregular pumping from groundwater which reduces the submarine groundwater discharge into the sea
- Anthropological impacts both on land and marine ecology (waste water treatment plant of Aqaba, traditional houses liquid wastes disposal methods and solid wastes disposal methods and sites)
- Industrial impacts (dust particles on land and marine ecology, gases, solid and liquid wastes)
- Eutrophication process in the coasts (causes, effects and solutions)
- Visible pollution (irregular and old building such as the old town of Aqaba)
- Noise pollution (Industrial constructions, vehicles, airport and general circulation)

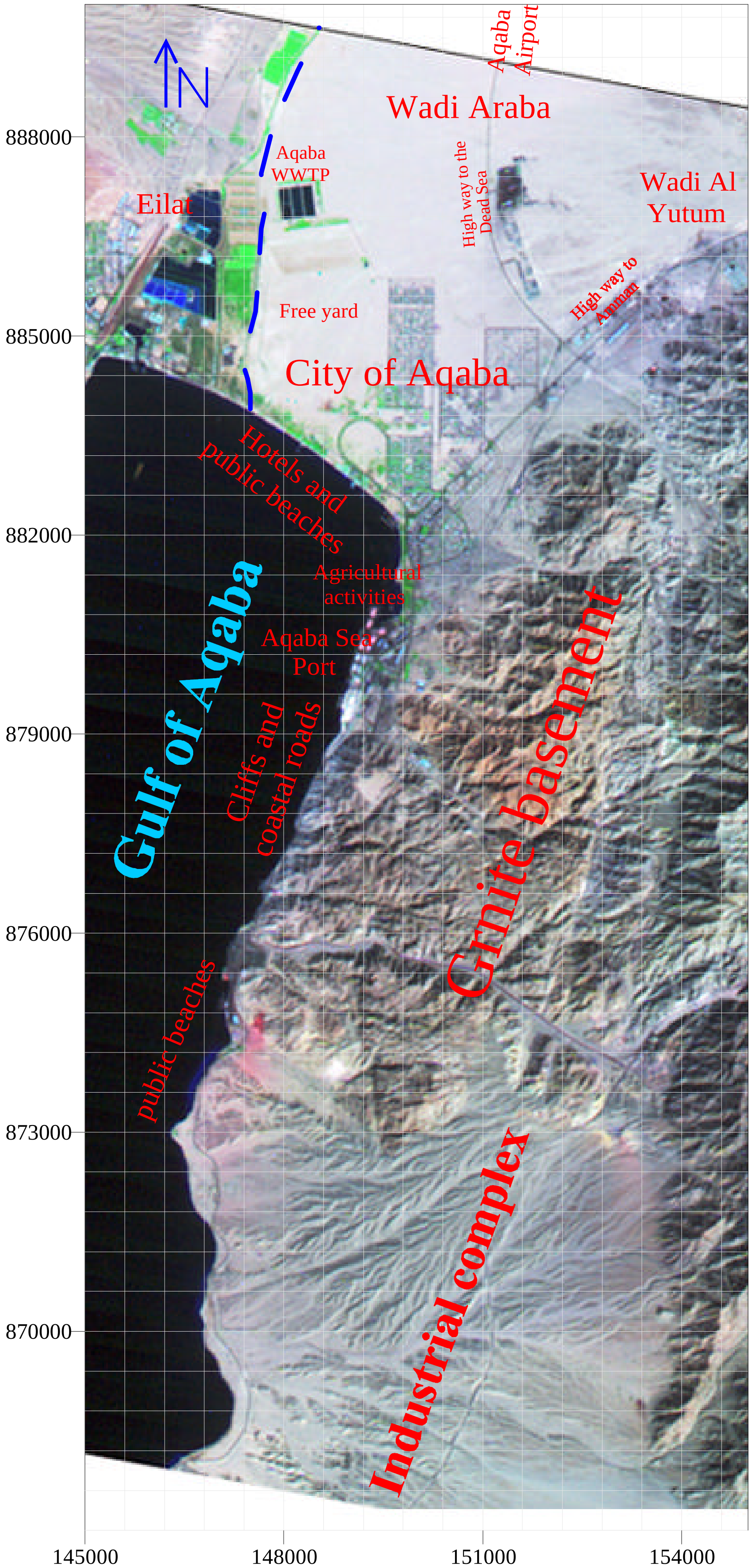


Fig. (102): LandSat image of Aqaba coastal zones shows some urbanization units.

Management issues:

- Water future (resources and demands)
- Well planned integrated plan between the different sectors building the region including society, general health, environment, natural resources and economy
- Allowing the vulnerable to pollution 27 km of coastal zones to satisfy multiple and different demands in social and recreation fields, industrial, agricultural and economic activities

Recent water demands of the city of Aqaba are summarized in Table (2) which represents the consumption distribution of the city water according to the type of consumption for the year (1997). The total consumption was about 9 million cubic meter per year of fresh water. This number will double in the coming few decades under the expected higher activity of the different sectors and increasing population. The same aquifer which feeds the Aqaba region – Disi Aquifer- will also serve the demands of the Jordanian capital Amman.

The southern part of the study area which is the only free ***region*** in Jordan that overlooks the open sea (Gulf of Aqaba) and still free of land use units is expected to be in the next few decades occupied by residential areas and industrial activities according to the Master Land Use Plan of the city (2000-2020). For a country like Jordan stressed in terms of its water conditions and having the problems characterised by scarcity in resources (surface and ground), several types of pollution, increasing salinity and high population growth, such a ***region*** must incorporate strategic alternative solution where big scales seawater desalination processes may become a necessity.

Side wadis, especially Wadi Al Yutum, should be given a special interest. Their yields potentials of good quality groundwater is good. The most suitable choice to make use of these amounts is to dig pumping wells exactly at the lines where they meet the heads of their alluvial fans, because that the salinity increases downstream (going westwards to the Wadi Araba). Regarding the side wadis overlooking the southern Wadi Araba and the increasing precipitation amounts going northward from Aqaba; the southern part of Wadi Araba should be studied in details on its groundwater potentials.
About 3.28 million cubic meter per year is the calculated safe yield in the northern part of the study area, where the total annual consumption for all sectors is about 9 million cubic meter per year (1997). This safe yield forms about 30% of the consumption. The required quality for the different use sectors may allow that safe yield to cover some of the demands from that source.

The waste water treatment plant of Aqaba leaks 1.5 million m^3/y of impaired quality water into the aquifer. Agriculture in the city consumed in the year 1997 about 0.2 million m^3/y, while industries consumed in the same year about 0.46 million m^3/y. The total annual consumption of both sectors equals about 44% of amount leaking from the plant. The required quality of these sectors is not far a way from the leakage quality, allowing making use of it.
The southern part of the study area was proven not to allow abstraction activities. Seawater encroachment into land modeled by several methods revealed that fact. In deep studies should be carried out to investigate the role of the revealed barrier in this area in capturing the groundwater.

