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FRESHWATER LOSSES TO THE SEA AND WATER LEVEL DECLINE IN NORTHWEST LIBYA

BY

MOHAMMED AHMED ATTIGA, 1941-

A THESIS

Presented to the Faculty of the Graduate School of the

UNIVERSITY OF MISSOURI-ROLLA

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Approved by

James C. Maxwell (Advisor) T R Beveridge

G. E. Vaughn

ABSTRACT

The area studied in this investigation, located in Tripolitania, Libya, between 13° and 16° east longitude and 31° and 33° north latitude, covers about 42,000 square kilometers. It is divided topographically into two parts. They are the coastal zone to the north and the Jebel (plateau) zone to the south. Some wadis which rise in the Jebel drain northward across the area to the sea.

The temperature in the area ranges from 5°C to 19°C in the winter and from 19°C to 40°C in the summer. Precipitation in the area ranges from 380 millimeters to less than 100 millimeters.

The area is underlain by unconsolidated sediments and semiconsolidated rocks which dip gently seaward (northward). These are limestone, marl, sandstone, sandy limestone and quartz sand. They are Mesozoic, Tertiary, Quaternary and Recent in age. The principal aquifers in the area are the Quaternary water-bearing formations which supply the shallow wells. Miocene aquifers supply artesian wells.

The source of fresh water in the area is precipitation which recharges the water-bearing formations by direct infiltration from precipitation or surface run-off in wadis. The amount of recharge is probably between 4 and 6 percent of precipitation. Groundwater discharge occurs both by natural and artificial means. The total discharge of groundwater from wells in the area is about 400 million cubic meters per year.

Yield of individual wells in the area ranges from about one m^3 per hour to as much as 300 m^3 per hour.

Quaternary aquifers have a permeability of about 2.3 $m^3/hr/m^2$. Their transmissibilities range from 35 $m^3/hr/m$ at Az Zahra to about 398 $m^3/hr/m$ at Bin Ghashir. Storage coefficients range from 0.00003 at El Guea near Qarahbulli to 0.036 at Bin Ghashir.

The author estimated the amount of fresh water loss to the sea by surface runoff from the area to be 138 x 10^6 m^3/yr and by subsurface flow near Aqaba Air Force Base and Qarahbulli at 15 x 10^6 m^3/yr. Considerable attention was given to the water levels in wells. The rate of water level decline was 0.25 m/yr for shallow wells and 0.5 m/yr for artesian wells near Aqaba Air Force Base, and 0.16 m/yr for shallow wells and 0.5 m/yr for artesian wells near Qarahbulli. There is no indication of major sea water intrusion in the area but groundwater contamination by sources other than sea water is evident.

ACKNOWLEDGEMENT

The author is indebted to the Libyan Arab Republic government for supporting him during his study at the University of Missouri-Rolla. The author expresses his thanks to Mr. George C. Taylor, Jr., Chief, Office of International Activities, Water Resources Division, U.S. Geological Survey, for use of his extensive public file of water well data, essential to this investigation. The author expresses his appreciation to Mr. James R. Jones of the U.S. Geological Survey, U.S. Aid/ Dacca, for his suggestions and guidance.

A special appreciation is extended to the individual who greatly assisted the author in the successful completion of this thesis, my advisor, Dr. James C. Maxwell.

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I. INTRODUCTION

> "We should look upon water with the eye of a Bedouin, cherish it like a treasure, remembering that even to be able to have it in limited quantities is a good priviledge which is not given to all." (Ardito Desio, D.J. Cederstrom, May 1960)

The above statement shows the importance of water to mankind, animals, and plants, and how their lives are fundamentally related to the availability of water. In Libya, groundwater is the only source of potable water for all purposes. The demand for additional water for agricultural use, industry, and public supplies has increased in the last ten years, because of the rapid economic development following the discovery of petroleum reserves. The result of this increase is an alarming decline of water levels in many of the developed areas. Because of the above reasons, the author made this study on groundwater conditions of the coastal plain of northwestern Libya.

A. Purpose and Scope of Investigation

The purpose of this thesis is to study groundwater occurrences, relationships between geology and groundwater, and quantity of loss of fresh water to the sea in the Jefara plain in the northwestern part of Libya. The objectives include determining the quantity of fresh water loss to the sea by surface and subsurface flow, water levels, and their decline, and the possibility of any subsurface salt water contamination. These objectives are accomplished by review of the previous literature, analysis of well data, use of lithologic logs, and interviews with United States Geological Survey hydrogeologists who have worked in Libya for several years.

