UNIVERSITY OF KHARTOUM
INSTITUTE OF ENVIRONMENTAL STUDIES

MODELLING AND HYDROCHEMICAL
ASSESSMENT OF THE GROUNDWATER
IN THE GEZIRA AREA -SUDAN

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The main purpose of the current research was to study the chemical quality of the groundwater in the Gezira area to achieve better management of its water resources. The study was carried out by utilizing the data obtained from recent and historical analyses of more than 1300 of groundwater samples collected from various wells, which were selected to cover the whole area of study. The analyzed data was filtered using the imbalance ratio equation to determine the error in the chemical analysis of each sample. Only a 5% error was considered acceptable. The analyzed data was classified into two distinct classes pertaining to the Nubian and Gezira aquifers.

The area of study, which is greater than 26000 km², encompasses the two Niles and is approximately bounded by latitudes 13°-15.6° North and longitudes 32°-34.5° East.

Using GIS techniques, estimation models for the chemical constituents of the Gezira groundwater have been conveniently devised. The developed models can be used as primary predictors for estimating the expected values of the chemical constituents of the groundwater pertaining to new locations in the map. The GIS tools were utilized efficiently and a comprehensive map of the Gezira
groundwater was produced. The map is composed of all the collected data and the established models of the chemical parameters (Integrated model). The developed integrated map was extended to include also the mapping of groundwater clusters, ionic ratios and saturation indices.

The essential chemical parameters of the groundwater were analyzed using conventional statistical methods. The values of the mean concentrations of the total dissolved solids, Sodium, Sulphate, Silica and Chloride ions were higher in the groundwater of the Gezira formation than in the Nubian aquifer. The groundwater of both the Nubian and Gezira aquifers was found to be slightly or moderately alkaline and most of the analyzed chemical parameters were found to lie within the permissible ranges stated by the WHO and Sudanese standards except in the Gezira aquifer where very confined areas were noted to have high levels of salinity.

The sources of salinity in the Gezira area were found to be related to the high concentrations of the ions of Ca, Mg, Na, HCO₃, and Cl in the Gezira aquifer and Na, HCO₃, Mg, SO₄ and Cl in the Nubian aquifer.

The classification of the Gezira area groundwater was carried out using cluster analysis and the Piper, Durouv and Schoeller diagrams. The main water type and the dominant anion in both the Nubian and
Gezira aquifers were found to be (Na-Ca-HCO₃) and HCO₃, respectively.

Factor analysis was employed to study the factors that control the mineralization of the groundwater. The factors for the Gezira aquifer were: (SO₄, CaCO₃, TDS, Cl, and EC), (alkalinity HCO₃), and (Ca, Na, and Mg). The factors for the Nubian aquifer were: (EC, TDS, CaCO₃, and SO₄), (alkalinity), and (Mg and Ca).

Composition diagrams and ionic ratios were used to examine the cation exchange processes, and the hydrogeochemical processes that occur in the groundwater. The dissolution of sulphide minerals, halite and magnesium carbonate minerals has been noted to take place in the Gezira aquifer. The oxidation of sulphide minerals and dissolution of carbonate and dolomite have been identified in the Nubian aquifer. High values of bicarbonate, calcium, and magnesium were obtained close to the Blue Nile and high values of bicarbonate, sodium and potassium were also obtained close to the White Nile, indicating the contribution of the two rivers to the recharge of the groundwater in the Gezira area.

The evaporation process in the Gezira and Nubian aquifers is minor as indicated by the low correlation between Na and Cl and as shown from their composition diagrams. The negative ion exchange, where
Ca and Mg are replaced by Na in the water is the dominant process in both aquifers.

The groundwater in both aquifers has been found undersaturated in terms of anhydrite, CO$_2$, and Gypsum, and oversaturated in terms of Aragonite, Calcite and Dolomite.

It is worth mentioning here that the hydrochemical analysis of the groundwater in the Gezira area has yielded similar facies for both the Nubian and Gezira aquifers. This is an indication of interconnection of the two aquifers.
خلاصة البحث

الهدف الأساسي لهذا البحث هو دراسة النوعية الكيميائية للمياه الجوفية في منطقة الجزيرة من أجل تحسين إدارة مواردها المائية. وقد أجريت هذه الدراسة باستخدام بيانات قديمة، وأخرى حديثة، من التحليل الكيميائي لأكثر من 1300 من العينات، التي جمعت من أبار مختلفة، والتي تم اختيارها على أساس تمثيلها لكل المنطقة. وقد تم تصفية البيانات الم محللة باستخدام معادلة نسبة الخطأ، وذلك لإيجاد الخطأ في التحليل الكيميائي لكل عينة. واعتمدت نسبة 5% كخطأ مقبول.

منطقة الدراسة تحتوي على النيلين الأزرق والأبيض، وتقع بين خطى عرض ٢٢° ٣٠ عمومًا وخطي طول ٣٠° ٥ً٨ عمومًا، ومساحتها أكثر من ١٦٦٣ كم².

وباستخدام نظام المعلومات الجغرافية GIS، تم إنشاء نماذج لتقييم الوضعية الكيميائية للمياه الجوفية بالجزيرة. هذه النماذج يمكن استخدامها للتقييم الأولي للقيم المتوقعة للمعامل الكيميائية للمياه الجوفية في المواقع الجديدة بالخريطة. وقد تم استخدام معدات نظام المعلومات الجغرافية لكشف نماذج متكامل، يشمل كل البيانات التي جمعت، وكل النماذج التي أنشئت للمعالي الكيميائية الأساسية للمياه الجوفية في الجزيرة. وقد أعد النموذج المتكامل لتشمل تحليل الممتلكات والنسب الأيونية ومعاملات التشبع للمياه الجوفية.

 تم استخدام الطرق الإحصائية التقليدية لتحليل المعالم الكيميائية الأساسية للمياه الجوفية. وكانت قيم متوسطات تركز أيونات الأملاح ذاتية والصوديوم والبرونتات والكلورايد في المياه الجوفية لجزيرة الجزيرة أعلى من تلك التي بخزان المياه الجوفية للحجر النوبي. ولقد أظهر التحليل الإحصائي قلوبية بسيطة ومتوسطة للمياه الجوفية في منطقة الجزيرة للخزانين. كما أثبت التحليل أن المواد الكيميائية للمياه الجوفية في كلا الخزانين مطابقة
لمعايير ومواصفات هيئة الصحة العالمية، وهيئة المقايس والممارسات السودانية، ما عدا

في مناطق ضيقة في خزان الجزيرة الجوفي، حيث توجد بها ملوحة عالية.

أما مصادر الملوحة في منطقة الجزيرة فقد وجد أن لها علاقة بالتركيز العلامة لأيونات الكالسيوم والصوديوم والبKERبونات والكلوريد في خزان الجزيرة، والصوديوم والبKERبونات والماغنيزيوم والكبريتات في خزان الحجر النوبي.

وقياس استخدام التحليل الطبي الإحصائي، والرسومات التشريحيه لباير ودروف وشولر،

إتضح أن النوعية الأساسية للمياه الجوفية في كلا الخزانين في الجزيرة هي: صوديوم-
كالسيوم- بKERبونات. وقد وجد أن الأنيون الأساسي هو البKERبونات.

ولقد استعمل أيضا التحليل العاملي لدراسة العوامل التي تتحككم في معدنية المياه الجوفية.

على العوامل في خزان الجزيرة هي: (الكبريتات والKERبونات والأملاح الذائبة والوصيلة الكهربائية)، (المغناة والبKERبونات)، (الكالسيوم والصوديوم والماغنيزيوم). والعوامل في خزان الحجر النوبي هي: (الوصيلة الكهربائية والأملاح الذائبة والKERبونات والكبريتات)، (المغناة)، (الماغنيزيوم والكالسيوم).

كما تم استخدام رسومات المكونات الكيماوية، والنسب الأيونية لدراسة عمليات التبادل الأيوني، والعمليات الهيدروجيوكيميائية التي تحدث في المياه الجوفية. وقد وجد أن العمليات الهيدروجيوكيميائية التي تحدث في حووض الجزيرة هي: ذوبان معدن الكبريت وناتردن الصوديوم وKERبونات المغليزيوم، وفي الحووض النوبي هي: أكسدة معدن الكبريتية وذوبان معدن الكبرونية ومعден الدولومايت. وقد تم العثور على قيم عالية للبKERبونات والكالسيوم والمغليزيوم بالقرب من النيل الأزرق، وعلى قيم عالية للبKERبونات والصوديوم والبوتاسيوم بالقرب من النيل الأبيض، مما يشير إلى مشاركة النهرين في تغذية المياه الجوفية في منطقة الجزيرة. أما عملية التبخير، فقد وجدت بسيطة في كلا الحووصين الجوفيين كما يستند من ضعف معامل الربط بين الصوديوم والكلوريد، وكم هو واضح في أشكال
المكونات الكيميائية لهما. وقد وجد أن التبادل الأيوني السالب، الذي يحل فيه الصوديوم محل الكالسيوم والماغنيزيوم في الماء، هو العملية الغالبة. ووجد أن المياه الجوفية في كلا الحوضين، النوبي والجزيرة، تميز بأنها تحت المشبعة بالنسبة للأنهيدرات، ثاني أكسيد الكربون، والجبس، وأنها فوق المشبعة بالنسبة للأروجانيةت، والكالسايت، والدولومايت. ومما يجدر ذكره هنا أن التحليل الهيدروجيوكيميائي قد أعطى وجوه مشابهة في كلا الحوضين الجوفييين، مما يدل على إتصال بعضهما بالبعض.
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CHAPTER I
INTRODUCTION

1.1 General
Fresh water is vital for the existence of the human life. It is naturally available from different sources, of which the mostly utilized one is groundwater. Groundwater is considered as an unseen source of water unless it emerges from springs or tapped by wells. In the year 1992, the UNESCO stated that the survival of more than half the world’s population is dependent on groundwater as a source of fresh water (IHP, UNESCO, 2000).

Groundwater is considered as an important part of the earth’s water cycle. This cycle is initiated by solar energy and characterized by the never-ending movement of water from ocean to atmosphere and back to the ocean. Groundwater is recharged by precipitation of rain water which infiltrates downwards by gravity or by horizontal movement of water from sea or rivers.

1.1.1 Groundwater in Sudan
Groundwater is extensively utilized in Sudan for domestic, agricultural and industrial purposes. It derives its importance
mainly from the mere fact that over 50% of the country lies within the desert or semi-arid zones where rainfall and run-off are scarce. Deep boreholes and shallow wells are generally preferred to the other sources of water in Sudan due to their attractive economic, technical and environmental characteristics. Thus, for example, more than a thousand and a half wells have been drilled in the Gezira area irrespective of their presence near or far away from the two Niles, so as to maintain sustainable water supplies especially for areas remote from the present distribution network. The annual withdrawal of groundwater in the Gezira Province is 120 million cubic meters but the total groundwater storage is large (20 milliard cubic meters) (Ahmed 2003). The annual withdrawal of water in Butana and Um El Gura is 14 million cubic meters (Ali, 2004). In Kamlin and Hasahisa Provinces the annual withdrawal is estimated to be 33 million cubic meters, which is equal to 7% of the aquifer storage (Gar El Nabi, 2004). The annual withdrawal in Managil Province is estimated to be about 4.3 millions cubic meters (Abdel Rahman, 2003).

**1.1.2 Groundwater Quality**

The value of groundwater lies not only in its widespread occurrence and availability but also in the good quality of its
constituents. The term quality as specified for groundwater refers to the physical, chemical and biological characteristics of water. These characteristics are produced as a result of the reaction between the water, originally, precipitated from the atmosphere and the soil or rocks that water passes through.

There are major dissolved constituents which form the bulk of the chemical composition of groundwater. The most common of these are Sodium, Calcium and Magnesium. These constituents combine chemically with Chlorides, Bicarbonates and Sulphates to form the majority of the salt minerals normally found in groundwater. Most of these dissolved minerals are rarely harmful to health and some of them are even necessary for good health. However, high concentrations of other dissolved minerals in groundwater may generate toxic effects. The perception of the fact that some of these mineral concentrations are unacceptable has led to the development of drinking water standards (Appendix A). These standards are employed to assess the chemical analyses of water.

In Sudan, groundwater quality is generally good except for a few localities. Certain aquifers in residential areas especially with shallower groundwater levels are susceptible to pollution and contamination especially the alluvium aquifers, (IHP of the

1.1.3 Groundwater Information

It is now well recognized that abstraction of groundwater does not involve only the drilling process but also the documentation of all relevant data. This information has been found necessary for planning, management and protection of groundwater resources. The essential data usually recorded involves geophysical surveys, drilling and testing programs and water quality surveys. The basic groundwater information in Sudan can be found in the national and regional archives or can be filtered out from the numerous published and unpublished reports and maps. The old system for data storage used the method of file archives, while currently all assembled data has been transferred to computerized systems. However, deficiencies in the registered data have been realized and continued endeavors are being made to build a comprehensive data bank for groundwater in Sudan.

1.2 Geographic Information Systems (GIS)

Although the well known spreadsheet and data base techniques have helped greatly in the recording, retrieval and analysis of
groundwater data, yet there is a growing trend in the country to make use of the powerful tools of the geographic information systems (GIS) as the nature of the data, itself, is related to locations on the land.

The GIS is an interface between user and machine. The term ‘Geographic’ stands for data referenced in space while ‘Information’ can be considered as data with added attributes. The four functions of GIS are: data acquisition and pre-processing, data management, storage and retrieval, manipulation and analysis and product generation. This research is concerned with employing relevant GIS techniques to establish a graphical interface for the chemical composition of groundwater in the Gezira area from the available recorded data. Also ArcMap of the GIS is used to create models of the chemical constituents of groundwater in the area.

1.3 Groundwater Hydrogeochemical Processes

In groundwater several solutes react with each other where the solubility of each mineral depends on the nature and concentrations of the dissolved constituents. As a result of these reactions, some minerals precipitate and others are dissolved in the water. These different reactions that occur in groundwater are known as the
hydrogeochemical processes. Through these processes the water acquires its chemical composition. The major processes occurring in normal fresh groundwater are dissolution, adsorption and ion exchange (Groundwater Geochemistry, Nanaimo Group aquifers, Post 2004, Internet), and (S. Mandel, and Z.L. Shifftan, 1981).

The interpretation of the hydrogeochemical processes that occur in the Gezira groundwater aquifers can be achieved by using multivariate analysis, graphical representations and ionic ratios between the major cations and the major anions as will be described in chapters 6 and 7.

1.4 Objectives

Due to the expansion of urbanization and agricultural activities in the Gezira area, well-documented information on the quality of its groundwater is becoming of major concern. Also the establishment of models for the prediction of the quality of the groundwater is likewise becoming very important to assist in the decision process whenever the drilling of a new well is undertaken. Therefore, this study is meant to place particular emphasis on the hydrogeochemical interpretation, and the documentation and modeling of the quality of the groundwater in the Gezira area. The
chemical quality of groundwater in the Gezira area is mainly presumed to be modified and controlled by:

1. The lithology and the mineral composition of the aquifers.
2. The recharge from the Blue and White Niles.
3. The evapotranspiration and evaporative processes.
4. The infiltration and recharge from the irrigation canals.

To carry out the study of the chemical quality of the groundwater in the Gezira area and to investigate the above mentioned main hypotheses, the following objectives have been pursued:

1. Acquisition and classification of the existing chemical data of the Gezira groundwater from the available current and historical records.
2. Production of informative maps for the Gezira groundwater regarding the spatial distribution of the most basic chemical constituents, clusters and essential ionic ratios using GIS techniques.
3. Development of GIS contour models for the prediction of chemical values for the groundwater in the Gezira area.
4. Utilization of the established GIS models for the assessment of groundwater quality in the study area.
5. The study of the evolution of the groundwater in the Gezira area.


1.5 Methodology

The chemical data gathered for modeling the Gezira groundwater were organized using Microsoft Excel and Database techniques. Also the inverse distance weighted (IDW) modeling method of the GIS was used to classify the data with regard to the main aquifers of the study area.

The recent chemical data samples of the Gezira groundwater used for comparison with the model results were collected and analyzed in the laboratories of the Ministry of Physical Planning and Public Works (Gezira State Water Corporation). All the analyses were performed by a Palintest Photometer 7000.

The statistical package SPSS 13.0 was utilized to determine the frequency distribution (histogram) of each individual parameter of the chemical data and its corresponding statistics regarding central
tendency, dispersion, distribution and correlations. Also the package was used to determine regression expressions for the individual chemical parameters.

Multivariate statistics of the SPSS package was used to classify the Gezira data into clusters and determine the factors controlling the chemical quality.

The Piper, Durouv and Schoeller diagrams of the AquaChem software version 3.7.0.42 (1997) were used to produce graphs to help in the assessment of the Gezira groundwater.

The methods employed in the chemical analysis of the Gezira data will be described in Chapter three.

The equilibrium between the mineral species and water is determined from the saturation indices calculated using the PHREEQC for windows Program.

GIS techniques were employed for the classification, mapping and modeling of the chemical data of the groundwater of the Gezira area as will be described in Chapter four and five.
1.6 Area of Study

1.6.1 Location

The area of study contains the two Niles and is approximately bordered by latitudes $13^\circ$-$15.6^\circ$ North and longitudes $32^\circ$-$34.5^\circ$ East, Figure (1.1).

The Gezira area is chosen to be the area of study where the large and major agricultural scheme in Sudan is located. The Gezira area is located in the central clay plains of the Sudan. It forms a triangle bounded by The White Nile in the west and The Blue Nile in the east. The south of the Gezira area is bounded by the railway line joining Sennar and Kosti (Whiteman, 1971).

The Gezira State is divided into six provinces, namely Kamlin and Hasahisa Provinces at the north, Managil Province at the west, Butana and Um El Gura Provinces at the east and the Gezira Province at the south.

1.6.2 The Gezira Scheme

The Gezira Scheme is the largest Irrigated Farm in Africa with a total area of 2.1 million feddans (a feddan =1.038 acre) under one management (Agro-Ecological Zonation of The Gezira Scheme, 2002). The scheme is fed principally by gravity irrigation from
Sennar dam and simultaneously with Roseires dam. The Gezira is the most important Scheme for the economy of the Sudan (National council for Research, 1975). About 30% of the world's long-stable cotton comes from the Sudan, and over 75% of it is grown on irrigated clay soils are in the Gezira. The Gezira Scheme was originally developed to grow cotton for export, with some other crops, such as sorghum and lubia, to satisfy tenants' needs. When more irrigation water became available after the construction of Roseires Dam, the cropping system in the Gezira was diversified and intensified through the introduction of groundnuts and wheat (Agro-Ecological Zonation of The Gezira Scheme, 2002). Limited areas of vegetables and of fruit gardens were established where permanent irrigation is available (Ibid).

1.6.3 Economic and Social Activities

The population of the Gezira State is about 3.2 million inhabitants, and about one million of them lives in the Gezira Province (i.e. more than 30%), (after Ahmed, 2003), 820000 thousands (about 25.4%) in Managil Province (1993 census, after Abd El Rahman, 2003) and about 760 thousands (23.7%) in Kamlin and Hasahisa Provinces (1993 census, after Gar El Nabi, 2004) and less than 20% in Butana and Um El Gura.
The social life is greatly influenced by the presence of the University of Gezira, Ministry of Irrigation, and Agricultural Research Corporation, together with the Gezira Scheme. The State is also rich with different industries especially at Maringan, Giad Industrial area, El Geined Sugar Project, and also with different factories at different provinces specialized mainly in textile, soap, and food. Also the Kamlin and Hasahisa provinces are rich with industrial activities. Other sources of income for the Gezira inhabitants are trading and animal production. The animal production represents an important activity especially in Butana and Um El Gura Provinces, and the main animals are cattle, sheep, goats and camels (Ali, 2004). The most famous camel market in Sudan and Arab World is Tamboul's market where camels are exported (Ibid).

1.6.4 Topography

The Gezira area is flat alluvial clay plain, 25 m thick and with a general slope from southeast to northwest. The average gradient of the area is 10 cm/ km, which makes it ideal for gravity irrigation. It ranges in elevation from 420m to 380m above sea level (Agro-Ecological Zonation of The Gezira Scheme, 2002). Sand dunes are generally scattered in the south of the area.
1.6.5 Drainage System

The main natural drains are the Blue Nile, the White Nile and the natural drainage lines (khores and rahads). The artificial drainage system consists of 1500 km of major drains and 6000 km of minor drains. In the Gezira Scheme there are no on-farm drainage facilities due to the nature of the soil and the absence of high groundwater table. The main purpose of the drainage system is to remove the surface runoff due to rain or excess irrigation (Ibid).

1.6.6 Climate

The whole Gezira Scheme lies within the Dry Zone. The annual rainfall is 150-350 mm and the rainy season is very short, from July to September. The mean annual temperature is 28°C and the relative humidity is considered low. The combination of low rainfall, high solar energy and low humidity in the area, yields a high rate of evaporation (Ibid).

1.6.7 Vegetation

The vegetation cover reflects the temperature and the magnitude of rainfall in the area which is arid savannah. At The Gezira Area the woodland and the scrub was cleared to develop The Gezira Scheme. Also the area is greatly affected by grazing of cattle,
sheep, camels and goats. The area falls broadly within the three major vegetation units outlined by Harrison & Jackson (1958), (after Williams A.J., and Adamson A.D.). The three units were determined in relation to rainfall as semi-desert scrub, semi-desert grassland on clay and Acacia mellifera thorn-land alternating with grass areas. F. Andrew (in Tothill, 1948), (after Abdel Salam, 1966), recognized two natural vegetation belts, Acacia Desert Scrub in the north and Acacia short grass in the south. The first region is characterized by scattered species of Acacia, Panicum, Aristida, "Laota" (Acacia nubica), "Sider" (Acacia tortilis), "Heglig" (Balanites aegyptica), "Sunt" (Acacia nilotica), and "Usher" (Calotropis procera). The Southern region is characterized by coarse grass, herbs and scattered "Kiter" (Acacia mellifera), "Laota" (Acacia nubica), "Sider" (Acacia tortilis) (Ibid). Gum forests are also found in Gezira Area. Blocks of forests were grown in certain areas to satisfy local markets with building materials and wood fuel.

1.6.8 Soils

The soils are of uniform pattern and are classified as vertisols that crack widely. These soils are believed to be sediments of the Blue Nile (Agro-Ecological Zonation of The Gezira Scheme, 2002).
Physiographically the area is vast clay plain almost flat and very gently sloping from south east to North West. The superficial clay mantle is underlain by sandy alluvium resting on bed rock mainly of Nubian Sandstone which is underlain by metamorphosed Basement Complex Rocks ((Ibid). Clay mineralogy revealed the dominance of 2:1 lattice clay minerals such as smectite (Hydrous aluminium Silicate). Kaolinite (Al$_2$Si$_2$O$_5$(OH)$_4$) is relatively small in amount whereas chlorite ((Mg,Fe,Al)$_6$(Si,Al)$_4$O$_{10}$(OH)$_8$, and mica (shiny silica minerals), exist as traces. The clay content has a high exchange capacity. Movement of the water in the soil is very slow. Soil moisture at depths of few meters or more has been observed to be virtually constant and there are no indications of a downward percolation of irrigation water. These soils show a tendency to water logging attended with bad aeration and yield reduction (Herve Plusquellec, 1990).

1.6.9 Geology

The Gezira area is an alluvial plain. The sediments forming the Gezira have been supplied mainly by the Blue Nile from the Ethiopian Highlands with some locally derived material. According to Worrall (1956), the heavy mineral assemblage in the Gezira clay indicates a volcanic origin and also the assemblage is similar to
that of the present day sediments of the Blue Nile. The coarse fractions are probably derived from weathering of the Nubian Sandstone and Basement Complex Formations (Abdel Salam, 1966). Taken as a whole, the surface of the Gezira is variable despite its apparent flatness and uniformity (Williams and Adamson, 1976).