Studying the potentials of the sun energy in desalinating seawater, which is a good choice regarding the high rates of temperature around the year and the long sunshine rates in the area.

Recycling of baths and kitchens waste water of the residential areas, schools, hospitals, factories and hotels for their gardening purposes and/or toilet uses. This emphasizes on sorting the small scale liquid waste types exactly as the case of the solid wastes.

Calling and encourage the hotels and factories to use local desalination units for seawater to reduce pressures on the public water supply. While installing of saving types of indoor water tools instead of the dominant traditional tools is of a paramount importance in reducing consumption.

Environmental restoration is the process of minimizing or eliminating the threat that contaminated sites pose to human health and the environment. Initially, effort should be focused on a screening process to determine which sites require cleanup. Sites should be evaluated through a search of historical records and collection of soil and/or water samples. By comparing site concentrations of hazardous or substances with naturally occurring "background" levels, it is possible to determine the level of contamination, if any, that exists at the site. For those sites with contamination, risk analysis is then used to evaluate whether it presents a threat to human health or the environment. For sites that pose a threat, cleanup actions can vary greatly depend on the types of contaminants and individual site characteristics. Most cleanup actions should involve removal of contaminated soil and hazardous waste.
In Aqaba the attention should be given to some environmental issues including:

- ***Phosphate dust particles*** that accumulate at the surfaces of the granite mountains east of the Gulf of Aqaba, should be given an interest. They still accumulate until a precipitation event sweeps the area and flushes them into the marine water body. One solution is to prevent or to reduce the dust production of porting processes. Other method is by constructing buffering zones along the end of the coastal wadis that can absorb or infiltrate the floods from the phosphate dust particles.

- ***Residential areas which are still not connected to the Aqaba waste water treatment plant***, their liquid wastes are disposed into the subsurface. Besides damaging the available groundwater, the risk on the marine ecology exists. These areas should be connected to the plant.

- ***The methods followed in disposing the treated waste water from the Aqaba waste water treatment plant***. About 1.5 MCM/y of this water are allowed to join the shallow aquifer. In advanced stages it will join the marine body located less than 3 km to the south. There are 15 leaking pools in the plant with a surface area of 22500 m^2, which allow about 4100 m^3/day to join the groundwater body, this amount can be used for other purposes as mentioned previously. If the process of leakage has no other alternative, then establishing capturing zones for this water by drilling some pumping wells in the downstream area of the groundwater flow is another solution. The water after being partially purified by the aquifer matrices should be of better quality. Accordingly it may be used for different purposes.

- ***Solid wastes from the industrial complex*** including gypsum should be disposed in special areas not allowing them to reach the groundwater body. These industrial wastes can be reused or recycled in other industries requiring such raw materials.

- ***Trucking and porting processes in the sea ports*** produce dust particles that can cover to a specific manner the existing pores that enhance the infiltration of rainwater. This in turn may enhance the run off process, especially in the southern subarea, where under heavy rainfall coastal side wadis are able to discharge floods into the marine water. The washing products in advances stages may disturb the life features in the Gulf of Aqaba. This emphasizes on the importance of controlling the porting processes lest the dust particles been produced.

- More studies on ***eutrophications*** and relating it with the quality of the discharged groundwater into the Gulf.

- Applying the ***vulnerability studies of the aquifer*** and the related ecosystems for pollution before planning the city, taking into consideration the substances reminded in Table (48).

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Appendix A:

Calculations on the Groundwater Quality

The chemical concepts used in discussing the water quality are,

- **Water type**: The chemical facies is calculated as follows: the major cations Na, Ca, Mg and anions Cl, SO4, HCO3 are transformed to meq/l percentages. The water type expression is formed by those elements for which the concentration is higher than 10% in ascending order (cations first).
- **Ion balance**: Balance between sum of anion and cation equivalent charges. This value is useful to control the analysis quality (value should be < 5%) or to find typing mistakes.
- **Hardness:** Total and alkaline hardness in mmol/l Ca+Mg, French degrees (°f) and German degrees (°g). 1 °f = 10 mg/l CaCO3, 1 °g = 10 mg/l CaO.

The classes based on the classifications of Table (21).

Table (21): Water hardness classes.

HARDNESS IN (°F = 10 MG/L) AS $CaCO_3$	**WATER CLASS**
0-7.5	*Soft*
7.5-15	*Moderate Hard*
15-30	*Hard*
>30	*Very Hard*

* (After Sawyer and Mc-Carty, 1967)

The water quality regulations are those limits due to the hydro-chemical items, which the water should not exceed to be accepted for drinking.
For the irrigation purposes the salinity and the sodium absorption ratio with each other can govern the type of harvest suitable for the water. Sodium absorption ratio –SAR- is expressed as follows:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{+2} + Mg^{+2}}{2}}}$$ ....all are in meq/l.

The salinity as the water electrical conductivity has three categories; C1, C2,C3, and C4. These respectively are, low, medium, high, and very high salinity. And range from 100-250, 250-750, 750-2250, and more than 2250 uS/cm. The SAR has 3 categories; S1, S2, and S3. The values attributed to them are 0-10, 10-18, 18-26, and more than 26. These are classified as respectively; low, medium, high, and very high alkalinity hazards.

Table (22) shows the general regulations on the water for drinking purposes, From: Mineral Levels in Animal Health, Diagnostic Puls,1994. http://www.abs.sdstate.edu/labs_services/wql/drnk_wq_liv.htm

Table (22): Drinking Water Quality for Humans, Livestock & Poultry
Recommended Maximum Levels