To accomplish part of the objectives, the author chose two areas on the coastal plain of Tripoli in which to study the discharge by subsurface flow, water levels, and their decline, and the possibility of groundwater contamination. One of these areas is near Aqaba Air Force Base located about five kilometers east of the city of Tripoli, and the other is near Qarahbulli located about sixty kilometers east of Tripoli.

The study was undertaken because of the author's interest in working to solve his country's problems, especially those of groundwater development, and his strong beliefs that groundwater is a very important factor in the future development of Libya. It is the author's desire to continue working on this problem after he returns to his native country.

B. Location

The area under study is located in Tripolitania which was one of the three former provinces of Libya. The country prior to 1964 was divided into three provinces: Tripolitania to the west, Cyrenaica to the east and Fezzan to the south, as shown in Figure 1. Egypt (U.A.R.) lies to the east of Cyrenaica, Tunisia is to the west of Tripolitania and Chad and Sudan are to the south of Fezzan. The Mediterranean Sea forms the northern boundary of the country and of the area under investigation. The area under this investigation covers about 42,000 square kilometers. It extends from 13° to 16° east longitude and from the town of Misda on the west, eastward along the Mediterranean coast to near Buerat and from Tripoli on the north, southward to the Wadi

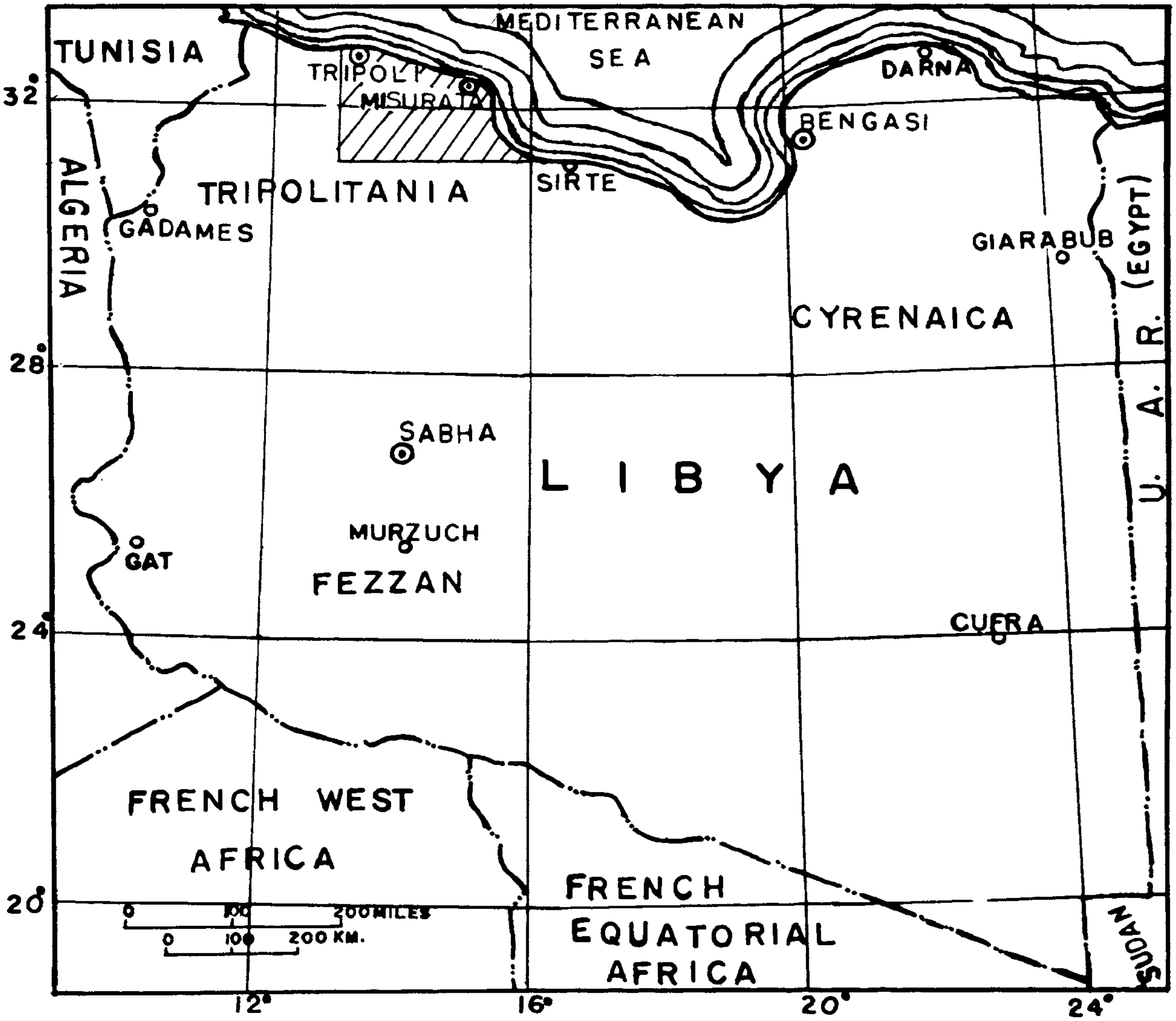


Figure 1. Map of Libya Showing the Area Covered by This Thesis. (After D.J. Cederstrom, May 1960)

Zamzam.

C. Method of Study

The author used available reports and maps to locate the wadis which discharge fresh water to the sea. The general topographical map of Libya (1962) and the topographic map of Jebel Tarhunah, Tripolitania, Libya (1966) were used to determine the topography of the wadis under study. The amount of precipitation as well as the rate of runoff which occurs in the area were obtained from previous unpublished reports and rainfall maps. The average area in square kilometers drained by the wadis was estimated from United States Army maps (1959), the geological map of Libya (1964), and other published and unpublished reports to the Libyan Government.

The author estimated the amount of fresh water flow to the sea through the major wadis by multiplying the area drained by the wadi and the rate of runoff per year. To estimate the fresh water loss to the sea by subsurface flow, the author chose the areas near Aqaba Air Force Base and near Qarahbulli for two examples of the subsurface flow. Many well logs, and generalized and detailed geological reports, including two geological maps, were used by the author to determine the structure, permeability, hydraulic gradient and cross-sectional area necessary to apply Darcy's Law to estimate the amount of subsurface fresh water flow to the sea. Because