The geological structure of the area is divided into three main formations, ordered from bottom to top as described below:

1.6.9.1 Basement Complex Rocks
These rocks are the oldest exposed ones in the Gezira area and occur on the western south, east and eastern north of the area. From a hydrological point of view, they bear no water or little quantities of water which may be saline. The rocks include metasediments which consists mainly of limestone (mainly CaCO₃), quartz, feldspar or albite (NaAlSi₃O₈), epidote (Ca₂(Al,Fe)₃(SiO₄)₃(OH)), and chlorite (Mg,Fe,Al)₆(Si,Al)₄O₁₀(OH)₈ (Whiteman, 1971).

1.6.9.2 Nubian Sandstone Formation
The Nubian Rocks overlay the Basement Rocks in the Gezira area. They are highly rich with water. The Nubian Sandstone Formation occupies about 28% of the surface area of the Sudan and is the main sedimentary aquifer in the Sudan. It crops out at a few
localities in the Gezira. The formation consists of conglomerates, sandstones, feldspathic sandstones, sandy mudstones, and mudstones (Abdel Salam, 1966). The cement in the Nubian formation is iron oxide, iron carbonate, calcium carbonate or silica. When the Nubian rocks are unoxidised they become pyritous (sulphur minerals) and carbonaceous in borehole. Kankar nodules are very common in the Nubian formation especially along the Blue Nile.

1.6.9.3 Gezira Formation

The Gezira formation and the superficial deposits lie above the Nubian Formations and in some places lie directly over the basement rocks. These formations are rich with water and they are of variable thickness (El Boushi and Abdel Salam, 1982). The thickness ranges up to 110 m (Williams and Adamson, 1976). Three lithological divisions can be recognized according to (Abdel Salam, 1966):

1- Upper Clay member, Gezira Clay

2- Lower Sandy Member, which consist of sand and gravel, and silt with clay lenses.

3- Mungata Member, which is a subsurface unit recognized in the southern Gezira only.
The Upper Clay Member consists mainly of clay with occasional patches of sand and pockets of quartz pebbles. Kankar nodules occur frequently in the Clay Member (Abdel Salam, 1966). Shukri, (1950), and Worrall, (1956) after Whiteman, (1971), described the mineralogy of the Gezira Clay and recorded the following minerals: calcic plagioclase (composed of sodium, calcium, and aluminium silicates), augite (pyroxene group containing aluminium, calcium, iron, and magnesium), horn-blende (sulphide ore), biotite (silicate mineral), and olivine (MgFe)2SiO4.

The Gezira Formation is replaced by Al Atshan Formation at Sennar State.

1.6.10 Hydrogeology

The main groundwater aquifers are present in the Nubian Sandstone Formation and Gezira or Al Atshan Formations. The water moves generally in the Gezira area from east to west in its western parts and moves from west to east in its eastern parts. It also moves from south to north. The water level in the Gezira State ranges from 10.7-36.6m (The Investment Map by M.A. Abdel Salam, 1998, after Ahmed, 2003). Wells depth ranges from 61-366m, and their production varies from 300-15000 gallon/hour (about 1.36-68m³), (Ibid). The transmissivity ranges from 46-4476
m²/day in the Gezira Aquifer, in Gezira Province (Ahmed, 2003). The groundwater quality is acceptable (Ibid). The transmissivity ranges from 200-2700m²/day in the Gezira Aquifer, in Kamlin and Hasahisa Provinces (Gar El Nabi, 2004). The groundwater quality of the aquifer is good according to (WHO) and local standards except of the high salinity in Abu Gota and Wagara areas (Ibid). The transmissivity of the aquifer ranges from 83-1159m²/day in the Northern Eastern parts of Managil Province, and from 73-1884 m²/day in the Eastern and Western parts (Abdel Rahman, 2003). The groundwater quality is good in the Nubian Aquifer. In the Gezira Aquifer the groundwater quality is acceptable except in the Western and Northern parts of Managil Province (Ibid). The transmissivity ranges from 32-4385 m²/day in the Nubian Aquifer in Butana and Um El Gura Provinces (Ali, 2004). Low transmissivity values were found in the Northwestern part of the aquifer along the Blue Nile (Ibid). The Nubian Aquifer in this area is characterized by good quality of water (Ibid).

1.7 Thesis layout

Chapter two contains a review of the groundwater in terms of resources, quantity, quality, hydrogeochemistry, modeling and
previous work related to the subjects of this research. The methods utilized for analyzing the chemical constituents of groundwater are outlined in chapter three. Organization and mapping of the collected data are dealt with in chapter four. Modeling for the chemical composition of the groundwater in the area of study is presented in chapter five. Univariate and multivariate statistical analyses are presented in chapter six. The determination of the quality of the Gezira groundwater is thoroughly discussed in chapter seven. The overall conclusions for this work are finally furnished in chapter eight.
2. 1 World Water Resources

Water is a renewable natural resource. On a global scale it belongs to the inexhaustible natural resources and locally it is exhaustible. In other words, there is plenty of water in the earth, but there is a water shortage in some places because fresh water is not evenly distributed over the earth surface (IHP, UNESCO, 1990).

The total world’s water supply is 1400 million km\(^3\). From this quantity, 97.5% is salt water that is stored in oceans and is of little direct use to people. The rest 2.5% is fresh water, of which seventy seven percent (77%) is frozen in glaciers and ice caps (IHP, UNESCO, 2000). Groundwater constitutes 22 % of all fresh water in the world and 98.4% of the unfrozen fresh water in the world (Montgomery, Carla, 2000).

2.2 Groundwater as a Resource

Groundwater is stored in water - bearing layers called aquifers. An aquifer is any geological formation which, in addition to storing
and absorbing water in enough amounts, has the ability of water transmission. The main sources of aquifer recharge are rainfall and surface water (Montgomery, Carla, 2000).

Most of the world's fresh water is stored underground. Vast aquifers lie under parts of the Sahara and Arabian Desert. One basic reason for the use of groundwater in many dry areas is that little or no surface water is available where there is a substantial supply of water deep under the ground surface. So groundwater constitutes the main water resource in these areas.

Groundwater can move sideways as well as up and down by differences in elevation and differences in pressure. Groundwater movement in the aquifers is very slow compared to the movement of streams or rivers (Driscoll Fletcher G., 1989). In some regions groundwater is the main source of stream flow continuity during the long dry seasons or in winter (Julio A. Barberis, 1986).

Demand for fresh water has increased due to the increase in population and to the development of industry and agriculture. Fresh water shortages and water deficit exist in about 60% of the entire world. Groundwater plays an important role in solving this problem. In countries with arid or semi-arid regions, groundwater is widely used for irrigation.
2.3 Groundwater Quantity

The amount of groundwater which constitutes about 0.62% of all the water in the world is estimated to be about 8680 thousands km$^3$. The renewable groundwater in Sudan is about 4.1 km$^3$ (Ministry of Irrigation, Sudan National Water Policy, 1999). 67% of the annual groundwater abstraction from the basins of the Sudan is extracted from the Nubian Sandstone Basins. 17% and 16% of the water extraction is from the Alluvial Basins, the Detrital Quaternary Tertiary Basins respectively (IHP, UNESCO, 2000).

In the area of study, the water production differs from one province to another. At El Gezira province, the water production is 68 m$^3$/hour. At El Hasahisa and El Kamlin, the production is between 13.6-31.8 m$^3$/hour. The production is between 1.4-13.6 m$^3$/hour at Butana and Um El Gura. At El Managil, the production is between 6.8-13.6 m$^3$/hour (The Investment map by M.A., Abdel Salam, 1998) after (Ahmed, 2003).

2.4 Groundwater Chemical Quality

2.4.1 General

Water quality is a term which expresses the suitability of water to sustain various usages. The groundwater quality is determined by
the original source of water and by the kind of earth rocks it seeps through to reach the aquifer. Groundwater in its natural state is usually of excellent quality. The earth's material acts as a natural filter. It screens out impurities from groundwater. So groundwater is generally odorless and cleaner than most of the surface water. Also it contains no suspended particles and no bacteria or organic matter. It requires lesser treatment than surface water. Generally groundwater quality is relatively uniform with respect to location and time but sometimes major contrasts in natural quality appear (IHP, UNESCO, 2000).

One of the most important characteristics of water is its greater ability to dissolve a greater range of substances than any other liquid (Driscoll Fletcher G., 1989). So minerals in the soil and bed rock are dissolved slowly till a chemical equilibrium between the groundwater and the minerals is reached, and hence the natural chemical quality of groundwater is determined.

Calcium, Magnesium, Sodium, Potassium, Bicarbonate, Carbonate, Chloride, Sulphate and Silica are the major chemical constituents in groundwater. Iron, Manganese, Strontium and Fluoride are the minor constituents (Ibid).

Water well contractors and well design engineers usually focus on
the design and construction of wells that will yield adequate supplies of water. However, it is found that in many cases the chemical nature of the groundwater and not the volume of water obtained may be the major factor determining a well’s suitability. This means that the quality of groundwater is of equal importance to its quantity. Therefore the success of many wells depends on the drilling contractor’s knowledge of the chemical changes that occur in or near a pumping well, (Driscoll Fletcher G., 1989).

2.4.2 Definitions and Standards

The concentrations of the chemical constituents in groundwater are generally small and are measured in milligrams per liter (mg/l). The expression of the chemical constituents of groundwater in specific rates determines the suitability of the water for different purposes, and this establishes a quality criteria. Thus, water used for households should smell good, taste pleasant and must be free of bacteria and stain. Water used for industry should be non-corrosive, non-staining, non-scaling and not too hard. Water used for irrigation should be low in Sodium and low in minerals especially Boron, which is toxic to plants (Ibid). It is to be noted that water quality must be expressed not only in terms of physical, biological and chemical variations, but also according to quality
standards that vary according to use. Generally, ground water is regionally uniform which makes it an ideal source for all uses.

The definitions and standards of the most important chemical parameters of groundwater are given in the following sections. The references for the permissible levels of the chemical parameters are the Sudanese, WHO and APHA standards as shown in Appendix A.

2.4.2.1 Hydrogen Ion Concentration (pH)

Although water molecules are quite stable chemically, they tend to break down or dissociate into their component parts, $\text{H}^+$ (hydrogen) ions and $\text{OH}^-$ (hydroxyl) ions (Driscoll Fletcher G., 1989). The hydrogen ion concentration in water is expressed as pH. The pH is equal to the logarithm of the inverse of the hydrogen ion concentration. A pH less than 7 indicates an acidic solution, whereas a pH greater than 7 indicates an alkaline solution. Generally a value of pH between 6.5 and 8.5 is desirable as specified by the Sudanese (2002) and the WHO standards (1993). The APHA standard for pH is in the range of 6.5-9.

2.4.2.2 Total Dissolved Solids (TDS)

Total dissolved solids are the mineral constituents dissolved in water. Their concentration in groundwater ranges from less than
25mg/l to more than 300,000mg/l in brine water (Todd, D.K., 1980). But commonly it is less than 5000mg/l.

The maximum permissible limit by the WHO and Sudanese standards is 1000mg/l, whereas the maximum permissible limit set by the American Public Health Association (APHA), is 1500mg/l.

2.4.2.3 Specific Electrical Conductivity (E.C.)

The specific electrical conductivity (E.C.) of a substance is its ability to conduct an electrical current. The unit of measurement for E.C. is mho/cm which is the inverse of ohms, the unit of resistivity (Driscoll Fletcher G., 1989).

In groundwater and other dilute solutions, the specific conductivity varies almost directly with the amount of dissolved minerals. Water that has relatively high specific conductivity can corrode iron and steel, even though other properties of the water may not indicate a corrosion problem (Ibid).

The highest permissible level according to the World Health Organization (WHO) is 1400µmho/cm.

2.4.2.4 Calcium (Ca)

Amphiboles, feldspars, gypsum, pyroxenes, aragonite, calcite, dolomite and clay minerals are the major natural sources of
calcium. Generally calcium concentration in groundwater is less than 100mg/l; brines may contain as much as 75,000mg/l (Todd, D.K., 1980).

The maximum acceptable level of calcium concentration determined by the WHO (1999) is 75mg/l, whereas the maximum allowed level by the WHO is 200mg/l.

2.4.2.5 Magnesium (Mg)

Magnesium sources in nature are amphiboles, olivine, pyroxenes, dolomite, magnesite (naturally occurring magnesium carbonate) and clay minerals. Magnesium is generally found in groundwater less than 50mg/l (Todd, D.K., 1980).

The maximum acceptable concentration of magnesium according to the WHO (1999) is 50mg/l, whereas the maximum allowed concentration is 150mg/l. The permissible limit according to the APHA standards is 200mg/l.

2.4.2.6 Sodium (Na)

Sodium belongs to the alkali metals group. It is found in significant amounts in natural waters. The usual concentration of sodium ions in groundwater is 10-100mg/l (Driscoll Fletcher G., 1989).

The permissible level stated by the Sudanese and the WHO standards for sodium is 200mg/l, and by the APHA standards is
300mg/l.

2.4.2.7 Potassium (K)

Potassium natural sources are feldspars, feldspathoids, some micas and clay content. Generally it is in concentrations less than 10 mg/l, whereas in hot springs it may reach 100mg/l (Todd, D.K., 1980).

The highest permissible level determined by the Sudanese and the WHO standards for potassium is 10mg/l.

2.4.2.8 Alkalinity

Alkalinity is the term that expresses the ability of water to neutralize acids. Carbonate and bicarbonate ions contribute to alkalinity. Also, Alkalinity can rarely be due to the presence of hydroxides (Driscoll Fletcher G., 1989). The alkalinity of water passing through the distribution system should be in the range of 30-100mg/l to prevent serious corrosion. Corrosion of iron pipes can be prevented by maintenance of calcium carbonate stability. Up to 500mg/l of alkalinity is acceptable by the APHA standards.

2.4.2.9 Calcium Carbonate (CaCO₃)

Calcium Carbonate is one of the major salts which contribute to water hardness. Hard water is water requiring more soap to produce suds. Sawyer and Carty, (1967), have classified water
according to hardness into four classes: soft water (0-75mg/l), moderately hard (75-150mg/l), hard water (150-300mg/l) and very hard water (over 300mg/l). The permissible limit is 500mg/l According to the WHO and Sudanese standards, and 800mg/l according to the APHA standards.

2.4.2.10 Excess Alkalinity (Na₂CO₃)

Excess alkalinity is defined as the contribution of Sodium Carbonate to the alkalinity of water. The maximum accepted level of excess alkalinity is 500mg/l.

2.4.2.11 Chloride (Cl)

The chloride ion occurs in natural waters in fairly low concentrations, usually less than 100mg/L unless the water is brackish or saline (Fetter, C.W., 1993). Chloride is used by humans in many applications and can be added to the subsurface via industrial discharges, sewage, animal wastes, and road salting (ibid). Water that contains less than 150mg/l of chloride is satisfactory for most purposes. A chloride content of more than 250mg/l is generally objectionable for a municipal water supply and water containing more than 350mg/l is objectionable for most irrigation and industrial uses. Water containing as much as 500mg/l of chloride frequently has a disagreeable taste (Driscoll Fletcher G,
1989). The standard permissible level of chloride set by the Sudanese, APHA, and the WHO standards is 250mg/l.

### 2.4.2.12 Fluoride (F)

Fluoride occurs in water as F- ion. In natural waters, the amount of fluoride present is less than 1.0mg/L. Although Fluoride concentrations as great as 67mg/L have been reported, the fluoride concentration does not, generally, exceed 10mg/l (Todd, D.K., 1980). Fluoride is present in minerals such as fluorite (CaF$_2$) and apatite (Ca$_5$ (Cl, F, OH) (PO$_4$)$_3$). Weathering of these minerals may release fluoride. It may be released as a contaminant from some industries (Fetter, C.W., 1993). Excessive fluoride, more than 6.0 mg/l, causes mottling of tooth enamel and furthermore affects tooth density. On the other hand minute amounts are beneficial in preventing tooth decay. The usual recommended fluoride content is 1.4-2.4mg/l. The maximum permissible limit of fluoride in drinking water recommended by the Sudanese, APHA and the WHO standards is 1.5mg/l.

### 2.4.2.13 Sulphate (SO$_4$)

Sulphate is a combination of sulphur and oxygen which is released to the environment by the weathering of the evaporite minerals. Rocks containing pyrite can, in the presence of microorganisms
acting as catalysts, be oxidized to release sulphur (Fetter, C.W., 1993). Sulphuric acid is widely used in industrial processes that can result in the release of sulphur to the environment.

Groundwater in igneous or metamorphic rocks generally contains less than 100mg/l (Ibid), but it may reach higher sulphate content near evaporite deposits in sedimentary rocks. Sulphate is generally harmless. At levels greater than 1000mg/l, scaling can occur in boilers and heat exchangers. Also high levels may cause gastrointestinal discomfort, affect taste and can act as a laxative.

The maximum permissible limit of sulphate in drinking water as set by the Sudanese standards was 400mg/l, which was then lowered to 250mg/l. This latter limit is also the highest permissible limit according to the WHO standards. The permissible limit according to the APHA standards is 500mg/l.

2.4.2.14 Bicarbonate (HCO₃)

Bicarbonate concentration in groundwater is generally less than 500mg/l. However, in water highly charged with carbon dioxide, it may exceed 1000mg/l (Todd, D.K., 1980).

2.4.2.15 Ammonia (NH₃)

Rainwater contains dissolved nitrate and ammonia. Under oxidized conditions ammonia is converted to nitrite, which is converted to
nitrate (Fetter, C.W., 1993). Organic matter will decay to ammonia under reducing conditions e.g. septic tank effluent. The maximum permissible limit by the Sudanese and the APHA standards is 1.5mg/l for ammonia.

2.4.2.16 Nitrite (NO$_2$)

Nitrite is a very reactive ion and is almost immediately converted to nitrate. So, small values of nitrite are normally found in the environment (Fetter, C.W., 1993). The maximum permissible limit by the Sudanese and the APHA standards is 2mg/l.

2.4.2.17 Nitrate (NO$_3$)

Nitrate is one of the inorganic forms of nitrogen. Nitrate is an important natural constituent. Unlike most other elements in groundwater, nitrate is not derived primarily from the minerals in the rocks that make up the groundwater reservoir. Instead, nitrate enters groundwater from another part of the nitrogen cycle in the Earth’s hydrosphere and biosphere (Driscoll, 1989). Additional nitrogen may enter the groundwater from sewage discharges, or from industrial waste chemicals. High concentrations may indicate sources of past or present pollution (Todd, 1980). Natural nitrate concentrations in groundwater range from 0.1-10mg/l (Driscoll, 1989). Excessive nitrate content can be considered an indicator of
groundwater contamination. Nitrate in concentrations greater than 45mg/l is undesirable in domestic water supplies because of its potential toxic effect on young infants.

The Sudanese and the APHA standards upper limit for nitrate is 50 and 45mg/l respectively, while the WHO standards limit is 50mg/l.

2.4.2.18 Silica (SiO₂)

The natural sources of silica are feldspars, Ferro magnesium and clay minerals. The silica concentration ranges generally from 1 to 30mg/l, although as much as 100mg/l is fairly common (Todd, 1980).

2.4.2.19 Albuminoidal Ammonia (Albumin)

Albumen is a complex organic matter. It is a water-soluble protein coagulated by heat. It is found in high concentrations in water receiving forest drainage or in water with high algae growth. Greater than 0.15mg/l of Albumin is considered high concentration; from 0.06 to 0.15mg/l is moderate concentration and a concentration less than 0.06mg/l is a low one.

2.5 Groundwater Geochemistry

Moving groundwater reacts with the rocks it passes through and this reaction gives the water its chemical characteristics. Silicate
minerals, which most rocks comprise, do not react readily with most groundwaters. On the other hand carbonate minerals do react readily with water. Carbonates are present in different types of rocks including most sedimentary rocks and even most igneous and metamorphic rocks, so they play an important role in the evolution of most groundwaters (Groundwater Geochemistry, Nanaimo Group aquifers, Post 2004, Internet). Groundwaters primarily controlled with carbonates reactions will have relatively high calcium and bicarbonates content and if the rock includes some dolomite, high magnesium levels can appear. The ions in water have a tendency to be attracted onto solid surfaces because of their electrical charges resulting in an ion exchange. This process is called adsorption. Clays are also highly adsorbing to cations because their surfaces are negatively charged (Ibid).

In order to obtain hydrogeologic information from a chemical data, it is necessary to reconstruct the path of the geochemical evolution, i.e., the sequence of processes through which the water acquires its chemical composition (S. Mandel, and Z.L. Shifman, 1981). The factor and cluster analyses are very useful tools in hydrogeochemistry. They are used in evaluating the combination of large hydrogeochemical datasets into groups with similar
characteristics, (Senthilkumur, G., Al, (and others), 2008).
Ionic ratios between major cations and anions expressed in meq/l, are used to study and elucidate the subsequent evolution of water chemistry, (K. Sami, 1992). The sequences of the major anions and cations are: Cl/HCO₃, SO₄/HCO₃, Cl/SO₄, (Na+K)/Cl, Ca/(Na+k), Mg/(Na+K), and Ca/Mg. The ratio, (Na+K)/Cl, is considered as a link between cations and anions (Al-Ruwaih, 1984).
Graphical representations for the chemical data are used to determine the water types in a visual manner. The major graphical methods used extensively in water researches are, Piper, (1944), Expanded Durouv, (1951) and Schoeller, (1954) diagrams.

2.6 Groundwater Modeling

2.6.1 General
Since the mid twentieth century, hydrogeologists, hydrologists, environmental scientists and engineers have been using various modeling techniques to understand the aquifer systems (IHP, UNESCO, Anna University, 2001). Groundwater models are used to interpret measured head, understand the mechanisms of flow and transport and identify the boundaries. Also they are used to understand the interaction between surface water bodies and
aquifers, understand the geochemical and microbiological reactions and to estimate contaminant degradation rates. Prediction of future heads, determination of new groundwater development schemes and identification of locations suitable to be used as landfills could be achieved through modeling. Groundwater models are mathematical and digital tools of analyzing and predicting the behavior of aquifer systems on local and regional scale, under varying geological environments (Ibid). Groundwater modeling has become a widely used environmental tool, since the development of digital computers and appropriate numerical techniques during 1960-1990’s. Groundwater models are constructed using different parameters for solving many field problems. However, understanding the physical, chemical and biological processes is important and their modeling poses great challenges in groundwater management.

Mathematical models provide a quantitative framework for analyzing data from monitoring and assess quantitatively responses of the groundwater systems subjected to external stresses, (IHP, UNESCO, Anna University, 2001). Over the last four decades there has been a continuous improvement in the development of numerical groundwater models. Earlier models had concentrated
on the analysis of flow behaviour in groundwater systems whereas the recent attempts have aimed at addressing the water quality problems and the simulation of the transport of contaminants in groundwater (Ibid).

2.6.2 GIS Modeling

The most important characteristic of a GIS is its enormous capability to analyze a database of spatial data coupled with their attributes. The main function of a GIS in hydrology is to assist in the management of the land and water resources. It is used for answering questions about the real world as the database of a GIS is a simplified model of reality which is used to represent certain aspects of this reality only. The GIS does not limit itself to the presentation in the form of spatial entities (e.g. river systems, groundwater bodies) but also it takes into account the properties and characteristics of these entities.

Collecting a large number of geographical data required for groundwater modeling is very laborious if done by hand. The use of GIS for both pre-processing and post-processing saves the time, (Allard, M.J. ‘(and others)’ (Post1993). An important function of GIS is to present the results of hydrologic studies in a format which is understandable to different persons who have to act upon the
results. Geographic information systems are increasingly being built around existing database management systems which are used to store, manipulate and retrieve data from a database (Ibid).