PARAMETER	HUMAN	LIVESTOCK	POULTRY	UNITS
Alkalinity	30-500	<2,000	<1,000	mg/L @
Ammonia (as N)	<.05			mg/L
Arsenic	<0.025	<0.05-0.2	<0.2	mg/L
Bicarbonate (HCO_3)		<1,000		mg/L
Cadmium	<0.001	<0.05		mg/L
Calcium	200	<1,000	35-600	mg/L
Chloride	<250	<1,000	<14-200	mg/L
Chromium	<0.05	<0.1		mg/L
Cobalt		<1.0		mg/L
Copper	<1.0	<0.5	<0.6	mg/L
Fluoride	<1.5	<1.2-2.0	<2.0	mg/L
Hardness ($CaCO_3$)	180	<2,000	<2,000	mg/L
Iron	<0.3	<0.4	<0.4	mg/L
Lead	<0.05	<0.05-0.1	<0.1	mg/L
Magnesium	150	<90-250	<35-250	mg/L
Manganese	<0.05	<0.05	<0.05	mg/L
Nickel		<1.0		mg/L
Nitrogen (from NO_2 + NO_3)	<10	<23	<11	mg/L
Nitrate (NO_3)	<44	<100	<50	mg/L
pH	6.5-8.3	5.5-8.3	6.4-8.0	Units
Phosphate (total P)	<0.1	<0.7		mg/L
Potassium	<10	<20	<300	mg/L
Sodium	<10	<150-800	<50	mg/L
Specific Conductance		<3,000	<1,000	uS/cm *
Sulfate	<250	<500	30-50	mg/L
Sulfide (as H_2S)	<0.05			mg/L
Zinc	<5.0	<5.0-25	<2.5	mg/L

@ mg/l = milligrams per lliter
* uS/cm = micro-Siemens per centimeter

Location : **Tap water sample (piped Disi water).**
Water type : Ca-Na-HCO3-Cl
Sum of Anions (meq/l) : 3.42
Sum of Cations (meq/l) : 3.21
Balance: : 3.0%

Total dissolved solids : 6.60 meq/l 233.3 mg/l
Total hardness : 1.07 mmol/l 10.69 °f 5.99 °g
Alkalinity : 1.63 mmol/l 8.15 °f 4.56 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	21.9	< 20	< 150
Ca	31.8	40- 100	
NH4	1.7193	< .05	< .5
Cl	32.96	< 20	< 200

Irrigation water:
Conductivity = 344 uS (group C2: Medium salinity water)
Sodium Adsorption Ratio (SAR) : 0.92

Location : **Wadi Al Yutum Well**
Water type : Na-Ca-Cl
Sum of Anions (meq/l) : 10.49
Sum of Cations (meq/l) : 10.84
Balance: : 1.6%
Total dissolved solids : 21.3 meq/l 665.7 mg/l
Total hardness : 2.92 mmol/l 29.17 °f 16.33 °g
Alkalinity : 2.04 mmol/l 10.20 °f 5.71 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	114	< 20	< 150
F	1.5		< 1.5
Cl	210	< 20	< 200
SO4	83.8	10- 50	< 200
NO3	27.5	< 25	< 40

Irrigation water:
Conductivity = 1048 uS (group C3: High salinity water)
Sodium Adsorption Ratio (SAR) : 2.90

Location : **Winds Hedges Project Well**
Watertype : Na-Ca-Cl
Sum of Anions (meq/l) : 12.33
Sum of Cations (meq/l) : 12.56
Balance: : 0.9%
Total dissolved solids : 24.9 meq/l 771.5 mg/l
Total hardness : 3.29 mmol/l 32.90 °f 18.42 °g
Alkalinity : 1.96 mmol/l 9.80 °f 5.49 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	136	< 20	< 150
Cl	256	< 20	< 200
SO4	104.2	10- 50	< 200
NO3	35.3	< 25	< 40

Irrigation water:
Conductivity = 1205 uS (group C3: High salinity water)
Sodium Adsorption Ratio (SAR) : 3.26

Location : **Taiser Al Kholi Farm Well**
Watertype : Na-Ca-Mg-SO4-Cl

Sum of Anions (meq/l) : 48.02
Sum of Cations (meq/l) : 51.59
Balance: : 3.6%

Total dissolved solids : 99.6 meq/l 3123.5 mg/l
Total hardness : 14.22 mmol/l 142.25 °f 79.66 °g
Alcalinity : 2.14 mmol/l 10.70 °f 5.99 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	497	< 20	< 150
Mg	137.4	5- 30	< 50
Ca	343.6	40- 100	
NH4	26.468	< .05	< .5
F	3.6		< 1.5
Cl	556.8	< 20	< 200
SO4	1364.4	10- 50	< 200
NO3	61.6	< 25	< 40

Irrigation water:
Conductivity = 3510 uS (group C4: Very high salinity water)
Sodium Adsorption Ratio (SAR) : 5.73

Location : **Southern Aqaba Gas Station Well**
Watertype : Ca-Na-Cl

Sum of Anions (meq/l) : 119.89
Sum of Cations (meq/l) : 120.95
Balance: : 0.4%

Total dissolved solids : 240.8 meq/l 7005.8 mg/l
Total hardness : 33.55 mmol/l 335.52 °f 187.89 °g
Alcalinity : 1.85 mmol/l 9.25 °f 5.18 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
pH	6.68	7- 8	< 9.2
Na	1220	< 20	< 150
K	28.5	0- 10	
Mg	87.8	5- 30	< 50
Ca	1200	40- 100	
NH4	.913	< .05	< .5
F	1.5		< 1.5
Cl	3424.138	< 20	< 200
SO4	511.0565	10- 50	< 200
NO3	419	< 25	< 40

Irrigation water:
Conductivity = 7150 uS
Sodium Adsorption Ratio (SAR) : 9.16

Location : **S.O.S Village**
Watertype : Ca-Na-Cl

Sum of Anions (meq/l) : 16.78
Sum of Cations (meq/l) : 17.52
Balance: : 2.2%

Total dissolved solids : 34.3 meq/l 1002.3 mg/l

Total hardness : 5.21 mmol/l 52.11 °f 29.18 °g
Alcalinity : 1.60 mmol/l 8.00 °f 4.48 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
pH	8.04	7- 8	< 9.2
Na	160	< 20	< 150
Mg	35.7	5- 30	< 50
Ca	150	40- 100	
NH4	1.3642	< .05	< .5
F	1.5		< 1.5
Cl	461.6	< 20	< 200
SO4	59	10- 50	< 200
NO3	33.2	< 25	< 40

Irrigation water:
Conductivity = 1647 uS (group C3: High salinity water)
Sodium Adsorption Ratio (SAR) : 3.05

Location : **Northern Al Kasar Hotel Well**
Watertype : Na-Ca-Mg-SO4-Cl

Sum of Anions (meq/l) : 27.08
Sum of Cations (meq/l) : 28.11
Balance: : 1.9%

Total dissolved solids : 55.2 meq/l 1749.3 mg/l
Total hardness : 8.01 mmol/l 80.06 °f 44.83 °g
Alcalinity : 2.68 mmol/l 13.40 °f 7.50 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	271.6	< 20	< 150
Mg	69.2	5- 30	< 50
Ca	206.8	40- 100	
NH4	2.5195	< .05	< .5
F	3		< 1.5
Cl	350.4	< 20	< 200
SO4	622	10- 50	< 200
NO3	54.8	< 25	< 40