There are several ways of organizing geographic data in a computer. The data model of the earth or the description of entities and their relationships are represented by means of points, lines, areas and surfaces. The spatial distribution of points, lines, areas and surfaces are represented in digital form in two basic types of spatial models; raster and vector models. Vector is defined as a quantity with a starting coordinate and an associated displacement and direction. The approach used in the vector model is to precisely specify the position of the points, lines and polygons used to represent the data model. The raster model is the cellular organization of the spatial data. In a raster structure, a value for the parameter of interest is developed for every cell in any array over space.

2.7 Related Previous Studies

2.7.1 Geological

Whiteman, (1971) has written detailed reports on the geology of the Sudan and in particular the geology of the Gezira area and the
mineralogy of its formations.

2.7.2 Geophysical

El Zein (2006) has proposed a conceptual model for the exploration of groundwater in the Gezira area. The results of a vertical sounding method that was applied through the whole of Gezira area were correlated with well logs data to determine the geoelectrical characteristics of the main groundwater aquifers in the Gezira area.

Abdel Rahman (2003) has reported, in his M. Sc. Thesis that the water quality of the Nubian Aquifer in Managil Province is better than that of the Gezira Aquifer, and that the groundwater in the Western and Northern part of the province is more saline. The geophysical studies in the area have shown that the area is underlain by the Basement Complex which is characterized by the absence of water bearing formations.

2.7.3 Hydrogeological

El Boushi and Whiteman (1967) have found that the Nubian Aquifer has groundwater which is fit for human and animal consumption, with Total Dissolved Solids ranging from 100 to 300 p.p. million and total hardness from 60 to 264 p.p. million. In certain areas in the southern parts of the Gezira the water is salty.
due to leakage of saline water from the Gezira Formation.

Abdel Latif (1976) has mentioned that the main aquifers in the area, (Blue Nile Basin between Wad Medani and Abu Huggar) are the Nubian and the Alluvial. The Alluvial aquifers include El Atshan and El Gezira formations. The groundwater salinity ranges from 183 to 2093 p.p.million, which is fit for domestic use. Two types of water have been found to occur in the area: bicarbonate water and chloride water.

Nash (1979) has reviewed the available literature on groundwater resources in Sudan; their aquifer characteristics and water quality. The main aquifers of the Blue Nile Basin are the Gezira, Al Atshan, and the Nubian Sandstone aquifers. The quality of groundwater in all the formations is generally good except in the area of stagnation between the two rivers where the total dissolved solids exceed 2000 mg/l in the Gezira aquifer.

NRWC (1993) carried out an appraisal of the groundwater in the Sudan and evaluated the available data. The Gezira and Khartoum areas have been found to be important areas for groundwater abstraction, so they are given priority in documentation.

Salih (1997) has reviewed the groundwater resources in Sudan: the basins and the groundwater formations and their chemical
characteristics. Salih has also discussed the constraints facing the groundwater development in Sudan.

Salama (1994) has stated that the highly saline groundwater bodies that occupy the flowing end of each of the rift basins in the Sudan are due to the buried saline lakes or playa. He has also stated that there is widespread of kankar nodules in the sediments as a result of continuous efflorescence, leaching, and evaporative processes. The saline water bodies are formed through salt leaching and groundwater discharge.

2.7.4 Hydrogeochemical

Abdel Salam (1966) has studied the groundwater geology of the Gezira. The lithology of the sampled wells and the thickness of the Gezira aquifer have been studied in detail.

Salama (post 1975) has found that the chemical quality of the Blue Nile Basin is varying. The total dissolved solids value is low along the Blue Nile, ranging from 300 to 500 p.p. million, and high along the White Nile, ranging from 1000 to 5000 p.p. million. This is due to the variations of the formations, which accordingly result in variations of permeability, recharge, potentialities and contact time between the groundwater and the formation.

Saeed (1976) analyzed Groundwater samples representing the three
aquifers, the Basement Complex, the Gezira and the Nubian aquifers at Khartoum province and northern Gezira. The results of the chemical analysis of the most common groundwater chemical components have been discussed.

El Tahir (2003) in his M. Sc. research has studied the groundwater as a source of water supply in Eastern Khartoum State. The groundwater quality was determined. Hydrogeochemical facies were determined using Durouev diagram. Composition and scattered diagrams were used to show the relationship between different ions, and Ionic ratios were employed to trace the different processes occurring in the aquifer.

Awad (2002) carried out an assessment of the groundwater chemistry of Khartoum State by using different statistical techniques. X-Y plots, correlation, cluster, principal components and factor analyses. In his work, Khartoum's groundwater was classified into different hydrochemical facies. Saturation indices of groundwater with respect to carbonate and sulphate, as well as carbon dioxide were determined.

Cuneyt Guler (and others) (2002) evaluated the groundwater of south Lahontan region, southeastern California by graphical (Piper, Collins Bar Diagram, Pie, Stiff, and Schoeller). Multivariate
statistical analysis was used in the classification of water Chemistry data.


Mohamed (2009) carried out an assessment of the groundwater at Gash basin, Kassala Area. The study determined the groundwater potential and pollution risk by using mathematical modeling. The classification of groundwater was performed using the graphical representations of Piper and Durouv. Chemical equilibrium and saturation indices were determined.

Mohamed (2010) studied the hydrogeological and hydrochemical characteristics of the lower aquifer of the Nubian sandstone formation. Graphical representations of Piper, Schoeller and Durouv were used to classify the groundwater and also ionic ratios were employed to interpret the chemical processes occurring in the aquifer. The degree of saturation of groundwater was determined.

IHP of the Sudanese National Commission for Education, Science and Culture, technical report (2000) reviewed the groundwater resources of Sudan. The resources were found vulnerable to pollution risks from agricultural, industrial and urbanization
activities. The level of pollution was assessed, and the major pollutants identified. A groundwater pollutant transport model was developed and applied to simulate the transport of contaminants in groundwater in Khartoum State.

Elk rail (and others) (Map Asia 2003) have evaluated the hydrochemical composition of the groundwater in Khartoum State. The ions concentrations were found to have the tendency to increase with the increase of distance from the surface water systems. The salinity was found to appear in the upper aquifer.

Ahmed (2003) has stated, in his M. Sc. Thesis, that the chemicals of the groundwater in Gezira Province are below the standard permissible limits and that its physical quality is good.

Ali (2004) in his study of the water supply in Butana and Um El Gura Provinces has shown that the wells in the Nubian Aquifer are shallow with water of good quality. The Nubian Aquifer is underlain by the Basement Complex which covers almost 40% of the area. Boreholes in the Basement Aquifer are extremely saline. Boreholes represent the main source of water in the area.

Gar El Nabi (2004) M. Sc. Thesis: Groundwater in EL Hasahisa and El Kamlin Localities, has found that the quality of groundwater is good and complying with the international and local standards.
An area of high salinity appears at Abu Gota and Wagra, so the saline Gezira aquifer is sealed and the Nubian Aquifer is tapped in these areas.

Modawi (2003) studied the groundwater around the Blue Nile between El Kamlin and Wad Medani in the Gezira State. The groundwater in the Nubian Sandstone aquifer was classified as fresh water with isolated pockets of brackish water. The groundwater in the Gezira Aquifer was classified as fresh water and slightly hard. Generally it was found suitable for human and irrigation purposes.

2.7.5 Water Quality

Boutros (1977) has mentioned that the chemical quality of boreholes in Sudan water may vary due to a number of factors and may undergo very slight changes with time. From the analysis carried out by the chemical laboratories of the Ministry of Health for 8761 deep boreholes, only 50 boreholes were found unfit to human consumption.

Mabrook (1981) tested the quality of groundwater used in south Khartoum to determine its mineral content and salinity necessary for irrigation.

Abdel Basit (1984), from the Blue Nile Health Project, has
reported that the groundwater of the Gezira Scheme is available in adequate quantities and acceptable quality in areas near the Blue Nile. In the Managil Extension, to the west of the Gezira Scheme, the groundwater is saline and unacceptable in upper aquifers, while in deep aquifers it is more acceptable and the salinity is less.

El Now (1984) has revealed apparent increase in inorganic content and coliform bacteria in Port Sudan Water Supply which is tapped from groundwater.

Abbo (1989) carried out an investigation to probe the impact of agricultural chemical-fertilizers, pesticides and organic waste on water quality of Shallow Aquifer with reference to Kassala Gash Basin. The data analyzed for bacterial contents and dissolved salts indicated an appreciable bacterial pollution and salt content. However, the chemical quality of water in these shallow aquifers was found satisfactory for drinking purposes as it was less than the limit suggested by The WHO.

Babiker (1992) has shown that effective and economical nitrate removal from the groundwater in rural areas can be achieved by adsorption with Charcoal.

Farah (1993) has shown that the groundwater in Khartoum Province and Northern Gezira area except the saline zone is fit for
all purposes (irrigation, drinking, and industry).

Abdel Malik (1997) studied the content, distribution, health effects and control of Fluoride, at Jabel Moya (Sennar State). The study showed relatively low rate of deterioration in groundwater. Although there were high concentrations of some salts, the water was found to meet the WHO permissible limits except in some wells. Twenty six percent of the total samples investigated, were found to have high concentrations of fluoride that were above the permissible limit.

Farah (1999) studied the groundwater in central Sudan and Khartoum area. He has found that the groundwater is fit for drinking and irrigation, except in the upper aquifer of Soba saline zone. So the water has to be extracted from the lower aquifer.

Fadol (2002) has found that the chemical constituents of Wad Medani Domestic water Supply are within the permissible international and local limits. She has indicated that pollution results from the intake portion of the well, or the surrounding pit latrines and septic tanks.

Yousif (2001) has pointed out in her M.Sc. thesis that the groundwater in west and center of Sennar State is available within the Nubian Sandstone and Al Atshan Formation aquifers. The study
has revealed that greater than 95% are suitable for human and animal consumption.

El Sheik (2005) has stated that the groundwater in the area of El Dali and Mazmum is limited due to the presence of the basement complex which covers about 95% of the area. The groundwater occurrence in this formation is restricted to major faults.
CHAPTER III

METHODS OF INVESTIGATION

3.1 Computer Work

3.1.1 Microsoft Office Excel and Database

Microsoft Office Excel and database formats were used to organize the collected data so as to comply with the format requirements of the SPSS and the GIS Packages, respectively.

Microsoft Office Excel was also used to produce the composition and scatter diagrams for the groundwater.

3.1.2 SPSS Package

The statistical package SPSS 13.0 was utilized to determine the frequency distribution (histogram) of each individual chemical data and its corresponding statistics regarding central tendency, dispersion, distribution, correlations and regression expressions.

The SPSS package was also used to classify the data into clusters and determine the factors controlling the chemical quality.

3.1.3 GIS Packages

ArcView GIS 3.3 and ArcGIS 9 (ArcMap) packages were utilized for the mapping and modeling of the collected data as will be shown in Chapters four and five.
3.1.4 AquaChem Software

The AquaChem software from Waterloo Hydrogeologic Company, version 3.7.0.42 (1997), was used to produce graphs to help in the interpretation of the geochemical data of the groundwater of the Gezira.

3.1.5 PHREEQC for Windows Software

PHREEQC for Windows software Version 2.8.03(uses source of PHREEQC-2 Version 2.8) is a hydrogeochemical transport model by D.L. Parkhurst and C.A.J.Appelo. The software was used for the calculations of the saturation indices of the groundwater minerals.

3.2 Field Work

Although the field work carried out in this research was mainly concerned with collecting a large number of data from the available sources, yet some representative Samples for Managil, Kamlin, Hasahisa, Butana, Um El Gura and Gezira Provinces were collected and analyzed (post 2006) at the laboratories of the Ministry of Physical Planning and Public Works (Gezira State Water Corporation). The purpose of collecting this data was mainly to perform a comparison between the results of the groundwater quality obtained from old samples with those from recent ones.
3.3 Methods of Chemical analysis of Groundwater

3.3.1 Main Chemical Data

The chemical data collected for the mapping, modeling and assessment of the quality of the Gezira groundwater to be performed in this research were obtained via the routine standard methods of chemical analysis that will be described below. This chemical data resulted from the analyses of various water samples that were analyzed in the Central Laboratories of the Ministry of Health in Khartoum. The methods adopted are described in the book of the “Approved Methods for the Physical and Chemical Examination of Water” by Hamence, (1960) and the manual of the Sudan Ministry of Health Laboratory.

The methods of chemical analysis of groundwater cover the tests for the major ions as described below.

1. Calcium (Ca) and Magnesium (Mg): are tested by titration with E.D.T.A. (Mackereth, 1978).

2. Sodium (Na) and Potassium (K): are tested by the flame photometric method (Mackereth, 1978).

3. Nitrate (NO₃): is determined by the Zinc- Copper Reduction Method (Hamence, 1960).

4. Nitrite (NO₂): is determined by Nesslerizor Methods using
Ilosvay’s solution No. 1 and No.2 (Hamence, 1960).

5. Silicate (SiO₂): is tested by a colorimetric method using Ammonium Molybdate (Tintometer, 1967).

6. Alkalinity: is tested by titration with HCl (Mackereth, 1978).

7. Excess Alkalinity (Na₂CO₃): is tested by titration with HCl (Sudan Ministry of Health Laboratory Manual)

8. Electrical Conductivity (E.C.): is determined by using the hand operated conductivity meter trade marked (Dionic).

9. Chloride (Cl): is determined as Silver Chloride by the titration method with Silver Nitrate solution (Vogel, 1961).


11. Total Dissolved Solids (TDS): are determined by putting 50 ml of a well-mixed and filtered sample into a weighed dry dish. The sample will then be evaporated to dryness on a steam bath (Hamence, 1960).


13. Sulphate (SO₄): is determined by the addition of Methyl Orange indicator and concentrated hydrochloric acid (Hamence, 1960).
14. Ammonia (NH₃) and Albumin (Alb): are determined by distillation, nesslerization and titration (Hamence, 1960).

15. Fluoride (F): is determined by a Visual Method using Mixed Zirconium Alizarin Reagent or the photometric method.

3.3.2 Chemical Data for Comparison

All the analyses of the chemical data samples of the Gezira groundwater collected for the purpose of comparison with the results of the models developed in this work (Chapter five) were performed by a Photometer manufactured by Palintest Company. This instrument is known as Photometer 7000.

3.3.2.1 Palintest Photometer 7000

The Palintest Photometer systems present new techniques of analysis for an extensive range of water tests. They are integrated with a range of tablet reagents and test tubes also manufactured by Palintest.

The Palintest Photometer 7000 is light weight and portable for field or laboratory use. It provides the user with a wide range of set up options. It can be interfaced with a computer or a printer to provide a direct printing of test results. It is ideally suited for the use with database and specialized water management software.
3.3.2.2 Operating Principle

The Palintest Photometer is an instrument for measuring colour intensity. Light from an incandescent lamp is passed through a test tube containing the sample solution and then through a colored filter onto a photocell. The filter slide enables different filters to be chosen so that light of a specific wavelength can be selected. The test comes to an end when the solution is completely colorless and all the light passes through the sample. With colored samples, light is absorbed and that which passes through the sample is proportionally reduced. The Palintest direct-reading photometer is used to measure the colour produced when the chemical reagents are reacted with the water sample. In these tests the intensity produced is proportional to the concentration of the parameter under test. The Palintest Photometer is pre-programmed with calibrations for each test parameter. The calibrations are accessed by entering a unique program number at the start of each test procedure. This allows the photocell response to be converted to a concentration reading and the instrument thus displays a direct reading of the test result.
3.3.2.3 Chemical Analysis

The Palintest Photometer can be utilized to test for the chemical parameters of water as described below.

1. pH

The Palintest Phenol Red test uses a tablet reagent containing the precise amount of Phenol Red indicator required for the test. Phenol Red reacts in water to produce a distinctive range of colours from yellow to red. The colour of the test solution is indicative of the pH value and is measured using a Palintest Photometer.

2. Magnesium (Mg)

The Palintest Photometer testing for Magnesium is based on a simple colorimetric procedure. Magnesium reacts with an organic reagent (Magnecol tablet) to produce an orange colored complex. The reagent itself is yellow and thus over the range of the test a series of colours from yellow through to orange are produced. The colour produced in the test is indicative of the magnesium concentration which is determined by direct reading on the Palintest Photometer and consultation of the Magnecol calibration chart.

3. Potassium (K)

The Palintest Potassium test is based on a single tablet reagent
containing sodium tetraphenylbor n. Potassium salts react with sodium tetraphenylbor n to form an insoluble white complex. At the potassium levels encountered in the test, this is observed as turbidity in the test sample. The degree of turbidity is proportional to the potassium concentration and is measured using a Palintest Photometer.

4. Chloride (Cl)

The Palintest procedure for Chloride detection is based on a tablet reagent system containing silver nitrate (Acidifying CD tablet and Chloridol Tablet). Chlorides react with the silver nitrate to produce insoluble silver chloride. The test is carried out under acidic and oxidizing conditions.

Chloride is determined by direct reading on the Palintest Photometer and consultation of the appropriate Chloridol chart.

5. Fluoride (F)

In the Palintest Fluoride test, two tablet reagents are used. Zirconyl Chloride and Eriochrome Cyanine R tablets are added to a sample of the water. Differing amounts of fluoride produce a range of colours from red to yellow and the colour produced in the test is indicative of the fluoride concentration and is measured using a Palintest Photometer.
6. **Alkalinity**

The Palintest procedure for alkalinity determination uses a colorimetric method and a single tablet reagent (Palintest Alkaphot Tablets). Under the controlled conditions of the test, a distinctive range of colours from yellow, through green, to blue is produced. Alkalinity is determined by direct reading on the Palintest Photometer and consultation of the Alkaphot calibration chart.

7. **Calcium (Ca)**

Calcium test is based on the Calcicol indicator reagent method. Calcium ions react specially with Calcicol indicator in alkaline solution to give an orange coloration. The reagent gives a violet colour in the solution. Thus distinctive range of colours from violet to orange is produced. The reagents for the method are provided in the form of two tablets (Palintest Calcicol No 1 Tablets and Palintest Calcicol No 2 Tablets). Calcium is determined by direct reading on the Palintest Photometer and consultation of the Calcicol calibration chart.

8. **Calcium Carbonate (CaCO$_3$)**

The test is based on a unique colorimetric method. Under the controlled conditions of the test calcium ions react with the reagent tablet (Palintest Hardicol No 1 Tablets and Palintest Hardicol No 2 Tablets).
Tablets) indicator to produce a purple coloration.

Calcium Carbonate is determined by direct reading on the Palintest Photometer and consultation of the Hardicol calibration chart.

9. **Sulphate (SO₄)**

The Sulphate test is based on a single tablet reagent containing barium chloride in slightly acidic formulation (Palintest Turb Tablets). The reaction of sulphates with barium salts form insoluble barium sulphate which is observed as turbidity in the test sample.

Sulphate is determined by direct reading on the Palintest Photometer and consultation of the Sulphate calibration chart.
CHAPTER IV
ORGANIZATION AND MAPPING OF THE DATA

4.1 Introduction

The main sources of the groundwater information in Sudan are the national and regional archives, research reports, non governmental organizations and private contractors.

The groundwater data collected from dug or drilled wells up to the year 1980 were kept in a file archive in Khartoum, and due to the decentralization policy adopted after that, the archive was partitioned and transferred to the regional offices (NRWC, 1993).

With the advent of computers in Sudan and their intensive utilization in the everyday office work, considerable recorded information on the national and regional archives was assembled, filtered out and registered onto a national computer archive. The computerized information was, of course, intended to help in examining and mapping of information as well as integrating with other data bases.
4.2 Data Collection

Despite the availability of a large amount of groundwater information in Sudan which has been stored in the computerized system of the national archive, many gaps have been identified regarding some essential aspects of the information. However, this research has made use of the fact that the national archive contains considerable data of water quality analyses pertaining to the central part of the country, which is the study area for this research.

More than 1300 wells representing the study area were gathered from historical records available in the national archives. The wells were selected in such a manner to cover most parts of the Gezira area and also according to the availability of chemical analysis results as per selected well.

4.3 Data Sources & Organization

The raw data for this research was obtained from two sources; the National groundwater information center at Kilo 10 in Khartoum (Groundwater and Wadies Administration) and from the Water Corporation of Gezira State. The data was partly computerized and partly in file form. For the data of the sampled wells, only the information regarding the location, geographical coordinates, water
levels and the essential constituents of water chemistry of the wells under consideration was found. It was not possible to gather other information such as borehole logs, gravity, resistivity, pumping tests and lithology.

The computerized and the file data were combined using Microsoft Excel tabulation. Furthermore, it was found necessary to transform the resulting information into database tables so as to suit the GIS environment.

4.4 Data Classification

By inspecting the collected data, it was found that the data was unclassified with regard to the two main aquifers, Nubian and Gezira that form the groundwater of the Gezira area. The aquifer classification of the data was missing.

However this problem was overcome by comparing the well depths included in the unclassified database file with the Gezira Aquifer thicknesses found separately recorded in some historical files. (Abdel Salam 1966, Information centre, Kilo 10, Abdel Rahman 2003, Ahmed 2003, Gar El Nabi, 2004).

Making use of the inverse distance weighted interpolation method of the GIS (section 5.3) a continuous mathematical surface was
produced for the recorded thickness values of the Gezira aquifer. The continuous surface would be stretched all over the Gezira area to represent thickness values of the Gezira aquifer against their corresponding geographical locations.

The unclassified data was formatted in a tabular form. Each row of the table would represent for the corresponding well: its name, geographical location, chemical parameters, and depth. To determine whether a well would belong to the Nubian or the Gezira aquifer, the GIS identifier tool was used to correctly place the location of the well on the continuous surface generated for the recorded Gezira aquifer thicknesses by the GIS modeling techniques. Therefore at the specified location, the surface would yield a thickness value that could be compared with the depth value shown in the row under consideration. If the well's depth noted from the specific table's row was less or equal to the corresponding value obtained from the surface, the well and its row's information would be categorized as Gezira aquifer otherwise it would belong to the Nubian aquifer.

Following the above mentioned method, it was fairly possible to divide the unclassified database file into two database files representing the Nubian and Gezira aquifers. The resulting number
of classified water samples was 753 for the Nubian aquifer and 619 for the Gezira aquifer.

4.5 Data Accuracy Assessment

The first step in assessing the accuracy of the classified database files was to convert all the chemical concentration values from mg/l into meq/l. To perform this conversion, the following equation was used:

\[ \text{Meq/l} = \text{mg/l} \times \text{conversion factor} \]  
(4.1)

The factors for the major cations and anions are given in Appendix (B), (after Hem from Todd, 1980).

The percentage error in the chemical analysis of any sample of water can be found by computing the imbalance ratio that is written as follows:

\[ \text{Imbalance Ratio} = 100\% \times \frac{(\sum \text{cations} - \sum \text{anions})}{(\sum \text{all ions})} \]  
(4.2)

In this work, only the major cations (\(\text{Ca}^{2+}, \text{Mg}^{2+}, \text{Na}^+\) and \(\text{K}^+\)) and the major anions (\(\text{HCO}_3^-, \text{Cl}^-\) and \(\text{SO}_4^{2-}\)) were considered. The effects of the other constituents of water were considered negligible. Thus those six major constituents were converted into meq/l using equation (4.1) and the error in the chemical analysis of each sample was obtained using equation (4.2). Only the data samples with 5% error was considered acceptable. The error results
for the Nubian and Gezira data are shown in Appendix (C).

4.6 Base Map and Essential Layers

A digital map for the study area was clipped from the hydrogeological map of the Sudan (scale 1: 200000), which was obtained from the National Information Centre.

The clipped map is contained within 12.00° - 16.00° N and 32° - 35° E. The map was transferred to GIS environment using ArcMap facilities. Fig (4.1) shows the study area map with the essential layers that are related to groundwater (Water flow, Drainage system, Hydrogeology).

4.7 Mapping of Data using GIS

The classified database files of the chemical data corresponding to the Nubian and Gezira Aquifers were converted into the shape file format of the GIS. The shape files were then added to the base map as extra layers using ArcMap of the GIS. Consequently, the chemical data was transformed into spatial form i.e. mapping the data in relation to geographical locations Fig. (4.2).

It can be noticed in Fig. (4.2) that the identifier tool has been used.
to show the geographical location of El Azaza village coupled with its recorded chemical data. Thus, using the effective tools of ArcMap, the data would be visualized geographically, updated or appended with a new data.
5.1 Introduction

Although the mapping of the Gezira chemical data presented in chapter four would yield an easy interactive system of representation for the data, it would be incapable of predicting the chemical values for new locations not included in the map. However, this estimation process is facilitated by using the powerful modeling tools supported by the Geostatistical analyst of the GIS. With this type of modeling, the whole area of the Gezira state would be described mathematically by continuous-surface functions representing each individual chemical parameter of the groundwater. The graphical representation of these mathematical functions in the GIS environment would eventually be converted into colored-filled contours covering the whole area under study.

5.2 Geostatistical Analyst of GIS

The Geostatistical analyst is one of the GIS modeling packages, which has been developed by tightly integrating geostatistical tools
within GIS modeling environments. The Geostatistical analyst utilizes samples collected from different locations in a landscape to interpolate a continuous surface. The surface is derived using the measured values from the sampled locations to predict values for each location in the landscape (ESRI, 2001).

Two groups of interpolation techniques are provided by the Geostatistical analyst: deterministic and geostatistical. Both techniques rely on the basic assumption of similarity of nearby sample points to create the surface.

The deterministic techniques use mathematical functions only while the geostatistical rely on both mathematical and statistical methods for the creation of a surface. The salient advantage of the geostatistical techniques over the deterministic is their capability to assess the uncertainty of the predictions depicted by the surface. However, the sample values will not be part of the surface created by the geostatistical methods. This is not the case when a surface is created by what is called an exact deterministic method, where the predicted surface is forced to pass through the measured values of the sample points.

As a large number of samples was used in this research, it was found well-suited to employ an interpolator that would result in a
surface maintaining the same sample values. The inverse distance weighted and the radial basis functions are exact interpolators, where the former is based on the extent of similarity while the latter is based on the degree of smoothness. Therefore the inverse distance weighted interpolator was chosen for modeling the chemical data since it was considered to satisfy both criteria of exactness and the assumption of similarity of chemical distribution in the vicinity of a prediction location.

5.3 The Inverse Distance Weighted Technique (IDW)

This interpolation technique is based on the assumption that things that are close to one other are more alike than those widely apart. To predict values for an unmeasured location, the IDW utilizes the measured values surrounding that location. The IDW assumes that each measured point has an influence on the prediction location that diminishes with distance. Thus, it gives greater weights to the measured points closer to the prediction location than those distant from it, hence the name inverse distance weighted.

The IDW algorithm is given by the following formula:

\[ Z(s_0) = \sum \lambda_i Z(s_i), \quad i = 1 \ldots N \]  

(5.1)
Where:

\( Z(s_0) \) is the predicted value at location \( s_0 \).

\( N \) is the number of measured values surrounding location \( s_0 \).

\( \lambda_i \) is the weight corresponding to the measured value at location \( s_i \).

\( Z(s_i) \) is the measured value at location \( s_i \).

The weighting factors, \( \lambda_i \), are obtained by the following formula:

\[
\lambda_i = \frac{(d_{i0})^p}{\sum (d_{i0})^p}, \quad \sum \lambda_i = 1, \quad i = 1 \ldots N \quad (5.2)
\]

Where:

\( d_{i0} \) is the distance between \( s_i \) and \( s_0 \).

\( p \) is a power parameter.

The weights shown in the above formula are scaled so that their sum is equal to one.

An optimal value for \( p \) is selected by the geostatistical analyst such that the root mean square error of prediction is minimum. The root mean square error is obtained for different values of \( p \) for the same dataset. Then the geostatistical analyst fits a curve to the calculated root mean square error values and subsequently determines the minimum value for \( p \) from the curve.
5.4 Chemical Data Models

The two database files of the chemical analysis samples of the Gezira and the Nubian aquifers categorized from the study area data, as explained in chapter four, were divided into 38 files. Each file consisted of three columns representing the identification and location of the well (longitude & latitude) and the value of the chemical parameter under consideration. Four extra database files for the depth and Static level of the sampled wells at the above mentioned aquifers were formed to correlate the model results with groundwater levels.

The individual database files were then converted into shape files (GIS format). The spatial data corresponding to each shape file would contain the geographic locations of the wells featured by points on the earth’s surface, along with attribute information describing what these features would represent.

The IDW interpolator of the geostatistical analyst was employed to create surfaces or models for the shape files previously obtained. The resulting models for the Gezira and Nubian aquifers are depicted as colored filled contours GIS maps (Figs.5.1 – 5.42). Each map is appended with a legend, two additional layers of the two Niles and a rectangular extent of grid between latitudes 13° -
15.6° N and longitudes 32° - 34.5° E.

It should be noted that the resulting chemical models can be utilized in a GIS environment to yield interactive maps that maintain the same values of the measured sampled locations and give predictions between the sampled locations.

5.5 Concluding Remarks on the Modeling Results

5.5.1 Hydrogen Ion Concentration (pH)

In the pH model of the Nubian aquifer (Fig. 5.1), low levels of pH are observed around the two banks of the Blue Nile and in the central part of Managil Province. High levels of pH are near the White Nile.

The pH model of the Gezira aquifer (Fig. 5.2) shows low values of pH around the two banks of the Blue Nile, especially in the Gezira Province. High levels of pH can be observed in the central part of Kamlin province and the eastern side of Managil Province.
5.5.2 Total Dissolved Solids (TDS)

As seen in the TDS model of the Nubian aquifer (Fig. 5.3), low TDS values are concentrated near the left and right banks of the Blue Nile (Nash, 1979, and Abdel Latif, 1976). The decrease in the TDS values towards the Blue Nile may be due to the leaching processes occurring nearby the river, and the fast annual recharge or renewal of the groundwater close to the river (Ahmed, 2003). Also, it can be observed in Fig. (5.3) that high values of TDS are in the north west of Kamlin Province, north east of Butana province, some localities near the White Nile, and the middle and south west of Managil Province.

In the Gezira TDS model (Fig. 5.4), high values of TDS can be seen concentrated in the west and centre of Gezira. This is interpreted as due to the movement of water. Because when water moves away from recharge areas, it dissolves more soluble salts from the sediments, leading to a high salt concentration in the central and other troughs in the Gezira (El Boushi, 1972). Low values of TDS can be noticed close to the Blue Nile Fig. (5.4), and this may be due to the recharging of the groundwater from The Blue Nile.
TDS values in the range of 2000mg/l to 4120mg/l can be observed in Wagara area (e.g. about 3000mg/l at Farageen), Abu Gouta area (e.g. 2458mg/l at Artimeli) and at some other places in Managil Province (e.g. El Amara Ali, Mabrouk Extension and Managil city).

5.5.3 Specific Electrical Conductivity (E.C.)

Figs. (5.5 & 5.6) show the E.C. models of the Nubian and Gezira aquifers, respectively. Low values of E.C. are observed in both models at the eastern side of Gezira State, close to the Blue Nile and high values are at the western side, close to the White Nile. Also in Figure (5.6) of the Gezira Aquifer, high values of E.C. are observed in the central parts of Kamlin and Managil Provinces. Generally for the two aquifers, low values of E.C. can be obtained at the eastern side of Gezira State, close to the Blue Nile and high values are at the western side, close to the White Nile.

5.5.4 Calcium (Ca)

In the Calcium model of the Nubian aquifer (Fig. 5.7), high values of Calcium are concentrated adjacent to the Blue Nile and in the central part of Gezira.
However, the high values of Calcium in the Gezira aquifer are observed in Managil region as shown in the Calcium model of Fig. (5.8). It is plausible to consider that the Gezira and Managil irrigation canals, which originate from the Blue Nile, are the sources of recharge to the groundwater in the central part of Gezira and Managil region (El Zein, 2006). Generally in the whole Gezira region, high concentrations of calcium are noticed around the Blue Nile, while low ones are around the White Nile (Saeed, 1976). It is known that the Blue Nile water is richer in calcium than the White Nile and moreover, the Gezira Formation, in the eastern part, is characterized by the presence of intercalation of kankar (CaCO₃) and gypsum beds.

**5.5.5 Magnesium (Mg)**

In the Magnesium model of the Nubian aquifer (Fig. 5.9), low values of Magnesium are observed around the White Nile. High values of Magnesium are close to the Blue Nile and in the centre of Kamlin and Managil Provinces.

In the Magnesium model of the Gezira aquifer (Fig. 5.10), high values of Magnesium are observed in the area of Managil and the area close to the Blue Nile. Low values of Magnesium are around the White Nile and in the centre of Gezira (Saeed, 1976).
The high values of Magnesium in the centre of Kamlin and Managil Provinces could also be explained by the previous suggestion of El Zein (2006), as stated in section 5.5.4.

5.5.6 Sodium (Na)

In the Sodium model of the Nubian Aquifer (Fig. 5.11), high values of sodium are observed in Butana Province (Wad Rawa and the surrounding area). This may be explained as caused by the leaching of the lithological constituents of the Nubian Aquifer (CaSO₄&NaCl) in the direction of the water flow, which is towards the east of the Blue and White Niles (Seed, 1976). In general, the concentrations are high in the centre of Gezira and as explained by Salama (1994): the buried saline lakes of the Gezira have been formed through a continuous process of evaporation coupled with alkaline and earth precipitation. As a result rain water has dissolved most of the soluble salts (NaCl&Na₂SO₄) and transported them towards the deepest part of the basin (centre of Gezira Area).

Also in the sodium model of the Nubian aquifer (Fig. 5.11), Low values of sodium are noticed around the Blue Nile (Saeed, 1976).

In the Sodium model of the Gezira aquifer (Fig. 5.12), high values of sodium are observed in Managil Province. Low values of sodium are around the Blue Nile.
In general, the high values of sodium are concentrated in the centre of Gezira and close to the White Nile, which is supposed to be the main recharge source of the groundwater in these areas. The water of the White Nile was analyzed by Saeed (1976) and found to be rich in sodium compared to the Blue Nile water.

**5.5.7 Potassium (K)**

The Potassium model of the Nubian aquifer, (Fig. 5.13), shows high values of Potassium in the centre of Gezira State (Saeed, 1976).

The Potassium model of the Gezira aquifer, (Fig. 5.14), shows low values of Potassium around the Blue Nile and also in the west of Managil Province. High levels of Potassium can be noticed in the centre and west of Kamlin Province, the centre of Managil Province and the east of Butana Province, and close to the White Nile.

**5.5.8 Alkalinity**

It is clear from the alkalinity model of the Nubian aquifer (Fig. 5.15) that high concentrations of Alkalinity are found at the eastern bank of the White Nile and the western side of Managil Province. Low values are observed around the Blue Nile and in the centre of Gezira.
In the alkalinity model of the Gezira aquifer (Fig. 5.16), high values of alkalinity are noticed around the banks of the White Nile and in the west of Kamlin Province and Managil Province. Low values are around the Blue Nile.

5.5.9 Calcium Carbonate

In the Calcium Carbonate model of the Nubian aquifer (Fig. 5.17), high values of CaCO$_3$ are observed in the north of Kamlin Province and the south west of Managil Province.

In the Calcium Carbonate model of the Gezira aquifer (Fig. 5.18), high values of CaCO$_3$ can be observed in the north of Kamlin Province and the centre of Managil Province.

5.5.10 Excess Alkalinity (Na$_2$CO$_3$)

In the Na$_2$CO$_3$ model of the Nubian aquifer (Fig. 5.19), high values of Na$_2$CO$_3$ are observed at the banks of the White Nile and the west side of Gezira State, while low values are close to the Blue Nile.

In the Na$_2$CO$_3$ model of the Gezira aquifer (Fig. 5.20), high values of Na$_2$CO$_3$ are observed at the banks of the White Nile. Low values are at the banks of the Blue Nile and in the centre of the Gezira State.
5.5.11 Chloride (Cl)

In the Nubian Chloride model (Fig. 5.21), high values of Chloride are observed in the centre of the northern part of Kamlin Province, the banks of the White Nile, the east of the Blue Nile (Butana Province) and the centre of Managil Province.

In the Gezira Chloride model (Fig. 5.22), high values are observed in the western side of Kamlin and Managil Provinces and close to the White Nile banks. Low values are noticed around the Blue Nile.

5.5.12 Fluoride (F)

In the Fluoride model of the Nubian aquifer (Fig. 5.23), high concentrations of Fluoride are observed in the north of Gezira state in Kamlin Province, the east of the Blue Nile in Butana Province and around the White Nile.

In the Fluoride model of the Gezira aquifer (Fig. 5.24), high concentrations of Fluoride are observed at different locations in Kamlin and Butana Provinces. Also, low values are noticed at different places in Kamlin, Gezira and Managil Provinces.
5.5.13 Sulphate (SO₄)

In the SO₄ model of the Nubian aquifer (Fig. 5.25), high values are observed in the centre of Gezira in Kamlin Province (Saeed, 1976). In the SO₄ model of the Gezira aquifer (Fig. 5.26), low values are observed in Gezira Province. High concentrations of SO₄ are noted at Wagara and Faragir, which are points of salinity, in Kamlin Province.

5.5.14 Bicarbonate (HCO₃)

In the HCO₃ model of the Nubian aquifer (Fig. 5.27), high values of HCO₃ are observed at Soba, and in the western and central parts of Kamlin Province and the central part of Managil Province. Low values of HCO₃ are noticed at Faragalla in Kamlin Province. In the HCO₃ model of the Gezira aquifer (Fig. 5.28), high values of HCO₃ are noticed at Soba, and in the western part of Kamlin Province and the central part of Managil Province. Generally, many parts of the Gezira State have high values of HCO₃ in both the Gezira and Nubian aquifers. This is because the Blue and White Niles, which are rich in bicarbonates, are the main sources of recharges to the two aquifers in the Gezira area (Saeed, 1976).
5.5.15 Ammonia (NH₃)

In the NH₃ model of the Nubian aquifer (Fig. 5.29), high concentrations of NH₃ are observed at Soba hospital and at various locations in the west of Kamlin Province, the west of Managil Province and the east and south of Butana and Umm El Gura Provinces. Low values are observed at the two banks of The Blue Nile in Kamlin and Butana Provinces and in the northern part of Managil province.

In the NH₃ model of the Gezira aquifer (Fig. 5.30), high values of NH₃ are observed at the two banks of the Blue Nile and at Kamlin, Butana and Gezira Provinces.

5.5.16 Nitrite (NO₂)

In the Nubian NO₂ model (Fig. 5.31), the high values were recorded in the west of Gezira Province (1.2mg/l at Asair).

In the Gezira NO₂ model (Fig. 5.32), the high values were in Managil Province (2mg /l at El Zareiba). For the two aquifers zero value of Nitrite is common.
5.5.17 Nitrate (NO₃)
In the NO₃ model of the Nubian aquifer (Fig. 5.33), high levels of NO₃ are noticed in the west of Gezira State near the White Nile and this may be due to local contamination.
In the NO₃ model of the Gezira aquifer (Fig. 5.34), high levels of NO₃ are observed at the banks of the Blue Nile and in Butana and Um El Gura Provinces.

5.5.18 Silica (SiO₂)
In the SiO₂ model of the Nubian aquifer (Fig. 5.35), high values of Silica are observed in the south of Gezira Province and the centre of Managil Province, while low values are noticed in the west of Gezira State. The high values may be due to the occurrence of agates and cherts in the aquifer's sediments (Abdel Salam, 1966).
In the SiO₂ model of the Gezira (Fig. 5.36), high levels of SiO₂ are observed near the White Nile in the southern part of the Gezira state.
5.5.19 Albuminoidal Ammonia (Albumin)

In the Nubian Model (Fig. 5.37), high values are found at the banks of the Blue and White Niles and in the north of Kamlin Province. In the Gezira Albumin Model (Fig. 5.38), high values are observed close to the Blue Nile (Hasahisa, Gezira and Um El Gura Provinces) and near the White Nile. These high values of albumin may be due to the presence of buried plant debris underneath these areas.

5.5.20 Well Depth

In the well depth model of the Nubian aquifer (Fig. 5.39), low values of depth are noticed around the Blue Nile and the White Nile. High values of depth are noticed in Kamlin Province and the western side of Managil Province. This proves that groundwater in the Gezira area is recharged from The Blue and White Niles, and as a result the hydraulic gradient increases away from the two Niles. In the well depth model of the Gezira aquifer (Fig. 5.40), high values of depth are noted in the south of Gezira Province, and Managil and Kamlin Provinces, while low values of depth are around the White Nile and the Blue Nile.
5.5.21 Static Water Level (SWL)

In the SWL model of the Nubian aquifer (Fig. 5.41), high values of SWL are realized in Kamlin and Managil Provinces, while low values of SWL are around the two Niles. In Butana and Umm El Gura Provinces, low static water levels are near the Blue Nile and increase towards the east direction. This is because the static water level is higher near the rivers than in the surroundings as a result of the reduction in effective head by frictional and capillary effects in the pore spaces of the aquifers (Abdel Salam, 1966).

In the SWL model of the Gezira aquifer (Fig. 5.42), low static water levels are observed around the two Niles, while high levels are found in Managil and Kamlin Provinces.

5.6 Comparison between Recent Data and model results

To show the credibility of the established chemical models in predicting reasonable chemical values, a comparison of a recent data (Appendix D) with the corresponding results obtained from the developed models was carried out. As mentioned in section (3.2), the recent data was collected from four regions, namely Managil, Kamlin and Hasahisa, Butana and Um El Gura and Gezira Provinces.
The borders of these regions were approximately determined and superimposed on each of the models achieved (Figs. 5.1 – 5.42). Then the identifier tool of the GIS was utilized to scan the filled contours of each region for determining the minimum and maximum values for the modeled parameter under consideration. The chemical parameters are in mg/l.

5.6.1 Managil Province

Managil Province is in the western side of The Gezira State between latitudes 13.58° - 14.62° N and longitudes 32.42° - 33.30°E. The area of the province is underlain by two aquifers, the Gezira aquifer and the Nubian sandstone aquifer. Their thicknesses have been found to be 40 m and 50 m, respectively. The quality of groundwater in the Nubian aquifer is better than that of the Gezira aquifer (Abd El Rahman, 2003).

Tables (5.1 & 5.2) show the chemical results obtained from the study of the sampled Nubian and Gezira wells in Managil Province (Appendix D.1) as compared to those identified using the established models.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recent Data</th>
<th>Model Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.4 - 9.5</td>
<td>7.35 – 9.5</td>
</tr>
<tr>
<td>TDS</td>
<td>203 - 2390</td>
<td>180 - 2587</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>100 - 475</td>
<td>75 - 565</td>
</tr>
<tr>
<td>Ca</td>
<td>13 - 210</td>
<td>10.7 - 209</td>
</tr>
<tr>
<td>Mg</td>
<td>6 -35</td>
<td>4.9 - 76</td>
</tr>
<tr>
<td>K</td>
<td>1.5 – 15.7</td>
<td>1.2 – 18.1</td>
</tr>
<tr>
<td>Na</td>
<td>45 - 470</td>
<td>26 - 464</td>
</tr>
<tr>
<td>F</td>
<td>0.01 - 0.9</td>
<td>0.01 - 0.99</td>
</tr>
<tr>
<td>SO₄</td>
<td>42 - 180</td>
<td>10.2 - 180</td>
</tr>
<tr>
<td>HCO₃</td>
<td>170 - 445</td>
<td>87 -414</td>
</tr>
<tr>
<td>NO₃</td>
<td>0.0</td>
<td>0.0 - 16</td>
</tr>
<tr>
<td>Cl</td>
<td>14.3 - 910</td>
<td>4 - 1080</td>
</tr>
</tbody>
</table>

**Table (5.1) Comparison for Managil Province**

*(Gezira Aquifer)*
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recent Data</th>
<th>Model Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.9- 8.1</td>
<td>7.5 - 8.5</td>
</tr>
<tr>
<td>TDS</td>
<td>166 - 510</td>
<td>152 - 780</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>140 - 250</td>
<td>76 - 340</td>
</tr>
<tr>
<td>Ca</td>
<td>20 - 53</td>
<td>10 - 71</td>
</tr>
<tr>
<td>Mg</td>
<td>21 – 60</td>
<td>6 - 69</td>
</tr>
<tr>
<td>K</td>
<td>3.8 –6.8</td>
<td>1 - 21</td>
</tr>
<tr>
<td>Na</td>
<td>70 –75</td>
<td>15- 123</td>
</tr>
<tr>
<td>F</td>
<td>0.0 - 0.9</td>
<td>0.001 – 1.09</td>
</tr>
<tr>
<td>SO₄</td>
<td>20.5 – 63.5</td>
<td>5 - 98</td>
</tr>
<tr>
<td>HCO₃</td>
<td>287 - 340</td>
<td>183 - 398</td>
</tr>
<tr>
<td>NO₃</td>
<td>0.0</td>
<td>0.0 - 7</td>
</tr>
<tr>
<td>Cl</td>
<td>18 - 144</td>
<td>4.2 - 160</td>
</tr>
</tbody>
</table>

Table (5.2) Comparison for Managil Province (Nubian Aquifer)

5.6.2 Hasahisa & Kamlin Provinces

Hasahisa and Kamlin Localities cover a vast area which forms about 21% of the Gezira State area. They lie between latitudes 14.6°- 15.5° N and longitudes 32.5° -33.4° E and are boarded by the Blue Nile to the east (Gar El Nabi, 2004). The groundwater occurs in the area at the two aquifers, Gezira and Nubian. The Gezira aquifer is the main aquifer in the area. There is an upper Gezira aquifer supplying the shallow wells at depths of 30- 45 m,
and a lower Gezira aquifer supplying deep boreholes at depths exceeding 90m. The Nubian sandstone in this area occurs at greater depths and so it is not exploited as in other parts of the Sudan.