Irrigation water:
Conductivity = 2127 uS (group C3: High salinity water)
Sodium Adsorption Ratio (SAR) : 4.18

Location : **Madi Yaseen Station**
Watertype : Na-Ca-Cl-SO4

Sum of Anions (meq/l) : 25.89
Sum of Cations (meq/l) : 26.68
Balance: : 1.5%

Total dissolved solids : 52.6 meq/l 1592.5 mg/l
Total hardness : 6.7 mmol/l 67.02 °f 37.53 °g
Alcalinity : 1.86 mmol/l 9.30 °f 5.21 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	301	< 20	< 150
Mg	59.2	5- 30	< 50
Ca	171	40- 100	
NH4	2.1428	< .05	< .5
F	2.3		< 1.5
Cl	568	< 20	< 200
SO4	346.2	10- 50	< 200
NO3	26.7	< 25	< 40

Irrigation water:
Conductivity = 1661 uS (group C3: High salinity water)
Sodium Adsorption Ratio (SAR) : 5.06

Location : **King Hussien Mosque Well**
Watertype : Ca-Na-Cl-HCO3

Sum of Anions (meq/l) : 9.10
Sum of Cations (meq/l) : 9.10
Balance: : 0.0%

Total dissolved solids : 18.2 meq/l 600.4 mg/l
Total hardness : 2.84 mmol/l 28.41 °f 15.91 °g
Alcalinity : 2.77 mmol/l 13.85 °f 7.76 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	76.4	< 20	< 150
NH4	1.2075	< .05	< .5
Cl	119	< 20	< 200
SO4	70.5	10- 50	< 200
NO3	57.3	< 25	< 40

Irrigation water:
Conductivity = 745 uS (group C2: Medium salinity water)
Sodium Adsorption Ratio (SAR) : 1.97

Location **: Jebra Dahdal Plantation Well**
Watertype : Ca-Na-Mg-Cl-SO4-HCO3

Sum of Anions (meq/l) : 16.22
Sum of Cations (meq/l) : 15.88
Balance: : 1.1%

Total dissolved solids : 32.1 meq/l 1053.7 mg/l
Total hardness : 4.85 mmol/l 48.47 °f 27.14 °g
Alcalinity : 4.10 mmol/l 20.50 °f 11.48 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	138.9	< 20	< 150
Mg	41.4	5- 30	< 50
Ca	126	40- 100	

NH4	1.1565	< .05	< .5
F	2.4		< 1.5
Cl	233	< 20	< 200
SO4	244	10- 50	< 200

Irrigation water:
Conductivity = 1085 uS (group C3: High salinity water)
Sodium Adsorption Ratio (SAR) : 2.74

Location : **Islamic Hospital Well**
Watertype : Na-Ca-Cl-SO4

Sum of Anions (meq/l) : 32.06
Sum of Cations (meq/l) : 33.79
Balance: : 2.6%

Total dissolved solids : 65.8 meq/l 2047.1 mg/l
Total hardness : 7.82 mmol/l 78.22 °f 43.80 °g
Alcalinity : 2.16 mmol/l 10.80 °f 6.05 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	411.4	< 20	< 150
Mg	71.4	5- 30	< 50
Ca	195.8	40- 100	
NH4	3.441	< .05	< .5
F	2.1		< 1.5
Cl	548.4	< 20	< 200
SO4	649.2	10- 50	< 200
NO3	31.2	< 25	< 40

Irrigation water:
Conductivity = 2225 uS (group C3: High salinity water)
Sodium Adsorption Ratio (SAR) : 6.40

Location : **Horse club2**
Watertype : Na-Ca-Mg-Cl

Sum of Anions (meq/l) : 15.66
Sum of Cations (meq/l) : 15.67
Balance: : 0.0%

Total dissolved solids : 31.3 meq/l 906.3 mg/l
Total hardness : 4.01 mmol/l 40.07 °f 22.44 °g
Alcalinity : 1.13 mmol/l 5.65 °f 3.16 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	169	< 20	< 150
Mg	41.6	5- 30	< 50
NH4	2.9862	< .05	< .5
Cl	470.8	< 20	< 200

Irrigation water:
Conductivity = 1636 uS (group C3: High salinity water)

Sodium Adsorption Ratio (SAR) : 3.67

Location : **Hafira Well 1**
Watertype : Na-Ca-HCO3-SO4-NO3

Sum of Anions (meq/l) : 13.18
Sum of Cations (meq/l) : 12.71
Balance: : 1.8%

Total dissolved solids : 25.9 meq/l 907.1 mg/l
Total hardness : 2.76 mmol/l 27.61 °f 15.46 °g
Alcalinity : 4.96 mmol/l 24.80 °f 13.89 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	159	< 20	< 150
K	10.5	0- 10	
F	1.8		< 1.5
Cl	89.4	< 20	< 200
SO4	141	10- 50	< 200
NO3	104	< 25	< 40

Irrigation water:
Conductivity = 990 uS (group C3: High salinity water)
Sodium Adsorption Ratio (SAR) : 4.16

Location : **Fertilizers Company Well**
Watertype : Na-Ca-Cl

Sum of Anions (meq/l) : 240.52
Sum of Cations (meq/l) : 237.79
Balance: : 0.6%

Total dissolved solids : 478.3 meq/l 13818.6 mg/l
Total hardness : 48.65 mmol/l 486.50 °f 272.44 °g
Alcalinity : 0.40 mmol/l 2.00 °f 1.12 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
pH	6.36	7- 8	< 9.2
Na	3192	< 20	< 150
K	62.8	0- 10	
Mg	98.2	5- 30	< 50
Ca	1788	40- 100	
NH4	.7315	< .05	< .5
Cl	7920	< 20	< 200
SO4	428	10- 50	< 200
NO3	304	< 25	< 40

Irrigation water:
Conductivity = 21080 uS
Sodium Adsorption Ratio (SAR) : 19.91

Location : **Arabian Palm Project N.Well**
Watertype : Na-Ca-Cl

Sum of Anions (meq/l) : 34.28
Sum of Cations (meq/l) : 33.26
Balance: : 1.5%

Total dissolved solids : 67.5 meq/l 1996.5 mg/l
Total hardness : 9.22 mmol/l 92.23 °f 51.65 °g
Alcalinity : 1.79 mmol/l 8.93 °f 5.00 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	338	< 20	< 150
Mg	65.9	5- 30	< 50
Ca	261	40- 100	
NH4	.3593	< .05	< .5
F	1.5		< 1.5
Cl	932	< 20	< 200
SO4	246.6	10- 50	< 200
NO3	38.6	< 25	< 40

Irrigation water:
Conductivity = 2258 uS (group C4: Very high salinity water)
Sodium Adsorption Ratio (SAR) : 4.84

Location : **Al Mahdud Children School Well**
Watertype : Na-Ca-Cl-SO4

Sum of Anions (meq/l) : 29.09
Sum of Cations (meq/l) : 29.78
Balance: : 1.2%

Total dissolved solids : 58.9 meq/l 1836.1 mg/l
Total hardness : 6.17 mmol/l 61.69 °f 34.55 °g
Alcalinity : 3.18 mmol/l 15.90 °f 8.90 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	396.2	< 20	< 150
Mg	48.2	5- 30	< 50
Ca	167.8	40- 100	
NH4	2.687	< .05	< .5
F	1.8		< 1.5
Cl	542.4	< 20	< 200
SO4	375.6	10- 50	< 200
NO3	105.2	< 25	< 40

Irrigation water:
Conductivity = 2592 uS (group C4: Very high salinity water)
Sodium Adsorption Ratio (SAR) : 6.94

Location : **Al Hussien Bin Ali Mosque Well**
Watertype : Ca-Na-Cl

Sum of Anions (meq/l) : 27.59
Sum of Cations (meq/l) : 27.30
Balance: : 0.5%

Total dissolved solids : 54.9 meq/l 1640.8 mg/l
Total hardness : 8.95 mmol/l 89.50 °f 50.12 °g
Alcalinity : 2.22 mmol/l 11.10 °f 6.22 °g
(1 °f = 10 mg/l CaCO3/ 1 °g = 10 mg/l CaO)

Drinking Water Quality Regulations:

Element		Recommended	Maximum
Na	211	< 20	< 150
Mg	42.4	5- 30	< 50
Ca	288.8	40- 100	
F	2.3		< 1.5
Cl	696	< 20	< 200
SO4	195.6	10- 50	< 200
NO3	60.4	< 25	< 40

Irrigation water:
Conductivity = 2193 uS (group C3: High salinity water)
Sodium Adsorption Ratio (SAR) : 3.07

Appendix B:

Rock-Water Interactions Thermodynamic and geo-chemistry of the Groundwater In the Study Area

Tap water sample (piped Disi water):

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	4.746	2.879	0.319	0.194
Ca/SO4	1.284	3.078	0.152	0.364
Na/Cl	0.664	1.025	0.556	0.858

Dissolved Minerals:	mg/l	mmol/l
Halite (NaCl) :	1.534	0.0262
Carbonate (CaCo3) :	26.03	0.2603
Dolomite (CaMg(CO3)2):	50.739	0.276
Anhydrite (CaSO4) :	35.108	0.258
SiO2 as Quartz :	10.581	0.176
or Feldspar (NaAlSi3O8):	46.202	0.176

Wadi Al Yutum Well:

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	3.617	2.194	0.319	0.194
Ca/SO4	0.958	2.297	0.152	0.364
Na/Cl	0.543	0.837	0.556	0.858

Dissolved Minerals:	mg/l	mmol/l
Halite (NaCl) :	290.083	4.9587
Carbonate (CaCo3) :	21.81	0.2181
Dolomite (CaMg(CO3)2):	168.121	0.913
Anhydrite (CaSO4) :	118.822	0.872
SiO2 as Quartz :	17.01	0.283
or Feldspar (NaAlSi3O8):	74.277	0.284

Winds Hedges Project Well:

Ratios			Seawater mg/l	mmol/l
Ca/Mg	3.962	2.403	0.319	0.194
Ca/SO4	0.893	2.141	0.152	0.364
Na/Cl	0.531	0.819	0.556	0.858

Dissolved Minerals:	mg/l	mmol/l
Halite (NaCl) :	346.064	5.9156
Carbonate (CaCo3) :	27.166	0.2717
Dolomite (CaMg(CO3)2):	177.966	0.967
Anhydrite (CaSO4) :	147.748	1.085
SiO2 as Quartz :	20.081	0.334
or Feldspar (NaAlSi3O8):	87.686	0.335

Taiser Al Kholi Farm Well:

Ratios			Seawater mg/l	mmol/l
Ca/Mg	2.501	1.517	0.319	0.194
Ca/SO4	0.252	0.604	0.152	0.364
Na/Cl	0.893	1.376	0.556	0.858

Dissolved Minerals:	mg/l	mmol/l
Halite (NaCl) :	25.915	0.443
Anhydrite (CaSO4) :	1934.614	14.204
SiO2 as Quartz :	27.408	0.456
or Feldspar (NaAlSi3O8):	119.684	0.457

Southern Aqaba Gas Station Well:

Ratios			Seawater mg/l	mmol/l
Ca/Mg	13.667	8.29	0.319	0.194
Ca/SO4	2.348	5.627	0.152	0.364
Na/Cl	0.356	0.549	0.556	0.858

Dissolved Minerals:	mg/l	mmol/l
Halite (NaCl) :	3104.393	53.0666
Carbonate (CaCo3) :	2102.904	21.029
Dolomite (CaMg(CO3)2):	664.911	3.612
Anhydrite (CaSO4) :	724.639	5.32
SiO2 as Quartz :	21.832	0.363
or Feldspar (NaAlSi3O8):	95.333	0.364

S.O.S Village:

Ratios			Seawater mg/l	mmol/l
Ca/Mg	4.202	2.548	0.319	0.194
Ca/SO4	2.542	6.093	0.152	0.364
Na/Cl	0.347	0.535	0.556	0.858

Dissolved Minerals:	mg/l	mmol/l
Halite (NaCl) :	407.134	6.9595
Carbonate (CaCo3) :	166.142	1.6614
Dolomite (CaMg(CO3)2):	270.357	1.469
Anhydrite (CaSO4) :	83.657	0.614
SiO2 as Quartz :	22.187	0.369
or Feldspar (NaAlSi3O8):	96.884	0.37

Northern Al Kasar Hotel Well:

Ratios			Seawater mg/l	mmol/l
Ca/Mg	2.988	1.813	0.319	0.194
Ca/SO4	0.332	0.797	0.152	0.364
Na/Cl	0.775	1.195	0.556	0.858

Dissolved Minerals:	mg/l	mmol/l
Halite (NaCl) :	16.308	0.2788
Anhydrite (CaSO4) :	881.948	6.475

SiO2 as Quartz : 27.879 0.464
or Feldspar (NaAlSi3O8): 121.737 0.465

Madi Yaseen Station:

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	2.889	1.752	0.319	0.194
Ca/SO4	0.494	1.184	0.152	0.364
Na/Cl	0.53	0.817	0.556	0.858