Table (5.3) shows the comparison between the chemical results obtained from the sampled wells in Hasahisa & Kamlin Provinces (Appendix D.2) as compared to those identified using the modeled parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recent Data</th>
<th>Model Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.5 - 8.9</td>
<td>7.4 - 8.8</td>
</tr>
<tr>
<td>TDS</td>
<td>190 - 4948</td>
<td>170 - 4120</td>
</tr>
<tr>
<td>CaCO$_3$</td>
<td>78 - 2100</td>
<td>44 - 1920</td>
</tr>
<tr>
<td>Ca</td>
<td>16 - 90</td>
<td>17.5 - 96</td>
</tr>
<tr>
<td>Mg</td>
<td>10 - 35</td>
<td>3.1 - 69</td>
</tr>
<tr>
<td>K</td>
<td>0 - 10</td>
<td>0.7 - 20</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>115 - 840</td>
<td>86 - 891</td>
</tr>
<tr>
<td>Na</td>
<td>21 - 82</td>
<td>10 - 102</td>
</tr>
<tr>
<td>F</td>
<td>0.0 - 2.5</td>
<td>0.05 - 1.5</td>
</tr>
<tr>
<td>SO$_4$</td>
<td>13 - 990</td>
<td>5 - 1141</td>
</tr>
<tr>
<td>SWL</td>
<td>17 - 34</td>
<td>12.5 - 39</td>
</tr>
<tr>
<td>Depth</td>
<td>40 - 100</td>
<td>25 - 121</td>
</tr>
<tr>
<td>Cl</td>
<td>5.6 - 972</td>
<td>6 - 980</td>
</tr>
<tr>
<td>HCO$_3$</td>
<td>16.8 - 342</td>
<td>65 - 393</td>
</tr>
<tr>
<td>NO$_3$</td>
<td>0.0 - 34</td>
<td>0.0 - 20</td>
</tr>
</tbody>
</table>

**Table (5.3) Comparison for Hasahisa & Kamlin Provinces**

*(Gezira Aquifer)*
5.6.3 Butana & Umm El Gura

Butana and Um El Gura Provinces, lie between latitudes 14.00° - 15.30° N and longitudes 33.00° - 34.25° E. The Nubian Sandstone formation represents the major aquifer in this area. The water occurs at shallow depths and is characterized by good quality, (Ali, 2004). Table (5.4.) shows the comparison between the chemical results obtained from the sampled wells in Butana & Umm El Gura (Appendix D.3) as compared to those identified using the modeled parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recent Data</th>
<th>Model Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.7 - 8.8</td>
<td>7.1 - 8.81</td>
</tr>
<tr>
<td>TDS</td>
<td>226 - 520</td>
<td>165 - 710</td>
</tr>
<tr>
<td>Ca</td>
<td>20 - 85</td>
<td>5 - 80</td>
</tr>
<tr>
<td>Mg</td>
<td>10 - 32</td>
<td>2.4 - 40</td>
</tr>
<tr>
<td>K</td>
<td>5 - 65</td>
<td>1 - 49</td>
</tr>
<tr>
<td>Na</td>
<td>10 - 155</td>
<td>10 - 140</td>
</tr>
<tr>
<td>F</td>
<td>0.2 - 1.0</td>
<td>0.02 - 1.4</td>
</tr>
<tr>
<td>SO₄</td>
<td>15 - 200</td>
<td>1.6 - 260</td>
</tr>
<tr>
<td>SWL</td>
<td>16.3 - 64</td>
<td>11.1 - 63.9</td>
</tr>
<tr>
<td>Depth</td>
<td>80 - &gt; 150</td>
<td>67 - 165</td>
</tr>
<tr>
<td>Cl</td>
<td>10 - 150</td>
<td>8 - 143</td>
</tr>
</tbody>
</table>

Table (5.4) Comparison for Butana & Um El Gura Provinces

(Nubian Aquifer)
5.6.4 Gezira Province

Gezira Province is one of the six provinces of the Gezira State. It is located between latitudes 14.36°- 14.51° N and longitudes 32.59°-33.30° E (Ahmed 2003). Groundwater occurs in the Nubian and the Gezira formations. Most of the drinking water in the Gezira Province comes mainly from the Gezira aquifer which is characterized by good water (Ibid).

Table (5.5) shows the comparison between the results obtained from the study carried out in Gezira province (Appendix D.4) and those identified using the established models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Field Results</th>
<th>Model Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.2 - 8.6</td>
<td>7.1 – 8.7</td>
</tr>
<tr>
<td>TDS</td>
<td>126 - 547</td>
<td>146 - 513</td>
</tr>
<tr>
<td>Ca</td>
<td>20 - 40</td>
<td>5 - 87</td>
</tr>
<tr>
<td>Mg</td>
<td>4.8 - 38</td>
<td>5.2 - 56</td>
</tr>
<tr>
<td>K</td>
<td>0 - 15</td>
<td>0.7 -10</td>
</tr>
<tr>
<td>Na</td>
<td>15 - 35</td>
<td>10 - 78</td>
</tr>
<tr>
<td>Cl</td>
<td>5 - 60</td>
<td>4.5 – 62.8</td>
</tr>
<tr>
<td>F</td>
<td>0.2 - 1.2</td>
<td>0.01 - 1.2</td>
</tr>
<tr>
<td>SO4</td>
<td>0.0 - 40</td>
<td>1.9 - 77</td>
</tr>
<tr>
<td>SWL</td>
<td>13 - 36</td>
<td>10.3 – 40.3</td>
</tr>
<tr>
<td>Depth</td>
<td>66 - 100</td>
<td>38 -123</td>
</tr>
</tbody>
</table>

**Table (5.5) Comparison for Gezira Province (Gezira Aquifer)**
5.7 Integrated Model for the Groundwater in the Gezira Area

As described in section (4.7), all the collected chemical data of the Nubian and Gezira aquifers was included in a single map using ArcMap of the GIS (Fig.4.2). Also, the models of the individual chemical parameters with regard to the two aquifers were obtained using the IDW method of the GIS (Figs. 5.1 – 5.42). Making use of the GIS mapping facilities, it was found possible to integrate the chemical data of the two aquifers and all the above mentioned models as layers of one model.

For clarification, part of this integrated model is shown in Fig. (5.43). To obtain the chemical attributes of any point within the geographical area represented by the integrated model, all the layers of the model must be maintained active by checking them as shown on the left pane of Figure (5.43). Then by using the identifier tool of the GIS, to determine the required location of the point on the map, and by double-clicking on the active layers of the model, predicted or recorded values of the chemical attributes of groundwater at the chosen location could be immediately obtained.
5.8 Evolution of the chemistry of the Gezira Groundwater

The changes that occur with time in the chemistry of the Gezira groundwater can be studied by taking water samples from earmarked wells throughout the Gezira at specified regular intervals of time. This would require scheduled monitoring of the selected wells and accurate recording of the results of the water analyses. Unfortunately, no such monitored data has been found in the entire historical records of the Gezira groundwater.

However in this research, a tentative conclusion of the effect of time on the Gezira groundwater chemistry was drawn by considering the comparison results shown in Tables (5.1 - 5.5). It is clearly evident that no considerable changes have occurred. Almost all the chemical parameter values determined from the field samples are contained within the ranges identified by the models.
CHAPTER VI

STATISTICAL ANALYSIS OF THE DATA

6.1 Univariate Statistical Analysis

6.1.1 Histograms and Statistics

The "Frequencies" tool of the statistical package SPSS 13.0 was utilized to determine the frequency distribution, (histogram) of each individual chemical data and its corresponding statistics, regarding central tendency, dispersion and distribution. The "Frequencies" tool provides a univariate description of the data. This tool generates the frequency distribution for each dataset of interest and calculates summary statistics. The bar graph of the frequency distribution displays how often the recorded values of a certain chemical fall within the specified classes of the data. As a consequence, the important features of the frequency distribution can be summarized by a few statistical measures that yield its central tendency (medium, median), spread (standard deviation, minimum, maximum & S.E. mean) and shape (skewness & kurtosis). The statistical parameters are given in Tables (6.1 - 6.4). All the Chemical parameters in these tables are in mg/l except pH and E.C.
<table>
<thead>
<tr>
<th>Chemical Parameter</th>
<th>No. of Samples</th>
<th>Mean</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Standard Error of mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>576</td>
<td>8.09</td>
<td>8.10</td>
<td>0.397</td>
<td>0.0165</td>
</tr>
<tr>
<td>TDS</td>
<td>597</td>
<td>364.8</td>
<td>320</td>
<td>177.145</td>
<td>7.250</td>
</tr>
<tr>
<td>EC</td>
<td>482</td>
<td>515</td>
<td>440</td>
<td>232.011</td>
<td>10.568</td>
</tr>
<tr>
<td>Ca</td>
<td>567</td>
<td>33.05</td>
<td>30</td>
<td>16.686</td>
<td>0.701</td>
</tr>
<tr>
<td>Mg</td>
<td>560</td>
<td>19.06</td>
<td>15</td>
<td>12.123</td>
<td>0.512</td>
</tr>
<tr>
<td>Na</td>
<td>433</td>
<td>51.12</td>
<td>45</td>
<td>32.214</td>
<td>1.548</td>
</tr>
<tr>
<td>K</td>
<td>324</td>
<td>7.12</td>
<td>5</td>
<td>7.959</td>
<td>0.442</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>594</td>
<td>245.5</td>
<td>230</td>
<td>118.813</td>
<td>4.875</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>591</td>
<td>165.5</td>
<td>140</td>
<td>119.480</td>
<td>4.915</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>470</td>
<td>124</td>
<td>105</td>
<td>104.208</td>
<td>4.807</td>
</tr>
<tr>
<td>Cl</td>
<td>572</td>
<td>34.52</td>
<td>25</td>
<td>32.042</td>
<td>1.340</td>
</tr>
<tr>
<td>F</td>
<td>510</td>
<td>0.536</td>
<td>0.5</td>
<td>0.397</td>
<td>0.018</td>
</tr>
<tr>
<td>SO₄</td>
<td>547</td>
<td>45.24</td>
<td>35</td>
<td>41.072</td>
<td>1.756</td>
</tr>
<tr>
<td>HCO₃</td>
<td>141</td>
<td>230.5</td>
<td>220.4</td>
<td>83.969</td>
<td>7.071</td>
</tr>
<tr>
<td>NH₃</td>
<td>121</td>
<td>0.181</td>
<td>0.06</td>
<td>.364</td>
<td>0.033</td>
</tr>
<tr>
<td>NO₂</td>
<td>118</td>
<td>0.059</td>
<td>0.003</td>
<td>.183</td>
<td>0.017</td>
</tr>
<tr>
<td>NO₃</td>
<td>179</td>
<td>1.8</td>
<td>0.40</td>
<td>3.233</td>
<td>0.242</td>
</tr>
<tr>
<td>SiO₂</td>
<td>31</td>
<td>11.22</td>
<td>8.00</td>
<td>13.461</td>
<td>2.418</td>
</tr>
<tr>
<td>Albumin</td>
<td>117</td>
<td>0.75</td>
<td>0.24</td>
<td>1.336</td>
<td>0.124</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>746</td>
<td>114.4</td>
<td>100.6</td>
<td>56.296</td>
<td>2.061</td>
</tr>
<tr>
<td>SWL (m)</td>
<td>626</td>
<td>28.7</td>
<td>26.4</td>
<td>14.337</td>
<td>0.573</td>
</tr>
</tbody>
</table>

Table (6.1) Summary of Statistics (Nubian Aquifer)
<table>
<thead>
<tr>
<th>Chemical Parameter (mg/l)</th>
<th>No. of Samples</th>
<th>Mean</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Standard Error of mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>457</td>
<td>8.15</td>
<td>8.20</td>
<td>0.387</td>
<td>0.0181</td>
</tr>
<tr>
<td>TDS</td>
<td>471</td>
<td>501.2</td>
<td>320</td>
<td>550.655</td>
<td>25.373</td>
</tr>
<tr>
<td>EC</td>
<td>408</td>
<td>717.2</td>
<td>473.5</td>
<td>743.840</td>
<td>36.826</td>
</tr>
<tr>
<td>Ca</td>
<td>450</td>
<td>35.9</td>
<td>30</td>
<td>24.115</td>
<td>1.1368</td>
</tr>
<tr>
<td>Mg</td>
<td>442</td>
<td>19</td>
<td>15.65</td>
<td>11.792</td>
<td>0.561</td>
</tr>
<tr>
<td>Na</td>
<td>324</td>
<td>79.5</td>
<td>55.5</td>
<td>81.062</td>
<td>4.503</td>
</tr>
<tr>
<td>K</td>
<td>177</td>
<td>6.3</td>
<td>5</td>
<td>5.063</td>
<td>0.381</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>452</td>
<td>222.1</td>
<td>200</td>
<td>101.093</td>
<td>4.755</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>463</td>
<td>185.5</td>
<td>150</td>
<td>180.692</td>
<td>8.397</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>338</td>
<td>105.1</td>
<td>84.5</td>
<td>96.723</td>
<td>5.261</td>
</tr>
<tr>
<td>Cl</td>
<td>446</td>
<td>77</td>
<td>25.0</td>
<td>163.734</td>
<td>7.753</td>
</tr>
<tr>
<td>F</td>
<td>376</td>
<td>0.5164</td>
<td>0.465</td>
<td>.344</td>
<td>0.018</td>
</tr>
<tr>
<td>SO₄</td>
<td>417</td>
<td>63.2</td>
<td>35</td>
<td>129.296</td>
<td>6.331</td>
</tr>
<tr>
<td>HCO₃</td>
<td>141</td>
<td>227.5</td>
<td>207</td>
<td>116.497</td>
<td>9.811</td>
</tr>
<tr>
<td>NH₃</td>
<td>163</td>
<td>0.232</td>
<td>0.04</td>
<td>0.602</td>
<td>0.047</td>
</tr>
<tr>
<td>NO₃</td>
<td>118</td>
<td>0.098</td>
<td>0.0025</td>
<td>0.281</td>
<td>0.026</td>
</tr>
<tr>
<td>NO₃²</td>
<td>208</td>
<td>2.736</td>
<td>0.58</td>
<td>5.497</td>
<td>0.381</td>
</tr>
<tr>
<td>SiO₂</td>
<td>76</td>
<td>25.124</td>
<td>15.50</td>
<td>23.914</td>
<td>2.743</td>
</tr>
<tr>
<td>Albumin</td>
<td>105</td>
<td>0.498</td>
<td>0.10</td>
<td>0.992</td>
<td>0.097</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>597</td>
<td>67.9</td>
<td>64.8</td>
<td>18.682</td>
<td>0.765</td>
</tr>
<tr>
<td>SWL (m)</td>
<td>541</td>
<td>23.24</td>
<td>21.40</td>
<td>7.955</td>
<td>0.342</td>
</tr>
</tbody>
</table>

**Table (6.2) Summary of Statistics (Gezira Aquifer)**
<table>
<thead>
<tr>
<th>Chemical Parameter (mg/l)</th>
<th>Min. Value</th>
<th>Max. Value</th>
<th>95% confidence interval of mean</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower bound</td>
<td>upper bound</td>
<td></td>
</tr>
<tr>
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**Table (6.3) Extra Statistical Parameters (Nubian Aquifer)**
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<th>Chemical Parameter (mg/l)</th>
<th>Min. Value</th>
<th>Max. Value</th>
<th>95% confidence interval of mean</th>
<th>Skewness</th>
<th>Kurtosis</th>
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<td>upper bound</td>
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<td>23.911</td>
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</table>

Table (6.4) Extra Statistical Parameters (Gezira Aquifer)
Figures (6.1 - 6.42) display normal distributions added to the histograms of the important chemical constituents of the groundwater samples of the Gezira area with respect to the Nubian and Gezira aquifers.

6.1.2 Remarks on the Conventional Statistical Results

In the following subsections the salient remarks on the results of the descriptive statistics of the chemical data of the Gezira area will be pointed out.

It should be noted that the column designated as "No. of Samples" (Tables 6.1 & 6.2) refers to the number of occurrences of the specified chemical parameter with respect to the chemical analysis of the total number of collected water samples. The total number of water samples considered was 619 for the Gezira aquifer and 753 for the Nubian aquifer (Section 4.4).

It should be pointed out that all the ranges of the data parameters to be discussed in the following sections are referred to the standards quoted in Appendix A.

6.1.2.1 Hydrogen Ion Concentration (pH)

The number of occurrences of pH in the analyzed water samples of the Nubian Aquifer is 576 with a mean value of 8.1. The pH range is from 6.7 to 9.4. About 43% of the samples lie between 7.0 and
8.0. About 90% of the samples are between 7.0 and 8.5 (Fig. 6.1). Therefore, the groundwater in the Nubian aquifer is slightly or moderately alkaline. About 10% of the samples are greater than the upper limit recommended by the Sudanese and the WHO standards (8.5).

The number of occurrences of pH in the analyzed water samples of the Gezira aquifer is 457 with a mean of 8.2. The minimum value is 7.1 whereas the maximum value is 9.5 (at Shikair, (Long. 32.630, Lat. 14.500), in Managil Region). About 85% of the samples are within the standard range. 59% of the samples are between 8.0 and 8.5. About 14% of the samples (Fig 6.2) have exceeded the upper limit set by the Sudanese and the WHO limit (8.5). The Gezira aquifer water is also identified as slightly or moderately alkaline (Saeed, 1976).

![Fig. (6.1) Histogram of pH (Nubian Aquifer)](image-url)
6.1.2.2 Total Dissolved Solids (TDS)

The number of occurrences of TDS in the analyzed water samples of the Nubian aquifer is 597 with a mean value of 365mg/l. The minimum value is 74mg/l and the maximum value is 1352mg/l (Fig. 6.3). All the sample values are below the maximum permissible limit set by the American Public Health Association. Ninety nine percent of the samples are less than 1000mg/l, which is in compliance with the Sudanese and the WHO standard range. Eighty two percent of the samples are less than 500mg/l. Thus, the Nubian aquifer water is fit for human and animal consumption (El

The number of occurrences of TDS in the analyzed water samples of the Gezira aquifer is 471 with a mean value of 501mg/l. The minimum value is 40mg/l and the maximum value is 4120mg/l (at Wagara (Long.32.700, Lat. 15.220) in Kamlin Province). 72% of the samples are less than 500mg/l and 90% of the samples are less than 1000mg/l. Only about 6% of the samples are greater than 1500mg/l (Fig. 6.4). Hence, the Gezira aquifer water is fit for domestic purposes except at locations of high salinity.

Fig. (6.3) Histogram of TDS (mg/l) (Nubian Aquifer)
6.1.2.3 Specific Electrical Conductivity (E.C.)

The number of occurrences of E.C. in the analyzed water samples of the Nubian aquifer is 482 with a mean value of 515\(\mu\)mho/cm. The minimum value is 139\(\mu\)mho/cm and the maximum is 1800\(\mu\)mho/cm (Fig. 6.5). 95% of the samples are less than 1000 \(\mu\)mho/cm.

The number of occurrences of E.C. in the analyzed water samples of the Gezira aquifer is 408 with a mean value of 718\(\mu\)mho/cm. The minimum value is 180\(\mu\)mho/cm and the maximum value is 5240\(\mu\)mho/cm (Fig. 6.6). The maximum value is recorded at Wagara (Long.32.700, Lat. 5.220) in Kamlin province. About 92% of samples are less than 1500\(\mu\)mho/cm (WHO standard) and 86%
of the samples are less than 1000\(\mu\text{mho/cm}\).

![Histogram of E.C. (\(\mu\text{mho/cm}\)) (Nubian Aquifer)](image_url)

**Fig. (6.5) Histogram of E.C. (\(\mu\text{mho/cm}\)) (Nubian Aquifer)**

![Histogram of E.C. (\(\mu\text{mho/cm}\)) (Gezira Aquifer)](image_url)

**Fig. (6.6) Histogram of E.C. (\(\mu\text{mho/cm}\)) (Gezira Aquifer)**

### 6.1.2.4 Calcium (Ca)

The number of occurrences of Ca in the analyzed water samples of the Nubian aquifer is 567 with a mean value of 33.4mg/l. The minimum value is 5mg/l and the maximum value is 98.4mg/l. All
the samples are less than 100mg/l, and this is in compliance with the WHO standard. Also, about 90% of the samples are less than 75mg/l.

The number of occurrences of Ca in the analyzed water samples of the Gezira aquifer is 450 with a mean value of 35.9mg/l. The minimum value is 4mg/l and the maximum is 210mg/l (Fig. 6.8). Only one sample has been found to exceed the maximum permissible limit set by the WHO standard, which is 200mg/l. About 95% of the samples are less than 75mg/l.

![Histogram of Ca (mg/l) (Nubian Aquifer)](image)

**Fig. (6.7) Histogram of Ca (mg/l) (Nubian Aquifer)**
6.1.2.5 Magnesium (Mg)

The number of occurrences of Mg in the analyzed water samples of the Nubian aquifer is 560 with a mean value of 19mg/l. The minimum value is 0.3mg/l and the maximum value is 95mg/l. Only 14 samples (about 2.5%) have exceeded 50mg/l, but they are less than the maximum permissible concentration (150mg/l).

The number of occurrences of Mg in the analyzed water samples of the Gezira aquifer is 442 with a mean value of 19mg/l. The minimum value is 0.9mg/l and the maximum value is 78mg/l. (Fig. 6.10). Similarly, About 2.5% of the samples have exceeded 50mg/l, but not the maximum permissible concentration set by the WHO standard (150mg/l).
6.1.2.6 Sodium (Na)

The number of occurrences of Na in the analyzed water samples of the Nubian aquifer is 433 with a mean value of 51mg/l. The minimum value is 3mg/l and the maximum value is 180mg/l (Fig. 6.11). All the samples are below the allowed limit of the WHO and the Sudanese standards (200mg/l). However, 94% of them are less
than 100mg/l.

The number of occurrences of Na in the analyzed water samples of the Gezira aquifer is 324 with a mean value of 79.5mg/l. The minimum value is 2mg/l (at Wad El Hadad (Long. 33.540, Lat. 13.830) in Gezira Province) and the maximum value is 492 mg/l (at Managil city, Long. 32.980, Lat. 14.380). Only about 3.7% of the samples are greater than 200 mg/l (Fig. 6.12).

**Fig. (6.11) Histogram of Na (mg/l) (Nubian Aquifer)**

**Fig. (6.12) Histogram of Na (mg/l) (Gezira Aquifer)**
6.1.2.7 Potassium (K)

The number of occurrences of K in the analyzed water samples of the Nubian aquifer is 324 with a mean value of 7.1mg/l. The minimum value is 0.2mg/l and the maximum is 50mg/l (Fig. 6.13). About 87% of the samples are below the permissible limit, which is 10mg/l.

The number of occurrences of K in the analyzed water samples of the Gezira aquifer is 177 with a mean value of 6.3mg/l. The minimum value recorded is 0.3 mg/l and the maximum is 32mg/l (at El Bagair, Long. 32.750, and Lat. 15.380). About 91% of the samples are below the permissible limit, which is 10mg/l (Fig. 6.14).

**Fig. (6.13) Histogram of K (mg/l) (Nubian Aquifer)**
6.1.2.8 Alkalinity

The number of occurrences of Alkalinity in the analyzed water samples of the Nubian aquifer is 594 with a mean value of 246mg/l. The minimum value is 18mg/l and the maximum value is 920mg/l. About 96.5% of the samples are less than 500 mg/l (Fig. 6.15).

The number of occurrences of Alkalinity in the analyzed water samples of the Gezira aquifer is 452 with a mean value of 222mg/l. The minimum value is 20mg/l and the maximum value, 895mg/l, is at Umm Degarsi (Long. 33.230, Lat. 14.980) in Kamlin Province. Only about 2% of the samples are greater than 500mg/l (Fig. 6.16).
6.1.2.9 Calcium Carbonate (CaCO$_3$)

The number of occurrences of CaCO$_3$ in the analyzed water samples of the Nubian aquifer is 591 with a mean value of 166mg/l. The minimum value is 20mg/l (at Hamadab, (Long.
32.800, Lat. 14.780) in Kamlin Province, and at Soba, Log. 32.650, Lat. 15.500). The maximum value is 1340mg/l (at Wad Limeid (Long. 32.980, Lat. 15.190) in Kamlin province). About 12% of the samples are in the range of 0 to 75mg/l (soft water). Forty two percent of the samples are in the range of 75 to 150mg/l (moderately hard), and about 40% of the samples are in the range of 150 to 300mg/l (hard water). About 6% of the samples are greater than 300mg/l (very hard water).