Dissolved Minerals: mg/l mmol/l
Halite (NaCl) : 765.92 13.0926
Dolomite (CaMg(CO3)2): 448.323 2.435
Anhydrite (CaSO4) : 490.885 3.604
SiO2 as Quartz : 25.589 0.426
or Feldspar (NaAlSi3O8): 111.739 0.426

King Hussien Mosque Well:

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	6.785	4.115	0.319	0.194
Ca/SO4	1.299	3.114	0.152	0.364
Na/Cl	0.642	0.99	0.556	0.858

Dissolved Minerals: mg/l mmol/l
Halite (NaCl) : 194.406 3.3232
Carbonate (CaCo3) : 99.715 0.9972
Dolomite (CaMg(CO3)2): 102.236 0.555
Anhydrite (CaSO4) : 99.964 0.734
SiO2 as Quartz : 12.632 0.21
or Feldspar (NaAlSi3O8): 55.159 0.211

Jebra Dahdal Plantation Well:

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	3.043	1.846	0.319	0.194
Ca/SO4	0.516	1.238	0.152	0.364
Na/Cl	0.596	0.919	0.556	0.858

Dissolved Minerals: mg/l mmol/l
Halite (NaCl) : 353.443 6.0418
Dolomite (CaMg(CO3)2): 313.523 1.703
Anhydrite (CaSO4) : 345.973 2.54
SiO2 as Quartz : 25.497 0.424
or Feldspar (NaAlSi3O8): 111.339 0.425

Islamic Hospital Well:

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	2.742	1.663	0.319	0.194
Ca/SO4	0.302	0.723	0.152	0.364
Na/Cl	0.75	1.157	0.556	0.858

Dissolved Minerals: mg/l mmol/l
Halite (NaCl) : 25.524 0.4363
Anhydrite (CaSO4) : 920.516 6.759
SiO2 as Quartz : 26.151 0.435
or Feldspar (NaAlSi3O8): 114.193 0.436

Horse club2:

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	2.212	1.341	0.319	0.194
Ca/SO4	2.12	5.08	0.152	0.364
Na/Cl	0.359	0.554	0.556	0.858

Dissolved Minerals: mg/l mmol/l

Halite (NaCl) : 430.035 7.351
Carbonate (CaCo3) : 13.249 0.1325
Dolomite (CaMg(CO3)2): 315.037 1.711
Anhydrite (CaSO4) : 61.538 0.452
SiO2 as Quartz : 1.844 0.031
or Feldspar (NaAlSi3O8): 8.053 0.031

Hafira Well 1:

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	4.399	2.668	0.319	0.194
Ca/SO4	0.571	1.368	0.152	0.364
Na/Cl	1.779	2.743	0.556	0.858

Dissolved Minerals: mg/l mmol/l
Halite (NaCl) : 4.161 0.0711
Dolomite (CaMg(CO3)2): 138.586 0.753
Anhydrite (CaSO4) : 199.927 1.468
SiO2 as Quartz : 23.518 0.391
or Feldspar (NaAlSi3O8): 102.697 0.392

Fertilizers Company Well:

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	18.208	11.044	0.319	0.194
Ca/SO4	4.178	10.012	0.152	0.364
Na/Cl	0.403	0.622	0.556	0.858

Dissolved Minerals: mg/l mmol/l
Halite (NaCl) : 8122.314 138.843
Carbonate (CaCo3) : 3615.167 36.1517
Dolomite (CaMg(CO3)2): 743.67 4.039
Anhydrite (CaSO4) : 606.871 4.456
SiO2 as Quartz : 0.984 0.016
or Feldspar (NaAlSi3O8): 4.295 0.016

Arabian Palm Project N.Well;

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	3.961	2.402	0.319	0.194
Ca/SO4	1.058	2.537	0.152	0.364
Na/Cl	0.363	0.559	0.556	0.858

Dissolved Minerals: mg/l mmol/l
Halite (NaCl) : 860.07 14.702
Carbonate (CaCo3) : 123.514 1.2351
Dolomite (CaMg(CO3)2): 499.062 2.711
Anhydrite (CaSO4) : 349.66 2.567
SiO2 as Quartz : 25.293 0.421
or Feldspar (NaAlSi3O8): 110.447 0.422

Al Mahdud Children School Well:

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	3.481	2.112	0.319	0.194
Ca/SO4	0.447	1.071	0.152	0.364
Na/Cl	0.73	1.126	0.556	0.858

Dissolved Minerals: mg/l mmol/l
Halite (NaCl) : 25.245 0.4315
Dolomite (CaMg(CO3)2): 365.019 1.983
Anhydrite (CaSO4) : 532.572 3.91
SiO2 as Quartz : 24.731 0.412
or Feldspar (NaAlSi3O8): 107.993 0.412

Al Hussien Bin Ali Mosque Well:

Ratios		Seawater	mg/l	mmol/l
Ca/Mg	6.811	4.131	0.319	0.194
Ca/SO4	1.476	3.539	0.152	0.364
Na/Cl	0.303	0.468	0.556	0.858

Dissolved Minerals:	mg/l	mmol/l
Halite (NaCl) :	536.907	9.1779
Carbonate (CaCo3) :	342.856	3.4286
Dolomite (CaMg(CO3)2):	321.096	1.744
Anhydrite (CaSO4) :	277.346	2.036
SiO2 as Quartz :	30.648	0.51
or Feldspar (NaAlSi3O8):	133.829	0.511

Appendix C:

Filed work results of the resistivity (Schlumberger Vertical Electrical Sounding Method)

Aqaba Hotel 1

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	17.000	1.000	17.000	1.000
2.000	9.500	2.000	9.500	1.000
4.000	7.000	4.000	7.000	1.000
6.000	6.850	6.000	6.850	1.000
8.000	7.000	8.000	7.000	1.000
10.000	7.500	10.000	7.500	1.000
15.000	8.500	15.000	8.500	1.000
20.000	10.700	20.000	10.700	1.000
25.000	12.200	25.000	12.200	1.000
30.000	14.000	30.000	14.000	1.000
40.000	15.000	40.000	15.000	1.000
50.000	16.100	50.000	16.100	1.000
60.000	17.000	60.000	17.000	1.000
80.000	19.000	80.000	19.000	1.000
100.000	19.500	100.000	19.500	1.000
120.000	17.500	120.000	17.500	1.000
140.000	15.500	140.000	15.500	1.000
160.000	14.000	160.000	14.000	1.000
200.000	11.500	200.000	11.500	1.000

Aqaba Hotel 2

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	4.200	1.000	4.200	1.000
2.000	3.200	2.000	3.200	1.000
4.000	4.400	4.000	4.400	1.000
6.000	5.800	6.000	5.800	1.000
8.000	6.700	8.000	6.700	1.000
10.000	7.500	10.000	7.500	1.000
15.000	9.500	15.000	9.500	1.000
20.000	11.800	20.000	11.800	1.000
25.000	14.000	25.000	14.000	1.000
30.000	15.000	30.000	15.000	1.000
40.000	17.000	40.000	17.000	1.000
50.000	17.800	50.000	17.800	1.000
60.000	18.500	60.000	18.500	1.000
80.000	19.500	80.000	19.500	1.000
100.000	16.500	100.000	16.500	1.000

120.000	14.500	120.000	14.500	1.000
140.000	12.500	140.000	12.500	1.000
160.000	10.800	160.000	10.800	1.000
200.000	8.800	200.000	8.800	1.000

Aqaba Hotel 3

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	2.400	1.000	2.400	1.000
2.000	2.500	2.000	2.500	1.000
4.000	3.500	4.000	3.500	1.000
6.000	4.900	6.000	4.900	1.000
8.000	6.500	8.000	6.500	1.000
10.000	7.500	10.000	7.500	1.000
15.000	10.200	15.000	10.200	1.000
20.000	13.000	20.000	13.000	1.000
25.000	14.500	25.000	14.500	1.000
30.000	16.000	30.000	16.000	1.000
40.000	18.000	40.000	18.000	1.000
50.000	19.500	50.000	19.500	1.000
60.000	21.000	60.000	21.000	1.000
80.000	22.000	80.000	22.000	1.000
100.000	23.000	100.000	23.000	1.000
120.000	23.000	120.000	23.000	1.000
140.000	21.000	140.000	21.000	1.000
160.000	19.000	160.000	19.000	1.000
200.000	15.000	200.000	15.000	1.000

Aqaba Hotel 4

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	7.600	1.000	7.600	1.000
2.000	8.000	2.000	8.000	1.000
4.000	5.600	4.000	5.600	1.000
6.000	5.100	6.000	5.100	1.000
8.000	4.900	8.000	4.900	1.000
10.000	5.100	10.000	5.100	1.000
15.000	6.400	15.000	6.400	1.000
20.000	7.500	20.000	7.500	1.000
25.000	8.500	25.000	8.500	1.000
30.000	9.400	30.000	9.400	1.000
40.000	11.000	40.000	11.000	1.000
50.000	11.950	50.000	11.950	1.000
60.000	12.000	60.000	12.000	1.000
80.000	11.500	80.000	11.500	1.000
100.000	10.000	100.000	10.000	1.000
120.000	8.500	120.000	8.500	1.000
140.000	7.500	140.000	7.500	1.000
160.000	6.600	160.000	6.600	1.000
200.000	5.000	200.000	5.000	1.000

Aqaba Hotel 5

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	3.200	1.000	3.200	1.000
2.000	3.000	2.000	3.000	1.000
4.000	3.000	4.000	3.000	1.000
6.000	3.600	6.000	3.600	1.000
8.000	4.200	8.000	4.200	1.000
10.000	4.000	10.000	4.000	1.000
15.000	3.500	15.000	3.500	1.000
20.000	2.850	20.000	2.850	1.000
25.000	2.450	25.000	2.450	1.000
30.000	2.550	30.000	2.550	1.000

40.000	3.200	40.000	3.200	1.000
50.000	3.800	50.000	3.800	1.000
60.000	4.000	60.000	4.000	1.000
80.000	4.600	80.000	4.600	1.000
100.000	4.600	100.000	4.600	1.000

Al Nakheel Plantation Project

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	68.000	1.000	68.000	1.000
2.000	70.000	2.000	70.000	1.000
4.000	80.000	4.000	80.000	1.000
6.000	49.000	6.000	49.000	1.000
8.000	49.000	8.000	49.000	1.000
10.000	42.000	10.000	42.000	1.000
15.000	28.000	15.000	28.000	1.000
20.000	25.000	20.000	25.000	1.000
25.000	22.000	25.000	22.000	1.000
30.000	21.200	30.000	21.200	1.000
40.000	17.500	40.000	17.500	1.000
50.000	17.000	50.000	17.000	1.000
60.000	16.000	60.000	16.000	1.000
70.000	15.900	70.000	15.900	1.000

Above the Aqaba Main Police Station

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	97.500	1.000	97.500	1.000
2.000	110.000	2.000	110.000	1.000
4.000	140.000	4.000	140.000	1.000
6.000	175.000	6.000	175.000	1.000
8.000	194.000	8.000	194.000	1.000
10.000	180.000	10.000	180.000	1.000
15.000	110.000	15.000	110.000	1.000
20.000	80.000	20.000	80.000	1.000
25.000	70.000	25.000	70.000	1.000
30.000	56.000	30.000	56.000	1.000
40.000	38.000	40.000	38.000	1.000
50.000	28.000	50.000	28.000	1.000
60.000	20.000	60.000	20.000	1.000
80.000	17.000	80.000	17.000	1.000
100.000	27.000	100.000	27.000	1.000
120.000	37.000	120.000	37.000	1.000
140.000	35.000	140.000	35.000	1.000
160.000	36.000	160.000	36.000	1.000
200.000	44.000	200.000	44.000	1.000

Winds Hedge Project (along the airport high-way)

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	800.000	1.000	800.000	1.000
2.000	500.000	2.000	500.000	1.000
4.000	328.000	4.000	328.000	1.000
6.000	270.000	6.000	270.000	1.000
8.000	250.000	8.000	250.000	1.000
10.000	246.000	10.000	246.000	1.000
15.000	255.000	15.000	255.000	1.000
20.000	285.000	20.000	285.000	1.000
25.000	323.000	25.000	323.000	1.000
30.000	350.000	30.000	350.000	1.000
40.000	350.000	40.000	350.000	1.000
50.000	320.000	50.000	320.000	1.000
60.000	300.000	60.000	300.000	1.000
80.000	260.000	80.000	260.000	1.000

100.000	235.000	100.000	235.000	1.000
120.000	210.000	120.000	210.000	1.000
140.000	195.000	140.000	195.000	1.000
160.000	185.000	160.000	185.000	1.000
200.000	120.000	200.000	120.000	1.000
250.000	91.000	250.000	91.000	1.000
300.000	80.000	300.000	80.000	1.000