The number of occurrences of CaCO₃ in the analyzed water samples of the Gezira aquifer is 463 with a mean value of 185.5mg/l. The minimum value is 16mg/l (at Soba West, Long. 32.610, Lat. 15.510), and the maximum value is 1920mg/l (at El Farageen (Long. 32.761, Lat. 15.180) in Kamlin Province). About 7% of the samples are less than 75mg/l (soft water), and about 43% of the samples are in the range of 75 to 150mg/l (moderately hard water). About 37.9% of the samples are in the range of 150 to 300mg/l (hard water), and 7% of the samples are greater than 300mg/l (very hard water) (Fig. 6.18).
6.1.2.10 Excess Alkalinity (Na$_2$CO$_3$)

The number of occurrences of Sodium Carbonate in the analyzed water samples of the Nubian aquifer is 470 with a mean value of 124mg/l. The minimum value is 2 mg/l, whereas the maximum value is 660mg/l. The maximum accepted level is 500mg/l. About
95% of the samples are less than 300mg/l. Only six samples, which constitute about 1.3% of the samples, have exceeded 500 mg/l (Fig. 6.19).

The number of occurrences of Sodium Carbonate in the analyzed water samples of the Gezira aquifer is 338 with a mean value of 105.1mg/l. The minimum value is 2; whereas the maximum value is 640mg/l. 89% of the samples are less than 200mg/l. Only four samples, which constitute about 1.2% of the samples, are greater than 500mg/l (Fig. 6.20).

![Histogram](image)

**Fig. (6.19) Histogram of Na$_2$CO$_3$ (mg/l) (Nubian Aquifer)**
6.1.2.11 Chloride (Cl)

The number of occurrences of Cl in the analyzed water samples of the Nubian aquifer is 572 with a mean value of 34.5mg/l. The minimum value is 2.8mg/l, whereas the maximum value is 210mg/l. All the sample values are below the level set by the Sudanese and the WHO standards, which is 250mg/l. Five samples, which constitute about 1%, have exceeded 150mg/l (Fig. 6.21).

The number of occurrences of Cl in the analyzed water samples of the Gezira aquifer is 446 with a mean value of 77mg/l. The minimum value is 2.3mg/l, whereas the maximum value is 1120mg/l. About 93% of the samples are below 250 mg/l. About 88% of the samples are less than 150mg/l. Therefore, as far as Chloride is
concerned, the Gezira aquifer water is appropriate for all purposes.

**Fig. (6.21) Histogram of Cl (mg/l) (Nubian Aquifer)**

**Fig. (6.22) Histogram of Cl (mg/l) (Gezira Aquifer)**

6.1.2.12 Fluoride (F)

The number of occurrences of Fluoride in the analyzed water samples of the Nubian aquifer is 510 with a mean value of 0.536mg/l. The minimum value is 0.02mg/l and the maximum is
2.1mg /l. About 98% of the samples are less than 1.5mg/l, and thus complying with the Sudanese and WHO standards (Fig. 6.23).

The number of occurrences of Fluoride in the analyzed water samples of the Gezira aquifer is 376 with a mean value of 0.516mg/l. The minimum value is 0.02mg/l, whereas the maximum value is 1.8mg/l (at Wad Hamadnalla (Long. 33.600, Lat. 15.050) in Butana Province). The same range of concentration of fluoride was found by Saeed (1976). 98.6% of the samples (Fig. 6.24) are less than 1.5mg/l (the Sudanese and WHO standards).

**Fig. (6.23) Histogram of F (mg/l) (Nubian Aquifer)**
6.1.2.13 Sulphate (SO₄)

The number of occurrences of SO₄ in the analyzed water samples of the Nubian aquifer are 547 with a mean value of 45.2mg/l. The minimum value is 0.2mg/l (at El Mahas El Rigaiba (Long. 33.260, Lat. 15.130) in Kamlin province), and the maximum value is 450mg/l (at Umm Alaga (Long. 32.530, Lat. 14.880) in the west of Kamlin Province) (Fig. 6.25). Only about 0.36% of the samples have exceeded the highest permissible limit of the Sudanese and the WHO standards (250mg/l).

The number of occurrences of SO₄ in the analyzed water samples of the Gezira aquifer is 417 with a mean of 63.2mg/l. The minimum value is 4mg/l, whereas the maximum value is 1250mg/l. About 98% of the samples are less than 250mg/l. About 1.6% of
the samples are greater than 250mg/l (Fig. 6.26).

![Histogram of SO₄ (mg/l) (Nubian Aquifer)](image)

**Fig. (6.25) Histogram of SO₄ (mg/l) (Nubian Aquifer)**

![Histogram of SO₄ (mg/l) (Gezira Aquifer)](image)

**Fig. (6.26) Histogram of SO₄ (mg/l) (Gezira Aquifer)**

### 6.1.2.14 Bicarbonate (HCO₃)

The number of occurrences of HCO₃ in the analyzed water samples of the Nubian aquifer are 141 with a mean value of 230.4. The minimum value is 18mg/l, whereas the maximum value is 479mg/l. All the samples are less than 500mg/l (Fig. 6.27).
The number of occurrences of $\text{HCO}_3$ in the analyzed water samples of the Gezira aquifer is 141 with a mean value of 228mg/l. The minimum value is 50mg/l, whereas the maximum value is 840mg/l at Soba Rabie (Long. 32.590, Lat. 15.470). About 95.7% of the samples are less than 500mg/l (Fig. 6.28).

**Fig. (6.27) Histogram of HCO$_3$ (mg/l) (Nubian Aquifer)**

**Fig. (6.28) Histogram of HCO$_3$ (mg/l) (Gezira Aquifer)**
6.1.2.15 Ammonia (NH₃)

The number of occurrences of NH₃ in the analyzed water samples of the Nubian aquifer is 121 with a mean value of 0.18mg/l. The minimum value is 0.1mg/l, whereas the maximum value is 2.46mg/l. About 98 % of the samples (Fig. 6.29) are less than the limit set by the standards (1.5mg/l).

The number of occurrences of NH₃ in the analyzed water samples of the Gezira aquifer is 163 with a mean value of 0.232mg/l. The minimum value is 0.1mg/l, whereas the maximum value is 3.88mg/l. About 96 % of the samples are below the maximum permissible level (Fig. 6.30).

![Histogram of NH₃ (mg/l) (Nubian Aquifer)](image)

**Fig. (6.29) Histogram of NH₃ (mg/l) (Nubian Aquifer)**
6.1.2.16 Nitrite (NO$_2$)

The number of occurrences of NO$_2$ in the analyzed water samples of the Nubian aquifer is 118 with a mean value of 0.058mg/l. The minimum value is zero; whereas the maximum value is 1.2mg/l. Almost half of the samples are zero. All the samples are below the maximum permissible limit of the Sudanese and the APHA standards, which is 2mg/l (Fig. 6.31).

The number of occurrences of NO$_2$ in the analyzed water samples of the Gezira aquifer is 118 with a mean value of 0.098mg/l. The minimum value is zero, whereas the maximum value is 2mg /l (at El Zareiba (Long. 32.980, Lat. 14.370) in Managil Province). Half of the samples are of zero value and the whole data is below the limit set by the Sudanese and APHA standards (Fig. 6.32).
6.1.2.17 Nitrate (NO₃)

The number of occurrences of NO₃ in the analyzed water samples of the Nubian aquifer is 179 with a mean value of 1.8mg/l. The minimum value is zero, whereas the maximum value is 20mg/l. One third of the samples are zero. According to The Sudanese,
WHO, and the APHA standards for Nitrate, which is 50mg/l, all the samples of the Nubian aquifer water are safe (Fig. 6.33).

The number of occurrences of NO$_3$ in the analyzed water samples of the Gezira aquifer is 208 with a mean value of 2.736mg/l. The minimum value is zero, whereas the maximum value is 27mg/l. the whole data of NO$_3$ is safe according to the WHO, Sudanese, and APHA standards. The Nitrate concentration in the Gezira Formation is low (Fig.6.34), which coincide with (Saeed, 1976).

![Histogram of NO$_3$ (mg/l) (Nubian Aquifer)](image)

**Fig. (6.33) Histogram of NO$_3$ (mg/l) (Nubian Aquifer)**
Fig. (6.34) Histogram of NO$_3$ (mg/l) (Gezira Aquifer)

6.1.2.18 Silica (SiO$_2$)

The number of occurrences of SiO$_2$ in the analyzed water samples of the Nubian aquifer is 31 with a mean value of 11.2mg/l. The minimum value is 0.005, whereas the maximum value is 50mg/l (Fig.6.35).

The number of occurrences of SiO$_2$ in the analyzed water samples of the Gezira aquifer is 76. The mean is 25.1mg/l (Fig. 6.36). The minimum value is 0.002mg/l and the maximum value is 90mg/l (at Wad El Naim (Long. 33.430, Lat. 14.330) in the south of Gezira Province).
6.1.2.19 Albuminoidal Ammonia (Albumin)

The number of occurrences of Albumin in the analyzed water samples of the Nubian aquifer is 117 with a mean value of 0.751mg/l. The minimum value is 0.004mg/l, whereas the maximum value is 8mg/l (Fig. 6.37). 31% of the samples are of
low concentration (less than 0.06mg/l), 10% are of moderate concentration (from 0.06 to 0.15mg/l) and 59% are of high concentration (Greater than 0.15mg/l).

The number of occurrences of Albumin in the analyzed water samples of the Gezira aquifer is 105 with a mean value of 0.497mg/l. The minimum value is 0.005mg/l, whereas the maximum value is 6mg/l. 37% of the samples are of low concentration and about 12% of the samples are of moderate concentration. Fifty two samples, which constitute about 50%, are of high concentration (Fig. 6.38).

![Histogram of Albumin (mg/l) (Nubian Aquifer)](image)

**Fig. (6.37) Histogram of Albumin (mg/l) (Nubian Aquifer)**
Fig. (6.38) Histogram of Albumin (mg/l) (Gezira Aquifer)

6.1.2.20 Well Depth

The number of occurrences of water depth along with the corresponding analyzed water samples of the Nubian aquifer is 746 with a mean of 114m. The minimum value is 22m, whereas the maximum value is 399m (at Debaisia (Long. 32.700, Lat. 15.160) in Kamlin Province). Almost half of the samples are less than 100m. Sixty seven samples, which constitute about 8.2%, are greater than 200m (Fig. 6.39).

The number of occurrences of water depth along with the corresponding analyzed water samples of the Gezira aquifer is 597 with a mean of 68m. The minimum value is 12m, whereas the maximum value is 129.6m. Twenty two samples, which constitute about 3.8 %, are greater than 100m (Fig. 6.40).
6.1.2.21 Static Water Level (SWL)

The number of occurrences of SWL along with the corresponding analyzed water samples of the Nubian aquifer is 626 with a mean value of 28.7m. The minimum value is 6m, whereas the maximum value is 108m. Only 6.6 % of the samples are greater than 50m (Fig. 6.41).
The number of occurrences of SWL along with the corresponding analyzed water samples of the Gezira Aquifer is 541 with a mean of 23.2m. The minimum value of SWL is 4.6m, whereas the maximum value is 50m (Fig. 6.42).

**Fig. (6.41) Histogram of SWL (m) (Nubian Aquifer)**

**Fig. (6.42) Histogram of SWL (m) (Gezira Aquifer)**
6.2 Correlations of the Data

As known, the correlation coefficient between any two chemical parameters is a statistical measure of their association. The statistical package, SPSS 13.0, was employed to compute the correlation coefficients for the chemical data of the Nubian and Gezira aquifers (Section 4.5). The results are shown in the tables of appendix E.

6.3 Regression Analysis of the Data

The stepwise method of the statistical package SPSS 13.0 was used to generate a regression expression for each chemical parameter as related to the observed parameters significantly correlated to it. These parameters were extracted from the correlation tables (appendixes E) by selecting only the parameters corresponding to the significant correlations.

The stepwise regression method would work optimally to find the best regression expression by entering those independent parameters that would yield the minimum standard error of estimation and the maximum value of the coefficient of determination (COD, $R^2$). The COD is a statistical factor used to measure how close the regression expression will represent the
relationship between the dependent and the independent parameters.

The regression expressions of the chemical parameters of the Nubian and Gezira aquifers are shown in Tables (6.5 & 6.6).

<table>
<thead>
<tr>
<th>Chemical parameter</th>
<th>Regression expression</th>
<th>COD (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PH</td>
<td>8.204-0.003Ca</td>
<td>0.02</td>
</tr>
<tr>
<td>TDS</td>
<td>41.858+0.627 EC</td>
<td>0.675</td>
</tr>
<tr>
<td>EC</td>
<td>122.436+1.076 TDS</td>
<td>0.675</td>
</tr>
<tr>
<td>Ca</td>
<td>25.2+0.05 CaCO₃-0.04 Na₂CO₃+0.02 EC-0.07 Na</td>
<td>0.336</td>
</tr>
<tr>
<td>Mg</td>
<td>7.706+0.04CaCO₃+0.141Ca</td>
<td>0.271</td>
</tr>
<tr>
<td>Na</td>
<td>6.717+0.148 HCO₃+19.049 F</td>
<td>0.196</td>
</tr>
<tr>
<td>K</td>
<td>4.993+0.062 Cl</td>
<td>0.062</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>8.307+0.766 HCO₃+0.489 Na₂CO₃</td>
<td>0.656</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>2.6Mg+.46SO₄+3.7Ca+.2TDS-.3EC-.28Alkal+0.85HCO₃-.025Na₂CO₃ - 96.2</td>
<td>0.483</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>55.418+0.572 Alkal-2.175 Ca</td>
<td>0.528</td>
</tr>
<tr>
<td>Cl</td>
<td>6.107+0.078 TDS</td>
<td>0.185</td>
</tr>
<tr>
<td>F</td>
<td>0.4+0.003Na</td>
<td>0.047</td>
</tr>
<tr>
<td>SO₄</td>
<td>12.896+0.064 EC-.003CaCO₃</td>
<td>0.129</td>
</tr>
<tr>
<td>NH₃</td>
<td>0.067+0.152 Alb</td>
<td>0.312</td>
</tr>
<tr>
<td>NO₃</td>
<td>1.252+0.774 Alb</td>
<td>0.102</td>
</tr>
<tr>
<td>Albumin</td>
<td>0.247+1.891 NH₃+0.088 NO₃</td>
<td>0.356</td>
</tr>
</tbody>
</table>

**Table (6.5) Regression Analysis (Nubian Aquifer)**
<table>
<thead>
<tr>
<th>Chemical Parameter</th>
<th>Regression expression</th>
<th>COD (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>8.19 - 0.365 NO₂</td>
<td>0.07</td>
</tr>
<tr>
<td>TDS</td>
<td>-14.306 + 0.719 EC</td>
<td>0.943</td>
</tr>
<tr>
<td>EC</td>
<td>59.856 + 1.312 TDS</td>
<td>0.943</td>
</tr>
<tr>
<td>Ca</td>
<td>18.4 + 0.1 CaCO₃ - 0.1 SO₄ - 0.1 TDS + 0.06 Cl + 0.15 Mg + 0.1 EC - 0.04 Na</td>
<td>0.599</td>
</tr>
<tr>
<td>Mg</td>
<td>12.275 + 0.051 Alkal - 0.055 Na₂CO₃ + 0.391 NO₃</td>
<td>0.203</td>
</tr>
<tr>
<td>Na</td>
<td>-4.959 + 0.167 Cl + 0.688 Ca + 0.211 Alkal</td>
<td>0.311</td>
</tr>
<tr>
<td>K</td>
<td>4.483 - 1.562 Alkal + 0.071 Ca</td>
<td>0.187</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>30.8 + 0.6 Na₂CO₃ + 0.12 EC - 0.13 TDS + 11.3 pH + 0.013 Cl + 0.15 Na</td>
<td>0.463</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>163.6 + 0.58 TDS + 0.68 SO₄ - 0.3 EC + 0.29 Na - 0.36 Cl - 0.92 Na₂CO₃</td>
<td>0.733</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>10.44 + 0.28 Alkal - 1.92 Mg + 57.3 F - 1.21 Ca + 0.37 HCO₃</td>
<td>0.643</td>
</tr>
<tr>
<td>Cl</td>
<td>-47.079 + 0.248 TDS</td>
<td>0.693</td>
</tr>
<tr>
<td>F</td>
<td>0.403 + 0.001 Na₂CO₃</td>
<td>0.092</td>
</tr>
<tr>
<td>SO₄</td>
<td>-52.58 + 0.347 CaCO₃ - 0.02 Cl + 0.083 TDS - 0.51 HCO₃</td>
<td>0.571</td>
</tr>
<tr>
<td>HCO₃</td>
<td>25.32 + 0.37 Alkal + 0.28 EC - 0.15 Cl + 0.58 Na₂CO₃ - 0.26 TDS</td>
<td>0.891</td>
</tr>
<tr>
<td>NH₃</td>
<td>0.083 + 0.301 Alb</td>
<td>0.246</td>
</tr>
<tr>
<td>NO₃</td>
<td>1.456 + 2.571 Alkal</td>
<td>0.215</td>
</tr>
<tr>
<td>Albumin</td>
<td>0.16 + 0.675 NH₃ + 0.066 NO₃</td>
<td>0.373</td>
</tr>
</tbody>
</table>

**Table (6.6) Regression Analysis (Gezira Aquifer)**

With reference to Table (6.5) and considering a coefficient of determination (R²) that is greater than 0.5 as acceptable, only the following regression expressions could be established for the Nubian aquifer:
TDS = 41.858 + 0.627 EC
EC = 122.436 + 1.076 TDS
Alkalinity = 8.307 + 0.766 HCO$_3$ + 0.489 Na$_2$CO$_3$
Na$_2$CO$_3$ = 55.418 + 0.572 Alkal - 2.175 Ca

Similarly, for the Gezira aquifer (table 6.6), only the following regression expressions could be recognized:

TDS = -14.306 + 0.719 EC
EC = 59.856 + 1.312 TDS
Ca = 18.425 + 0.055 CaCO$_3$ - 0.09 SO$_4$ - 0.102 TDS + 0.148 Mg + 0.06 Cl + 0.083 EC - 0.035 Na
CaCO$_3$ = 163.582 + 0.582 TDS + 0.679 SO$_4$ - 0.294 EC + 0.286 Na - 0.359 Cl - 0.922 Na$_2$CO$_3$
Na$_2$CO$_3$ = 10.439 + 0.279 Alkal - 1.917 Mg + 57.28 F - 1.208 Ca + 0.365 HCO$_3$
Cl = -47.079 + 0.248 TDS
SO$_4$ = -52.581 + 0.347 CaCO$_3$ - 0.02 Cl + 0.083 TDS + 0.051 HCO$_3$
HCO$_3$ = 25.319 + 0.374 Alkal + 0.277 EC - 0.153 Cl + 0.581 Na$_2$CO$_3$ - 0.258 TDS
6.4 Multivariate Statistical Analysis

6.4.1 Cluster Analysis

Cluster analysis is normally employed to identify groups of individuals or objects that are similar to each other but different from individuals in other groups.

In this work, the k-means clustering method of the SPSS package was adopted to classify the data of both the Gezira and Nubian aquifers.

The k-means clustering technique was used to classify the water samples into distinct hydrochemical groups. The k-means method is based on minimizing variability within clusters and maximizing variability between clusters.

The above mentioned clustering technique was applied on all the data of the Gezira and Nubian aquifers with the consideration of only the major chemical parameters. The clustering results of the data of the Gezira and the Nubian aquifers are shown in Tables (6.7, 6.8, 6.9 & 6.10).

The major clusters of the Gezira aquifer data are Clusters 3 and 5 (Tables 6.7 and 6.8). Cluster 3 contains 339 samples (about 63.2%) and Cluster 5 contains 111 samples (20.7%).
Parameter* | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 | Cluster 5
---|---|---|---|---|---
E.C. | 1760.25 | 4061.33 | 394.11 | 4067.50 | 894.1
pH | 8.16 | 8.18 | 8.13 | 8.09 | 8.24
TDS | 1694.26 | 1551.50 | 276.17 | 3571.11 | 584.89
CaCO₃ | 240.52 | 347.63 | 142.84 | 1040.75 | 208.53
Alkalinity | 341.59 | 292.81 | 192.69 | 195.25 | 269.60
Na₂CO₃ | 174.90 | 91.50 | 88.57 | 120 | 141.55
HCO₃ | 400.17 | 382.27 | 187.70 | 207 | 252.87
Cl | 306.26 | 387.44 | 25.01 | 902.67 | 88.85
SO₄ | 128.18 | 93.01 | 34.76 | 907.69 | 63.00
Ca | 45.70 | 109.51 | 31.41 | 27.7 | 37.34
Mg | 21.03 | 34.23 | 17.23 | 13.34 | 21.38
Na | 163.06 | 367.47 | 52.5 | 61.47 | 97.67
K | 7.11 | 13.91 | 5.77 | 5.00 | 6.26

**Table (6.7) Final Cluster Centers (Gezira Aquifer)**

* (Parameter concentrations are in mg/l)

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1</th>
<th>38</th>
<th>7.1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>23</td>
<td>4.3%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>339</td>
<td>63.2%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>4.7%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>111</td>
<td>20.7%</td>
<td></td>
</tr>
<tr>
<td>Valid</td>
<td>536</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missing</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table (6.8) Cluster Cases (Gezira Aquifer)**

The major Clusters (3 and 5) together with Cluster 1 (minor) of the Gezira Aquifer are of sodium- calcium- bicarbonate (Na-Ca-HCO₃) water type. These three clusters contain about 488 samples (about
91% of the data). Clusters 4 and 2, representing about 4.6% and 4% of Gezira aquifer data respectively, are minor. The water types in these two clusters are Na-Ca-SO\(_4\), and Na-Ca-Cl.

Sodium (Na), and Calcium (Ca), are the dominant cations in the Gezira aquifer water (all clusters), and the bicarbonates (HCO\(_3\)) are the dominant anions in Clusters 3, 5 (major clusters) and 1(minor cluster). The dominant anion in Clusters 2 and 4 are Cl, and SO\(_4\), respectively.

The sequence of the major cations and anions, in mg/l, according to their concentrations, in a descending order, in the clusters of the Gezira aquifer data are as follows:

Cluster 1: Na > Ca > Mg, HCO\(_3\) > Cl > SO\(_4\)
Cluster 2: Na > Ca > Mg, Cl > HCO\(_3\) > SO\(_4\)
Cluster 3: Na > Ca > Mg, HCO\(_3\) > SO\(_4\) > Cl
Cluster 4: Na > Ca > Mg, SO\(_4\) > Cl > HCO\(_3\)
Cluster 5: Na > Ca > Mg, HCO\(_3\) > Cl > SO\(_4\)

The major clusters of the Nubian aquifer data are Clusters 4, 2, and 3, which are composed of 340 (50%), 187 (27.6%), and 71 (11%) samples respectively (Tables 6.9 & 6.10).
Table (6.9) Final Cluster Centers (Nubian Aquifer)

* (Parameter concentrations are in mg/l)

<table>
<thead>
<tr>
<th>Parameter*</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
<th>Cluster 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>E.C.</td>
<td>2806.20</td>
<td>656.03</td>
<td>1308.8</td>
<td>371.21</td>
<td>6271.67</td>
</tr>
<tr>
<td>pH</td>
<td>8.16</td>
<td>8.03</td>
<td>8.23</td>
<td>8.09</td>
<td>8.18</td>
</tr>
<tr>
<td>TDS</td>
<td>1263.42</td>
<td>459.08</td>
<td>682.16</td>
<td>264.66</td>
<td>3007</td>
</tr>
<tr>
<td>CaCO3</td>
<td>266.39</td>
<td>171.98</td>
<td>201.38</td>
<td>136.09</td>
<td>848.38</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>418.02</td>
<td>269.05</td>
<td>323.14</td>
<td>198.68</td>
<td>329.05</td>
</tr>
<tr>
<td>Na2CO3</td>
<td>160.53</td>
<td>154.83</td>
<td>196.64</td>
<td>94.04</td>
<td>159.5</td>
</tr>
<tr>
<td>HCO3</td>
<td>219.3</td>
<td>279.02</td>
<td>349.71</td>
<td>190.03</td>
<td>207.4</td>
</tr>
<tr>
<td>Cl</td>
<td>62.57</td>
<td>40.36</td>
<td>71.43</td>
<td>23.12</td>
<td>65.58</td>
</tr>
<tr>
<td>SO4</td>
<td>76.29</td>
<td>52.84</td>
<td>71.83</td>
<td>33.7</td>
<td>252.74</td>
</tr>
<tr>
<td>Ca</td>
<td>43.17</td>
<td>35.73</td>
<td>41.12</td>
<td>30.86</td>
<td>24.16</td>
</tr>
<tr>
<td>Mg</td>
<td>27.48</td>
<td>19.06</td>
<td>25.48</td>
<td>17.32</td>
<td>16.08</td>
</tr>
<tr>
<td>Na</td>
<td>45.47</td>
<td>70.66</td>
<td>49.39</td>
<td>44.26</td>
<td>27.19</td>
</tr>
<tr>
<td>K</td>
<td>8.17</td>
<td>7.33</td>
<td>11</td>
<td>6.48</td>
<td>4.88</td>
</tr>
</tbody>
</table>

Table (6.10) Cluster Cases (Nubian Aquifer)

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Valid</th>
<th>Missing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>5.9%</td>
</tr>
<tr>
<td>2</td>
<td>187</td>
<td>27.6%</td>
</tr>
<tr>
<td>3</td>
<td>71</td>
<td>10.5%</td>
</tr>
<tr>
<td>4</td>
<td>340</td>
<td>50%</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>5.9%</td>
</tr>
</tbody>
</table>

The water type in the Clusters, 1, 2, 3, and 4 of the Nubian aquifer data is Na-Ca-HCO3. These four clusters constitute about 94% of the whole data. The remaining cluster, 5, is of Na-Ca-SO4 water
type; it constitutes about 6% of the data.

Na and Ca are the dominant cations in all clusters of the Nubian aquifer data; HCO$_3$ is the dominant anion in Cluster 1 (minor cluster) and in the major Clusters 4, 2, and 3; SO$_4$ is the dominant anion in Cluster 5 (minor cluster).

The sequence of the major cations and anions, in mg/l, according to their concentrations, in a descending order, in the clusters of the Nubian aquifer data is as follows:

Cluster 1: Na > Ca > Mg, HCO$_3$ > SO$_4$ > Cl
Cluster 2: Na > Ca > Mg, HCO$_3$ > SO$_4$ > Cl
Cluster 3: Na > Ca > Mg, HCO$_3$ > SO$_4$ > Cl
Cluster 4: Na > Ca > Mg, HCO$_3$ > SO$_4$ > Cl
Cluster 5: Na > Ca > Mg, SO$_4$ > HCO$_3$ > Cl

The clusters distribution for the Gezira and Nubian aquifers were drawn using the mapping functions of the GIS as shown in Figures (6.43 & 6.44).
6.4.1.1 Interpretation of the Gezira Aquifer Clusters

As shown in Table 6.7, Sodium (Na), and Calcium (Ca) are the dominant cations in all the clusters of the Gezira aquifer's water. The bicarbonates (HCO$_3$) are the dominant anions in the major clusters (3&5) and in Cluster 1 (minor cluster). This could be interpreted, from the mineralogy of the Gezira Clay, which is characterized by the presence of the mineral calcic plagioclase and kankar nodules. The calcic plagioclase is rich in sodium and calcium, while the kankar nodules are rich in bicarbonates and also calcium.

It can be noticed that only Cluster 4 has SO$_4$ as the dominant anion (Table 6.7). This could be due to the presence of horn-blende (sulphide ore), which is one of the minerals present in the Gezira Formation or could be due to the dissolution of gypsum (CaSO$_4$*H$_2$O).

Cluster 2 (minor cluster) has chloride as the dominant anion (Table 6.7). This may be due to the weathering of the halite and evaporate minerals from the underlying geology. It may also be due to the presence of water in closed conditions resulting in increased content of Cl in the groundwater (Rankama and Sahama, 1950), and according to El Boushi and Abdel Salam (1982): saline waters
might have accumulated in an internal drainage basin in the past during the dry episodes of the Quaternary.

**6.4.1.2 Interpretation of the Nubian Aquifer Clusters**

As previously stated, Cluster 4, 2, and 3 (major clusters) and Cluster 1 (minor cluster) in the Nubian aquifer constitute about 94% of the whole data. These four clusters are characterized by Na-Ca-HCO$_3$ water type (Table, 6.9). But Cluster 5 is of Na-Ca-SO$_4$ water type. Na and Ca are the dominant cations in all clusters; HCO$_3$ is the dominant anion in the major clusters (4, 2, and 3) and the minor Cluster 1; SO$_4$ is the dominant anion in Cluster 5. The dominance of Na and Ca is due to the presence of feldspathic sandstones, which contain varying proportions of calcium and sodium. The dominance of HCO$_3$ and Ca is due to the nature of cement in the Nubian formation, which contains iron carbonate and calcium carbonate. Their dominance may also be related to the presence of Kankar nodules which are very common in the Nubian formation, especially along the Blue Nile. The dominance of SO$_4$ in Cluster 5 (minor cluster) may be due to the fact that the Nubian rocks when unoxidised they become pyritous (sulphur minerals) (El Boushi and Whiteman, 1971).

From the above results of the cluster analyses for the data of the
Nubian and Gezira aquifers, it can be noticed that the dominant water type in the Gezira area is sodium-calcium-bicarbonate.

6.4.2 Factor Analysis

Factor analysis gives an insight into the sources of dissolved ions and the hydrogeochemical processes which are responsible for the water quality changes.

The basic purpose of the factor analysis in the study of hydrogeochemistry of an aquifer is to find a set of factors, few in number and which can explain a large amount of the variance of the analytical data.

The factor analysis results for the whole sets of data of the Gezira and Nubian aquifers are given in Tables (6.11, 6.12, 6.13 & 6.14). The scree plots are given in Figs, (6.45 & 6.46).

As can be noted from Table (6.11) of the Gezira aquifer, only three factors have met the cut-off criteria of an eigenvalue greater than one (Fig 6.45). The first factor has accounted for 24.8% of the variability in all the thirteen variables, the second for 14.5% and the third for 14.3%.
### Table (6.11) Total Variance Explained (Gezira Aquifer)

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial Eigen values</th>
<th>Rotation Sums of Squared Loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>% of Variance</td>
</tr>
</tbody>
</table>

### Table (6.12) Rotated Component Matrix (Gezira Aquifer)

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<tr>
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<tbody>
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<td>E.C.</td>
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<td>pH</td>
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<td>TDS</td>
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<td>CaCO₃</td>
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<td>Alkalinity</td>
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<tr>
<td>Na₂CO₃</td>
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<tr>
<td>HCO₃</td>
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<tr>
<td>Cl</td>
<td>.734</td>
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<tr>
<td>SO₄</td>
<td>.894</td>
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<td>Na</td>
<td>.165</td>
</tr>
<tr>
<td>K</td>
<td>.048</td>
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*(Parameter concentrations are in mg/l)*
<table>
<thead>
<tr>
<th>Component</th>
<th>Initial Eigen values</th>
<th>Rotation Sums of Squared Loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>% of Variance</td>
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<tr>
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<td>13.769</td>
</tr>
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<td>1.199</td>
<td>9.224</td>
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Table (6.13) Total Variance Explained (Nubian Aquifer)

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<th>Component</th>
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</thead>
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<tr>
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<td>CaCO₃</td>
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<td>Alkalinity</td>
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</tr>
<tr>
<td>Na₂CO₃</td>
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</tr>
<tr>
<td>HCO₃</td>
<td>0.006</td>
</tr>
<tr>
<td>CL</td>
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<tr>
<td>SO₄</td>
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<tr>
<td>Ca</td>
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</tr>
<tr>
<td>Mg</td>
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</tr>
<tr>
<td>Na</td>
<td>-0.024</td>
</tr>
<tr>
<td>K</td>
<td>0.122</td>
</tr>
</tbody>
</table>

Table (6.14) Rotated Component Matrix (Nubian Aquifer)

* (Parameter concentrations are in mg/l)
Fig. (6.45) Scree Plot (Gezira Aquifer)

Fig. (6.46) Scree Plot (Nubian Aquifer)
Only three factors have also been extracted for the Nubian data as shown in Table (6.13) and Figure (6.46). The first factor has accounted for 20.8% of the variability in all the thirteen variables, the second for 13.5% and the third for 11%.

Tables (6.11, 6.12, 6.13 & 6.14) show the Varimax Rotated factor matrix that consists of the component factors, the loading of variables on each factor and the percentage of data variance for each factor. The three components or factors could be the result of different controlling processes supposed to have produced the different water facies explained by each factor.

With reference to the data of the Gezira aquifer, factor 1 has high loadings of SO$_4$, CaCO$_3$, TDS, Cl, and EC; factor 2 has high loadings of alkalinity, excess alkalinity (Na$_2$CO$_3$), and HCO$_3$; factor 3 has high loadings of Ca, Na, and Mg.

As for the data of the Nubian aquifer, Factor 1 has high loadings of EC, TDS, CaCO$_3$, and SO$_4$; factor 2 has high loadings of alkalinity, excess alkalinity (Na$_2$CO$_3$) and HCO$_3$; factor 3 has high loadings of Mg, and Ca.
6.4.2.1 Interpretation of the Gezira Aquifer Factors

The mineralization of the groundwater in the Gezira aquifer as clearly indicated by Factor 1 (Table, 6.11) is due to the high concentrations of SO₄, CaCO₃, and Cl. The high TDS and EC are caused by the high concentrations of SO₄, CaCO₃, and Cl. The high loading of CaCO₃ may be due to the saturation of groundwater with respect to calcite, and this indicates that calcite (CaCO₃) is one of the constituents of the aquifer materials. The presence of SO₄ in great amounts is due to the oxidation of pyrites (sulphur minerals) and also due to the dissolution of gypsum. According to (El Boushi and Abdel Salam, 1982), high concentrations of CaCO₃ and SO₄ are due to the presence of gypsum and carbonates in the Gezira sediments. The high concentrations of Cl may be due to the presence of water in closed conditions (Rankama and Sahama, 1950), or due to a solution of solid salt from the aquifer (Shiftan, 1981). The high alkalinity associated with Factor 2 may be related to the high concentrations of NaHCO₃ and Ca(HCO₃)₂ in the Gezira Area at the two aquifers (Abdel Salam, 1966). The Bicarbonates (HCO₃) are generally present in most ground waters. However, in the Gezira area they are present in excess concentrations. This is because the groundwater of the Gezira is
recharged mainly from the Blue Nile water, which is rich with bicarbonates. The high loadings of Ca, Na, and Mg associated with Factor 3 could be due to the minerals present in the Gezira aquifer, like calcic plagioclase, augite (pyroxene group), olivine, and amphiboles, which are rich in Ca, Na, and Mg. Also Ca and Mg enter into the groundwater by the dissolution of carbonate minerals in water containing carbon dioxide (Shiftan, 1981). High concentrations of Ca, Mg, and Na could represent two processes occurring in the aquifer at the same time: weathering of halite and evaporate minerals from the underlying geology (Ibid).

### 6.4.2.2 Interpretation of the Nubian Aquifer Factors

The mineralization of the groundwater in the Nubian aquifer as given by Factor 1 (Table 6.13), is due to the high concentrations of CaCO₃, and SO₄. The high EC and TDS are due to the presence of high CaCO₃, and SO₄. The high CaCO₃ is related to the nature of the cement in the Nubian formation which contains considerable calcium carbonate in the Kankar nodules. The high SO₄ is due to the pyrites (sulphur minerals) oxidation, interaction with the geological formation and dissolution of gypsum. The high loadings of alkalinity, and excess alkalinity (Na₂CO₃) associated with Factor 2 (Table 6.13) are due to the presence of high
concentrations of NaHCO₃ and Ca (HCO₃)₂ in both aquifers of the Gezira Area and this may be the result of the dissolution of carbonate minerals present in the formation. The mineralization indicated by Factor 3 (Table 6.13) is due to Mg and Ca. The high concentrations of Mg and Ca may be due to the presence of two processes: the natural recharge of the groundwater from the Blue Nile water which is rich in Ca and Mg, and the dissolution of calcite, pyroxene, and amphiboles, which produce Mg and Ca.
CHAPTER VII

HYDROGEOCHEMICAL ANALYSES OF THE GEZIRA GROUNDWATER

In addition to the statistical methods employed in the study of the groundwater quality as discussed in the preceding chapter, a number of other techniques and methods which have been developed to interpret the groundwater chemistry can be cited from the literature (Hem, 1985).

The objective of the present chapter is to discuss the hydrochemical characteristics of the groundwater of the Gezira area. In this work the methods of composition diagrams, graphical representations proposed by Piper, Durouv and Schoeller, ionic ratios, and saturation indices have been used to determine the processes that affect the hydrochemistry of the groundwater of the Gezira area.

7.1 Composition Diagrams

The composition diagrams are x-y diagrams plotted to show relationships between pairs of measured chemical parameters and reveal the major patterns within the sampled data.
The major cations and anions in meq/l have been plotted with TDI (Total dissolved Ions) in x-y diagrams for the major clusters of the Gezira and Nubian aquifers. It should be noted that the cluster analyses performed here have been applied only to a reduced number of records selected from the complete sets of data. Only the records with no missing values for the major cations and anions of the data of the Gezira and Nubian aquifers have been chosen (Appendix C).

The clusters for the Gezira and Nubian aquifers of the reduced data are shown in Tables (7.1 & 7.2).

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>Ca</td>
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<td>1.735</td>
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<td>1.348</td>
<td>1.728</td>
<td>1.566</td>
<td>0.411</td>
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<tr>
<td>Na</td>
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<td>1.268</td>
<td>16.529</td>
<td>3.827</td>
<td>17.834</td>
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<td>K</td>
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<td>0.132</td>
<td>0.384</td>
<td>0.168</td>
<td>0.136</td>
</tr>
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<td>HCO3</td>
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<td>3.278</td>
<td>4.418</td>
<td>5.245</td>
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<tr>
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Table (7.1) Cluster Analysis for Reduced Data

(Gezira Aquifer)
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<tr>
<th>Cluster</th>
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<td>0.154</td>
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<tr>
<td>HCO₃</td>
<td>4.655</td>
<td>6.922</td>
<td>3.895</td>
<td>3.830</td>
<td>2.832</td>
</tr>
<tr>
<td>Cl</td>
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<td>1.117</td>
<td>0.770</td>
<td>3.787</td>
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<tr>
<td>SO₄</td>
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<td>0.866</td>
<td>1.458</td>
<td>0.767</td>
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</table>

<table>
<thead>
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</table>

**Table (7.2) Cluster Analysis for Reduced Data**

*(Nubian Aquifer)*

The results obtained from the composition diagrams depicted for the clusters of the reduced data of the Gezira and Nubian aquifers are discussed in the following sections.

**7.1.1 Composition Diagrams for the Gezira Aquifer**

The major clusters in the Gezira aquifer are 2 & 4. The other three clusters are negligible (Table 7.1). The correlation coefficients for the major cations and anions with regard to cluster 2 and 4 are...
shown in Appendix F.1. In Cluster 2, there are strong positive correlations between TDI and Ca, Mg, HCO$_3$, and Cl. The source of salinity in Cluster 2 of the Gezira aquifer is, therefore, associated with Ca, Mg, HCO$_3$, and Cl (Fig. 7.1). This can be related to the dissolution of dolomite and the hydrolysis of halite. In Cluster 4, there are high positive correlations between TDI and Ca, Mg, Na, Cl (Fig. 7.2). This may be attributed to the above mentioned dissolution processes and also to the chemical composition of the Blue Nile water. The strong positive correlation between Mg and HCO$_3$ in Cluster 2 (Fig. 7.1) may indicate dissolution of pyroxene and olivine. There are strong positive correlations between Ca and Cl in Cluster 2 and Cluster 4 (Figs. 7.1 & 7.2). This may be attributed to the Sodium-bicarbonate water type which is a modification of the (Ca, Mg) bicarbonate water, where Ca and Mg are exchanged with sodium from rocks (Abdel Latif, 1976). Also, the strong correlations may be due to the accumulation of saline waters in an internal drainage basin in the past (El Boushi and Abdel Salam, 1982).

The weak negative correlation between Ca and Na in Cluster 2 and Cluster 4 of the Gezira aquifer (Figs. 7.1 & 7.2) reveals that the base ion exchange is minor.
7.1.2 Composition Diagrams for the Nubian Aquifer

The major clusters in the Nubian aquifer are Clusters 1, 3 & 5 (Table 7.2). The correlation coefficients for the major cations and anions with regard to all clusters are shown in Appendix F.2. There are strong positive correlations: between TDI and Na, HCO₃, Mg, and SO₄ (Cluster 1, Fig. 7.3); between TDI and Na, Cl and SO₄ (Cluster 3, Fig. 7.5); between TDI and Na and Cl (cluster 5, Fig. 7.7).

The minor clusters in the Nubian aquifer are 2 and 4 (Table 7.2). There are strong correlations between: (a) TDI and Mg, Na, HCO₃, Cl, and SO₄ (Cluster 2, Fig. 7.4); (b) TDI and Ca, HCO₃, SO₄, and Cl (cluster 4, Fig. 7.6).

Thus, it can be deduced that the sources of salinity in the major clusters of the Nubian aquifer are associated with the high concentrations of: Na, HCO₃, Mg, and SO₄ in Cluster 1; Na, Cl, and SO₄ in Cluster 3; Na and Cl, in Cluster 5. But the sources of salinity in the minor clusters are associated with: Mg, Na, HCO₃, Cl, and SO₄ in Cluster 2, and Ca, HCO₃, SO₄, and Cl in Cluster 4.

The presence of high HCO₃ and Mg in the Nubian aquifer is due to the recharge of the groundwater by the Blue Nile. Also the high concentrations can be interpreted as follows: the surface water
charged with atmospheric and biogenic CO₂ infiltrates into the subsurface and aggressively attacks aluminosilicates present in the formation. As a result, cations such as Ca and Mg dissolve into water leaving residues of clay minerals (Freeze and Cherry, 1979). This dissolution process results in a rise in pH and HCO₃ concentrations. The reaction between carbonates and groundwater is characterized by high concentration of Mg and HCO₃. The presence of olivine also increases the amount of Mg. The high Cl could be due to the weathering of the halite and evaporate minerals from the underlying geology or due to the presence of water in closed conditions resulting in an increase in the content of the Cl in the groundwater (Rankama and Sahama, 1950, and El Boushi and Abdel Salam, 1982). The presence of SO₄ in great amounts is due to the oxidation of pyrites (sulphur minerals).

There are strong negative correlations between Ca and Na in Cluster 2 and Cluster 4 of the Nubian aquifer, which indicate strong ion exchanges between Ca and Na in the two clusters (Figs. 7.4 & 7.6).

There are very weak negative correlations between Ca and Na in Cluster 1 and Cluster 3 of the Nubian aquifer (-0.176 and -0.173, respectively) (Figs. 7.3 & 7.5). The correlation between Ca and Na
in Cluster 5 (Fig. 7.7) is negative and weak (-0.360). Therefore, there are minor ion exchanges between Ca and Na in cluster 1, 3, and 5 (Figs. 7.3, 7.5 & 7.7).

In Cluster 1 of the Nubian aquifer, there is a strong positive correlation (0.610) between Na and HCO$_3$ (Fig. 7.3). This indicates that albite weathering may be occurring in the Nubian sandstone and thus releasing Na, and HCO$_3$ ions. In Cluster 2 there are strong positive correlations between Na and SO$_4$ (0.696) and between Mg and Cl (0.511) (Fig. 7.4). This may be due to oxidation of pyrites, hydrolysis of sandstones, and weathering of halite. In Cluster 4 (Fig. 7.6), there are strong positive correlations between Ca and HCO$_3$ (0.642), Ca and Cl (0.771), and between Mg and HCO$_3$ (0.596). This may be due to the reaction between the carbonates and the groundwater or the dissolution of dolomite.

Considering the correlations between Na and Cl, (Appendix F: F.1, F.2), it can be noticed that evaporation processes are minor in both the Gezira and Nubian aquifers.
7.2 Groundwater Classification

The Piper, Durouv and Schoeller diagrams were used in this work for the classification of the Gezira groundwater. It is to be noted that the same reduced data of section 7.1 has been used here to produce these diagrams.

7.2.1 Piper Diagrams

The Piper diagram is composed of two triangles and a diamond-shaped diagram. Relative concentrations of the major cations (Ca, Na, Mg, K), are plotted on the left triangle and the major anions (HCO₃, Cl, SO₄) are plotted on the right triangle. The numbers along the sides of the triangle indicate the percentage of the ions specified. The diamond-shaped diagram above the cations and anions triangles is used to present cation and anion groups as a percentage of the sample.

The main water types of the Gezira aquifer as obtained from the Piper diagram of Fig. (7.8) are Na-HCO₃, Ca-HCO₃, and Na-Cl. The presence of these water types may be due to the chemical modification in the groundwater of the Gezira formation (El Boushi and Abdel Salam, 1982). This modification coincides with the movement of water away from the Blue Nile. The hydrochemical evolutionary trend is from calcium bicarbonate...
water near the recharge zone of the Blue Nile to sodium bicarbonate resulting from base exchange and finally to a sodium chloride zone which coincides with the area of stagnation (El Boushi and Abdel Salam, 1982).

Fig. (7.8) Piper Diagram (Gezira Aquifer)
The main water types of the Nubian aquifer as obtained from the Piper diagram of Fig. (7.9) are Na-HCO$_3$, Ca- HCO$_3$, and Ca-SO$_4$. 

**Fig. (7.9) Piper Diagram (Nubian Aquifer)**
These water types are due to the presence of feldspathic sandstones which contain varying proportions of calcium, sodium, and other minerals and also due to the presence of pyrites, and kankers which are very common in the Nubian Formation (Abdel Salam, 1966).

7.2.2 Durouv Diagrams

The Durouv (1948), diagram is generally used to give more information on the hydrochemical facies and the evolution of groundwater quality when compared to other graphical methods. The Durouv diagrams (Figs 7.10 & 6.11) drawn for the Gezira and Nubian aquifer have yielded the same results as those obtained by the Piper diagrams presented in the previous section.

7.2.3 Schoeller Diagrams

Schoeller Diagrams were employed to compare the groundwater analyses obtained for the Gezira and Nubian aquifer. In Figures (7.12 &7.13), the major ionic concentrations, expressed in meq/l, were plotted on six equally spaced logarithmic scales in special arrangement. The graphs drawn would give the absolute value of each ion and also the concentration differences among the various groundwater analyses. The Schoeller Diagram (7.12 &7.13) drawn for the Gezira and Nubian aquifer have yielded the same results as those obtained by the Piper diagrams presented in section 7.2.1.
Fig. (7.10) Durouvi Diagram (Gezira Aquifer)
Fig. (7.11) Durov Diagram (Nubian Aquifer)
Fig. (7.12) Schoeller Diagram (Gezira Aquifer)
Fig. (7.13) Schoeller Diagram (Nubian Aquifer)
7.3 Ionic Ratios for the Gezira and Nubian Aquifers

Ionic ratios were computed from ionic concentrations in meq/l for the ratios: Mg/Ca, Na/Cl, HCO3/Cl, SO4/Cl, (Cl-(Na+K))/Cl, and (Ca+Mg)/(K+Na). The other ratios Cl-(Na+K)/(HCO3+SO4+NO3), (Ca+Mg)/HCO3, (Ca+Mg-SO4)/(Na-Cl) were computed from ionic concentrations in millimoles/l.