Wadi Al Yutum Mouth

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	3110.000	1.000	3110.000	1.000
2.000	320.000	2.000	320.000	1.000
4.000	495.000	4.000	495.000	1.000
6.000	520.000	6.000	520.000	1.000
8.000	510.000	8.000	510.000	1.000
10.000	475.000	10.000	475.000	1.000
15.000	375.000	15.000	375.000	1.000
20.000	325.000	20.000	325.000	1.000
25.000	324.000	25.000	324.000	1.000
30.000	320.000	30.000	320.000	1.000
40.000	285.000	40.000	285.000	1.000
50.000	235.000	50.000	235.000	1.000
60.000	190.000	60.000	190.000	1.000
80.000	125.000	80.000	125.000	1.000
100.000	120.000	100.000	120.000	1.000
120.000	150.000	120.000	150.000	1.000
140.000	180.000	140.000	180.000	1.000
160.000	200.000	160.000	200.000	1.000
200.000	260.000	200.000	260.000	1.000
250.000	340.000	250.000	340.000	1.000
300.000	420.000	300.000	420.000	1.000

Aqaba Waste Water Treatment Plant (September 1998)

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	14.500	1.000	14.500	1.000
2.000	16.000	2.000	16.000	1.000
4.000	11.000	4.000	11.000	1.000
6.000	11.800	6.000	11.800	1.000
8.000	13.900	8.000	13.900	1.000
10.000	14.950	10.000	14.950	1.000
15.000	14.800	15.000	14.800	1.000
20.000	14.100	20.000	14.100	1.000
25.000	12.500	25.000	12.500	1.000
30.000	11.500	30.000	11.500	1.000
40.000	11.500	40.000	11.500	1.000
50.000	13.000	50.000	13.000	1.000
60.000	14.000	60.000	14.000	1.000
80.000	17.500	80.000	17.500	1.000
100.000	11.000	100.000	11.000	1.000
120.000	9.500	120.000	9.500	1.000
140.000	8.750	140.000	8.750	1.000
150.000	8.550	150.000	8.550	1.000

Aqaba Waste Water Treatment Plant (July/1987)

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	78.000	1.000	78.000	1.000
1.500	65.000	1.500	65.000	1.000
2.000	55.000	2.000	55.000	1.000
3.000	50.000	3.000	50.000	1.000
4.000	40.000	4.000	40.000	1.000

5.000	34.000	5.000	34.000	1.000
6.000	28.000	6.000	28.000	1.000
8.000	20.000	8.000	20.000	1.000
10.000	17.000	10.000	17.000	1.000
15.000	14.500	15.000	14.500	1.000
20.000	14.000	20.000	14.000	1.000
30.000	16.000	30.000	16.000	1.000
40.000	20.000	40.000	20.000	1.000
50.000	20.000	50.000	20.000	1.000
60.000	21.000	60.000	21.000	1.000
80.000	19.000	80.000	19.000	1.000
100.000	15.000	100.000	15.000	1.000
150.000	11.500	150.000	11.500	1.000
200.000	9.000	200.000	9.000	1.000
300.000	7.000	300.000	7.000	1.000
400.000	5.500	400.000	5.500	1.000
500.000	4.600	500.000	4.600	1.000

Aqaba Waste Water Treatment Plant (between the plant and the palm project)

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	125.000	1.000	125.000	1.000
2.000	128.000	2.000	128.000	1.000
4.000	100.000	4.000	100.000	1.000
6.000	68.000	6.000	68.000	1.000
8.000	54.000	8.000	54.000	1.000
10.000	44.000	10.000	44.000	1.000
15.000	29.000	15.000	29.000	1.000
20.000	17.000	20.000	17.000	1.000
25.000	13.500	25.000	13.500	1.000
30.000	11.800	30.000	11.800	1.000
40.000	11.700	40.000	11.700	1.000
50.000	15.000	50.000	15.000	1.000
60.000	17.000	60.000	17.000	1.000
80.000	17.000	80.000	17.000	1.000
100.000	14.500	100.000	14.500	1.000
120.000	13.000	120.000	13.000	1.000
140.000	12.000	140.000	12.000	1.000
160.000	11.500	160.000	11.500	1.000
200.000	11.000	200.000	11.000	1.000

West of Wehdat Garbia (Residential area)

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	55.000	1.000	55.000	1.000
2.000	45.000	2.000	45.000	1.000
4.000	67.000	4.000	67.000	1.000
6.000	70.000	6.000	70.000	1.000
8.000	63.000	8.000	63.000	1.000
10.000	63.000	10.000	63.000	1.000
15.000	46.000	15.000	46.000	1.000
20.000	38.000	20.000	38.000	1.000
25.000	31.000	25.000	31.000	1.000
30.000	27.000	30.000	27.000	1.000
40.000	25.600	40.000	25.600	1.000
50.000	23.000	50.000	23.000	1.000
60.000	24.000	60.000	24.000	1.000
80.000	19.000	80.000	19.000	1.000
100.000	19.500	100.000	19.500	1.000

Along the southern coasts1

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances

1.000	1500.000	1.000	1500.000	1.000
2.000	400.000	2.000	400.000	1.000
4.000	230.000	4.000	230.000	1.000
6.000	210.000	6.000	210.000	1.000
8.000	180.000	8.000	180.000	1.000
10.000	170.000	10.000	170.000	1.000
15.000	118.000	15.000	118.000	1.000
20.000	68.000	20.000	68.000	1.000
25.000	24.000	25.000	24.000	1.000
30.000	8.000	30.000	8.000	1.000
40.000	2.150	40.000	2.150	1.000
50.000	1.750	50.000	1.750	1.000
60.000	1.600	60.000	1.600	1.000
80.000	1.500	80.000	1.500	1.000
100.000	1.300	100.000	1.300	1.000
120.000	1.250	120.000	1.250	1.000
140.000	1.130	140.000	1.130	1.000
160.000	1.000	160.000	1.000	1.000
200.000	1.100	200.000	1.100	1.000
250.000	1.200	250.000	1.200	1.000

Along the southern coasts2

Raw Dist	Raw Res.	Smoothed dist	Smoothed Res.	variances
1.000	1500.000	1.000	1500.000	1.000
2.000	400.000	2.000	400.000	1.000
4.000	250.000	4.000	250.000	1.000
6.000	200.000	6.000	200.000	1.000
8.000	175.000	8.000	175.000	1.000
10.000	155.000	10.000	155.000	1.000
15.000	44.000	15.000	44.000	1.000
20.000	34.000	20.000	34.000	1.000
25.000	28.000	25.000	28.000	1.000
30.000	24.500	30.000	24.500	1.000
40.000	23.000	40.000	23.000	1.000
50.000	20.000	50.000	20.000	1.000
60.000	18.000	60.000	18.000	1.000
80.000	14.500	80.000	14.500	1.000
100.000	11.500	100.000	11.500	1.000
120.000	9.240	120.000	9.240	1.000
140.000	5.000	140.000	5.000	1.000
160.000	3.000	160.000	3.000	1.000