All the above stated ratios have been calculated using all the reduced data used for the composition diagrams discussed in section 7.1 (Appendix C).

7.3.1 Mg/Ca Ratio

The ratios for Fifty two samples (about 40%) of the Gezira aquifer are greater than 0.9. This may be due to the mineralogy of the Gezira Clay which is rich in aluminium silicate, calcium, and magnesium. Groundwater charged with CO2 reacts with aluminosilicates present in the formation releasing cations such as Ca, Mg into water. According to (Hem, 1970), these ratios characterize groundwater originating from silicate aquifers. The ratios for thirty one samples (23%) are in the range of 0.7- 0.9, which indicates the richness of the Gezira aquifer in Ca, Mg, and HCO3. According to (Hsu, 1963), this ratio range is commonly associated with dolomite, CaMg (CO3)2.
The ratios which are less than 0.5 constitute about 20% of the samples. These ratios indicate that the Gezira aquifer is rich in calcium. The ratios which are in the range of 0.5-0.7 constitute about 16% of the samples. These ratios can be due to the fact that the nature of cement in the Gezira formation is identified as calcium carbonate in some parts. According to Schoeller (1956) this is a characteristic of waters flowing through limestone aquifers.

As shown in Figure (7.14), the Mg/Ca ratio decreases slightly with increasing salinity in the Gezira aquifer. This is attributed to negative ion exchange, where calcium and magnesium are adsorbed to the aquifer material and sodium is released to water.

Considering the Nubian aquifer, 99 ratios (about 42%) are greater than 0.9, 54 ratios (about 23%) are in the range of 0.7 to 0.9, forty ratios (about 17%) are in the range of 0.5 to 0.7, and 42 ratios are less than 0.5. The same explanations as those given for the Gezira ratios can be applied to the Nubian aquifer's ratios.
It has been found that the Mg/Ca ratio increases slightly with increasing salinity in the Nubian aquifer Figure (7.15). This is attributed to positive ion exchange where Na is adsorbed to the aquifer material and Ca and Mg are released to the water.

7.3.2 Na/Cl Ratio

Ninety six ratios the Gezira aquifer (more than 81%) are greater than 1.0, indicating a negative ion exchange, where calcium and magnesium are replaced by sodium in the water (Sami, K, 1992). Also, these ratios may be due to Albite weathering occurring in the sandstone and releasing more Na. About 16% of the Gezira aquifer ratios are less than 0.876, which is indicative of positive ion exchange. In this case sodium replaces calcium in the aquifer rock (Hem, 1970, Schmorak and Mercado, 1969).

About 87% of the ratios for the Nubian aquifer are greater than 1.0 and 12% are less than 0.876. The ratios of the Nubian aquifer can be explained similarly as mentioned above for the Gezira aquifer.

It can be concluded from the ratio values obtained in the two aquifers that the two processes of ion exchange are present but the negative ion exchange is the dominant process.

As shown in Figures (7.16 & 7.17), the Na/Cl ratio decreases with increasing salinity in both the Gezira and Nubian aquifers.
7.3.3 HCO₃/ Cl Ratio

This ratio ranges from 0.09 to 50.0 in the Gezira aquifer. High ratios are encountered close to the Blue Nile bank in Managil Province, and at the banks of the White Nile.

For the Nubian aquifer, the ratio ranges from 0.49 to 54.37. It has been found that high ratios are close to the Blue Nile banks. Medium ratios are close to the White Nile banks, and low ratios are concentrated in the central part of the Gezira area.

The reason for obtaining high ratios, in the two aquifers, close to the banks of the Blue and White Niles, is that the two aquifers are recharged mainly with the Blue and White Niles waters, which are rich in bicarbonates (El Boushi, 1972; Saeed, 1976). Also it may be due to the fact that close to recharge areas, the anions are dominated by bicarbonates (Schoeller, 1962). The high ratios observed in Managil Province at the Gezira aquifer can be due to the recharge of the groundwater in this area from irrigation canals (El Zein, 2006).

The HCO₃/ Cl ratio decreases with increasing salinity in the two aquifers (Figures 7.18 & 7.19).
7.3.4 SO$_4$/Cl Ratio

The SO$_4$/Cl ratio ranges from 0.04 to 9.0 in the Gezira aquifer. This ratio is high in the centre of Kamlin Province. The high concentration of SO$_4$ is related to the dissolution of the sulphide minerals.

The SO$_4$/Cl ratio ranges from 0.03 to 8.0 in the Nubian aquifer. High ratios in this aquifer are recorded in Kamlin, Managil, and Butana Provinces. This could be the result of the increase in salinity and the presence of gypsum and carbonate in the sediments in the central and other troughs in the Gezira (El Boushi, 1972). Thus, high SO$_4$ and high values of Chloride are obtained in these areas. Although the concentrations of SO$_4$ and Cl increase in the downstream direction, the chloride concentration increases more rapidly. Hence, the SO$_4$/Cl ratio decreases downstream (Schoeller, 1962).

The SO$_4$/Cl ratio in the two aquifers decreases with increasing salinity (Figures 7.20 & 7.21).
7.3.5 (Ca+Mg)/(K+Na) Ratio

Near recharge areas, the ratio usually exceeds 1.0. A decrease in this ratio is encountered downstream with the increase in alkali metals (K+Na) resulting from ion exchange. The (Ca+Mg)/(K+Na) ratio ranges from 0.13 to 14.0 in the Gezira aquifer. Seventy two ratios (about 61%) are greater than 1.0, 45 ratios (about 38%) are less than 1.0, and 1 ratio is equal to 1.0. The high ratios in the Gezira aquifer are concentrated around the Blue Nile, especially in the south of the area, and in the east of Kamlin Province.

The (Ca+Mg)/(K+Na) ratio ranges from 0.1 to 10.9 in the Nubian aquifer. About 62% of the ratios are greater than 1.0, approximately 37% are less than 1.0, and only one ratio is equal to one. The high ratios in the Nubian aquifer are concentrated around the Blue Nile, in the centre of Kamlin, and the north west of Kamlin province, close to the White Nile.

The high ratios in the above mentioned areas, in the two aquifers, are attributed to the processes of natural recharge from the Blue Nile water which is richer in calcium and magnesium than the White Nile water. Moreover, the eastern part of the Gezira Formation is characterized by the presence of intercalation of
kankar (CaCO₃) and gypsum beds (Saeed, 1976).

The above ratio decreases with increasing salinity in the two aquifers (Figures 7.22 & 7.23).

7.3.6 (Cl-(Na+K))/Cl Ratio

This ratio is used to detect the degree of positive Base Exchange which is the reaction between cations adsorbed on the surface of the aquifer material and the cations in groundwater.

About 23% of the ratios for the Gezira aquifer are positive. The positive values indicate the replacement of Na by Ca and Mg ions in the water and then the adsorption of the Na ions by the clay particles. The positive ion exchange in the Gezira aquifer is a minor process (Figure 7.24).

About 10% of the ratios for the Nubian aquifer are positive which indicates that the positive ion exchange in the aquifer is a minor process, (Figure 7.25).
7.3.7 (Cl-(Na+K))/(HCO_3+SO_4+NO_3) Ratio

This ratio is used to detect the degree of negative Base Exchange and it is computed from ionic concentrations in millimoles/l.

About 39% of the Gezira aquifer samples show negative ion exchange (Figure 7.26). In this process a depletion of Ca and Mg ions in the water occurs with Ca and Mg being adsorbed to the clay rocks and Na released to the water.

In the Nubian aquifer, about 48% of the samples show considerable negative ion exchange (Figure 7.27).

7.3.8 (Ca+Mg)/HCO_3 Ratio

By this ratio, the sources of Ca and Mg in groundwater can be identified. If Ca and Mg originate only from the dissolution of carbonates, calcite (CaCO_3), pyroxene (CaMg(Si_2O_6) and from amphiboles (Ca_2Mg_5Si_8O_22(OH)_2 this ratio will be about 0.5 (Sami, K. 1992). High ratios indicate other sources of Ca and Mg such as cation exchange, or due to meteoric contribution such as gypsum. Low ratios can be the result of either Ca or Mg depletion by cation exchange, or HCO_3 enrichment (Ibid).
About 33.6% of the ratios for the Gezira aquifer are greater than 0.5. These high ratios can be due to the presence of other sources of Ca and Mg such as positive cation exchange, or due to meteoric contribution such as gypsum (Sami, K. 1992). About 66% of the ratios are less than 0.5. This could be the result of either Ca or Mg depletion by negative cation exchange processes, or water enrichment with HCO$_3$ (Ibid).

The ratio increases with increasing salinity in the Gezira aquifer (Figure 7.28).

About 30% of the ratios for the Nubian aquifer are greater than 0.5 and about 70% are less than 0.5.

The same explanations as mentioned above are valid for the ratios of the Nubian aquifer. High values of the ratio indicate that positive cation exchange processes, dissolution of gypsum, and weathering processes are occurring in the aquifers. Low values are due to Ca or Mg depletion by negative cation exchange, or HCO$_3$ enrichment as a result of carbonates dissolution and conversion into bicarbonates.

The ratio increases slightly with increasing salinity in the Nubian aquifer (Figure 7.29). In the two aquifers, both negative and positive cation exchange processes are present.
7.3.9 (Ca+Mg-SO4)/(Na-Cl) Ratio

This relationship provides information on the geologic sources of Ca and Mg in the aquifer (Sami, 1992). Meteoric Ca results from the dissolution of gypsum (CaSO₄) and its amount is equal to the amount of SO₄. The subtraction of meteoric calcium from the total amount of Ca and Mg gives the concentration of lithologic Ca and Mg.

About 52% of the ratios for the Gezira aquifer are greater than 0.5 and this is an indication that the cation exchange processes are not the only sources of Ca and Mg concentrations. Other sources like dissolution of gypsum (CaSO₄) may be occurring. About 47% of the ratios are less than 0.5 and these ratio values may be due to the presence of excess meteoric Na. Thus, the Ca and Mg sources can be identified to be from lithological origin (Ibid). From the total number of ratios, only about 18% were negative.

About 51% of the ratios for the Nubian aquifer are greater than 0.5 and about 48.5% are less than 0.5. From the total number of ratios, only about 13% are negative.

The Nubian Aquifer ratios could be explained similarly as stated above.
The negative ratios in the two aquifers could be due to the depletion of Ca and Mg because of its adsorption to the clay surface.

As shown in Figures. (7.30 & 7.31) most of Ca and Mg plot are above the 2: 1 line and this indicates that cation exchange processes in addition to hydrolysis of silicate minerals, are the prominent sources of Ca and Mg.
7.4 Saturation Indices of the Gezira Groundwater

The saturation index, SI, indicates if a solution is in equilibrium, under-saturated or super-saturated with regard to a solid phase. In practice, equilibrium is assumed to be in the range -0.05 to 0.05 (Border and Britta: Groundwater Geochemistry). If the determined value of SI is below -0.05, the solution is under-saturated with regard to the corresponding mineral phase. If SI exceeds 0.05, the solution is super-saturated with respect to this mineral.

In this work, the saturation indices have been calculated using the PHREEQC computer program. This program is designed to perform a wide variety of low-temperature aqueous geochemical calculations. All of PHREEQC calculation and reports are in molar concentrations. The input to the program contains pH, density and temperature, Salih and others (2000), after Awad (2002). The file also contains Ca, Mg, Na, K, Cl, SO4 and alkalinity in mg/l which are then converted by the program into molar concentrations.

The program has been employed to determine the saturation indices for the Gezira and Nubian aquifers. The two aquifers are represented by their cluster centers given in Tables (7.1 and 7.2). The saturation Indices of the Gezira Aquifer, (Table 7.3), show that the aquifer groundwater is undersaturated in terms of anhydrite
(SI= -2.0, -1.87 -2.56, -1.59, and -2.31) for all clusters. Also it is undersaturated with respect to CO₂ (SI= -2.64, -2.75, -2.84, -2.82, and -2.81), and Gypsum (SI= -1.8, -1.67, -2.36, -1.39, and -2.11). The water is oversaturated in terms of Aragonite (SI=0.68, 0.97, 0.37, and 0.64) for Cluster 1, 2, 3, and 5, but it is in equilibrium with Aragonite (SI= -0.04) in cluster 4. The water is oversaturated in terms of Calcite (SI=0.82, 1.11, 0.51, 0.1, and 0.78), and Dolomite (SI=1.72, 2.13, 1.16, 0.26, and 1.72) in all clusters.

### Table (7.3) Saturation Indices for the Gezira Aquifer

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
<th>Cluster 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhydrite</td>
<td>-2.00</td>
<td>-1.87</td>
<td>-2.56</td>
<td>-1.59</td>
<td>-2.31</td>
</tr>
<tr>
<td>Aragonite</td>
<td>0.68</td>
<td>0.97</td>
<td>0.37</td>
<td>-0.04</td>
<td>0.64</td>
</tr>
<tr>
<td>Calcite</td>
<td>0.82</td>
<td>1.11</td>
<td>0.51</td>
<td>0.10</td>
<td>0.78</td>
</tr>
<tr>
<td>CO₂(g)</td>
<td>-2.64</td>
<td>-2.75</td>
<td>-2.84</td>
<td>-2.82</td>
<td>-2.81</td>
</tr>
<tr>
<td>Dolomite</td>
<td>1.72</td>
<td>2.13</td>
<td>1.16</td>
<td>0.26</td>
<td>1.72</td>
</tr>
<tr>
<td>Gypsum</td>
<td>-1.8</td>
<td>-1.67</td>
<td>-2.36</td>
<td>-1.39</td>
<td>-2.11</td>
</tr>
<tr>
<td>H₂(g)</td>
<td>-33.19</td>
<td>-33.23</td>
<td>-33.13</td>
<td>-33.05</td>
<td>-33.35</td>
</tr>
<tr>
<td>H₂O(g)</td>
<td>-1.38</td>
<td>-1.38</td>
<td>-1.38</td>
<td>-1.38</td>
<td>-1.38</td>
</tr>
<tr>
<td>O₂(g)</td>
<td>-15.08</td>
<td>-15.00</td>
<td>-15.20</td>
<td>-15.36</td>
<td>-14.76</td>
</tr>
</tbody>
</table>

### Table (7.4) Saturation Indices for the Nubian Aquifer

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
<th>Cluster 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhydrite</td>
<td>-2.19</td>
<td>-2.37</td>
<td>-2.22</td>
<td>-2.58</td>
<td>-1.94</td>
</tr>
<tr>
<td>Aragonite</td>
<td>0.79</td>
<td>0.44</td>
<td>0.74</td>
<td>0.34</td>
<td>0.41</td>
</tr>
<tr>
<td>Calcite</td>
<td>0.93</td>
<td>0.58</td>
<td>0.88</td>
<td>0.48</td>
<td>0.55</td>
</tr>
<tr>
<td>CO₂(g)</td>
<td>-2.54</td>
<td>-2.59</td>
<td>-2.73</td>
<td>-2.78</td>
<td>-2.66</td>
</tr>
<tr>
<td>Dolomite</td>
<td>2.08</td>
<td>1.29</td>
<td>1.96</td>
<td>1.11</td>
<td>1.32</td>
</tr>
<tr>
<td>Gypsum</td>
<td>-1.99</td>
<td>-2.17</td>
<td>-2.02</td>
<td>-2.38</td>
<td>-1.74</td>
</tr>
<tr>
<td>H₂(g)</td>
<td>-33.19</td>
<td>-32.93</td>
<td>-33.33</td>
<td>-33.05</td>
<td>-33.23</td>
</tr>
<tr>
<td>H₂O(g)</td>
<td>-1.38</td>
<td>-1.38</td>
<td>-1.38</td>
<td>-1.38</td>
<td>-1.38</td>
</tr>
<tr>
<td>O₂(g)</td>
<td>-15.08</td>
<td>-15.60</td>
<td>-14.80</td>
<td>-15.36</td>
<td>-15.00</td>
</tr>
</tbody>
</table>
The saturation Indices of the Nubian groundwater, (Table 7.4), show that the aquifer groundwater is undersaturated in terms of anhydrite (SI= -2.19, -2.37, -2.22, -2.58, and -1.94), CO₂ (SI= -2.54, -2.59, -2.73, -2.78, and -2.66), and Gypsum (SI= -1.99, -2.17, -2.02, -2.38, and -1.74) in all Cluster. The water is oversaturated in terms of Aragonite (SI=0.79, 0.44, 0.74, 0.34, and 0.41), Calcite (SI=0.93, 0.58, 0.88, 0.48, and 0.55), and Dolomite (SI=2.08, 1.29, 1.96, 1.11, and 1.32).
8.1 Conclusions
The GIS facilities have been successfully employed to convert all the collected chemical data of the Gezira area into spatial form, resulting in an easy interactive system for representation of the data. The main advantage of such a data storage technique is the convenience with which the recording and retrieval of specific information is achieved as related to the exact geographical locations contained in the map (Fig. 4.2). Also, the established map can be easily updated or supplemented with new data.

Using GIS techniques, estimation models for the chemical constituents of the Gezira groundwater have been conveniently devised. The developed models can be used as primary predictors for estimating the expected values of the chemical constituents of the groundwater pertaining to new locations in the map.

It has been found that the GIS tools and techniques can be utilized efficiently to produce a comprehensive map of the Gezira groundwater. The map is composed of all the collected data and the established models of the chemical parameters, (Integrated model,
Section 5.8). The developed integrated map can be extended to include also the mapping of groundwater clusters, ionic ratios and saturation indices. The remarkable achievement of this integrated model will be attributed to its readiness to provide this huge information by just a click of a button on a requested location in the map.

The Blue and White Niles are the main sources of recharge to the groundwater in the Gezira area. The water depths and the static water levels in the two aquifers are low around the Blue Nile and the White Nile and high in Kamlin and the western side of Managil Provinces. The high values of bicarbonate, calcium, and magnesium close to the Blue Nile and also the high values of bicarbonate, sodium and potassium close to the White Nile, indicate that the recharge of groundwater is derived from the Blue Nile, which is rich in HCO$_3$, Ca, and Mg ions, and from the White Nile, which is rich in HCO$_3$, Na, and K ions.

The ground water in the Gezira and Nubian aquifers is slightly or moderately alkaline and the concentrations of most of its chemical constituents have been found to lie within the permissible ranges stated by the WHO and Sudanese standards. However, high values of TDS have been noted in the Gezira aquifer in the North West
and centre of Kamlin Province and the north western part of Managil Province. Also high values of sodium have been recorded in Managil Province, and high values of Sulphate in Kamlin Province in the two aquifers.

The sources of salinity in the Gezira area are associated with the high concentrations of ions of Ca, Mg, Na, HCO₃, and Cl in the Gezira aquifer and Na, HCO₃, Mg, SO₄ and Cl in the Nubian aquifer.

The values of the mean concentrations of the total dissolved solids, Sodium, Sulphate, Silica and Chloride ions are higher in the groundwater of the Gezira formation than in the Nubian aquifer.

The classification of the groundwater using cluster analysis and Piper, Durouv and Schoeller diagrams has shown three water types in the Gezira aquifer. The main water type is (Na-Ca-HCO₃), and the minor water types are (Na-Ca-SO₄) and (Na-Ca-Cl). However, the main water type in the Nubian aquifer is (Na-Ca-HCO₃), and the minor water type is (Na-Ca-SO₄).

The Sodium (Na) and Calcium (Ca) are the dominant cations in all clusters of the Gezira and Nubian aquifers. The bicarbonates (HCO₃) are the dominant anions in the major clusters and in one minor cluster in the Gezira aquifer (91% of the samples) and
similarly they are dominant in the major clusters and in one minor cluster in the Nubian aquifer (94% of the samples). SO\(_4\) and Cl are the dominant anions in the minor clusters of the Gezira aquifer, and SO\(_4\) is the dominant anion in the minor cluster of the Nubian aquifer. Hence it can be concluded that the ground water in the major clusters of the two aquifers have similar facies.

The factor analysis of the Gezira aquifer data has indicated three essential factors which control the mineralization of the groundwater. The first factor has accounted for 24.8%, the second for 14.5% and the third for 14.3%. Factor 1 (SO\(_4\), CaCO\(_3\), TDS, Cl, and EC), represents the dissolution of sulphide minerals and halite, and indicates saturation of ground water with respect to calcite. The high alkalinity associated with Factor 2 (alkalinity, excess alkalinity (Na\(_2\)CO\(_3\)), and HCO\(_3\)), is related to the high concentrations of NaHCO\(_3\) and Ca(HCO\(_3\))\(_2\) in the two aquifers of the Gezira area. Factor 3 (Ca, Na, and Mg), represents the hydrolysis of the Gezira aquifer minerals (calcic plagioclase, augite (pyroxene group), olivine, and amphiboles).

The factor analysis of the Nubian aquifer data has yielded three essential factors which control the mineralization of groundwater. Factor 1 (EC, TDS, CaCO\(_3\), and SO\(_4\)), is related to the presence of
kankar nodules, and the oxidation of sulphide minerals. Factor 2 (alkalinity, and Na₂CO₃), is related to the dissolution of carbonate minerals present in the formation. Factor 3 (Mg and Ca), is related to the processes of natural recharge of groundwater from the Blue Nile water and ion exchange processes.

The strong positive correlation between Mg and HCO₃, in the Gezira aquifer (Fig. 7.2) indicates dissolution of Magnesium Carbonate minerals. Also, the small value of negative correlation between Ca and Na in the Gezira aquifer (Figs. 7.1 & 7.2) has revealed that ion exchange is minor in the Gezira aquifer.

The reaction between the carbonates and groundwater or the dissolution of dolomite in the Nubian aquifer is possible as evident from the strong positive correlations between Ca and HCO₃, and between Mg and HCO₃ (Fig. 7.2). This is supported by the high saturation indices of Aragonite, Calcite and Dolomite as given in Tables (7.3 and 7.4).

The evaporation process in the Gezira and Nubian aquifers is minor as indicated by the low correlations between Na and Cl.

It is evident from the ionic ratios: Mg/Cl, Na/Cl, Cl-(Na+K)/(HCO₃+SO₄+NO₃) and (Ca+Mg)/HCO₃, that the positive ion exchange process, in which sodium replaces calcium and
magnesium in the aquifer rock, and the negative ion exchange process, where calcium and magnesium are replaced by sodium in the water, are present in both aquifers. However, the negative ion exchange is the dominant process in both aquifers.

The ratios $\text{HCO}_3/\text{Cl}$ and $(\text{Ca+Mg})/(\text{K+Na})$, in the two aquifers, attain high values close to the banks of the Blue and White Niles and this confirms that the two aquifers are recharged mainly from the Blue and White Niles.

The high $\text{SO}_4/\text{Cl}$ ratios in the central part of Kamlin Province in the Gezira aquifer, and in Kamlin and Managil Provinces in the Nubian aquifer, are indicative of oxidation of pyrites or possibly dissolution of gypsum in the centre of the Gezira area.

The groundwater in both the Gezira and Nubian Aquifers is undersaturated in terms of anhydrite, $\text{CO}_2$, and Gypsum, and oversaturated in terms of Aragonite, Calcite and Dolomite.

8.2 Recommendations

It is highly recommended that any project for drilling a new well should be accompanied by

1- Full chemical analysis and documentation for all essential chemical parameters of groundwater.
2- Classification of groundwater aquifers.

3- The use of modern GPS equipment for the exact determination of the coordinates of the well.

4- The recording of permeability and lithology files of the aquifer under consideration.

5- Taking water samples from earmarked wells throughout the Gezira at specified regular intervals of time. This would require scheduled monitoring of the selected wells and accurate recording of the results of the water analyses.

The research work presented in this thesis can be extended in future to:

1- Study the relationship between the groundwater quality and the lithology of the groundwater aquifers.

2- Produce geochemical models for the Gezira and Nubian aquifers.
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