part of this investigation is to study the water levels and their decline, the relation between the sea level and the groundwater table, and the possibility of any salt water contamination near Aqaba Air Force Base and Qarahbulli, the author used data from ten water wells near Aqaba Air Force Base and nine wells in the Qarahbulli area to draw five cross sections, two at Aqaba Air Force Base and three at Qarahbulli area. In addition to these five cross sections, the author drew two longer cross sections at Qarahbulli to show the structure and the stratigraphy of the area.

Well data have been used to locate the position of water levels and its rate of decline. For some wells, the author calculated the amount of decline of the water levels in the last ten years (1960-1970) assuming that the decline was steady in some cases and unsteady in others. The ground water quality in the area was studied by compiling previous published data to determine what process of salinity affects the water in the area. The results of this investigation are shown in section V.

The author spent one month in Washington, D.C. evaluating available information, lithological logs, files of the United States Geological Survey International Activity (Libyan section) and interviewing some of the U.S.G.S. geologists and hydrologists who have worked in Libya. Two who were interviewed were Mr. J. Jones and Mr. D.J. Cederstrom who lived in Libya for more than three years, working on indigenous water problems. The author contacted many officials in the Libyan Ministries of Agriculture, Planning, and Development and the Libyan Water Bureau, seeking more information on the groundwater problems of Libya.

D. Description of Well Numbering Systems

Most of the wells in this study are identified by numbers based on the latitude and longitude of their site. Each well is identified and its location is given by two four-digit numbers and a one-digit number. The first series of four digits describes the north latitude and the second four digits describes the east longitude of the southwest corner of an area of one minute which contains the well. The last digit is the sequence number of the well within the area. For example, well 3244-1336-1 is the first well described in an area bounded by 32°44' and 32°45' north latitude and 13°36' and 13°37' east longitude.

For various reasons some well locations are described only within five minutes of latitude and longitude. The numbers of such wells are distinguished by the addition of the numeral 5 set off by hyphens between the four digit designation of the area and the sequence number designating the specific well. Many other well numbering systems have been used in Libya by Italians and other foreign technicians. For example, in this thesis, the Aqaba Air Force Base wells will be identified by Arabic numbers only.

E. Previous Investigations

Since Greek and Roman times, or about 630 B.C., water resources in Libya have been developed through construction of hundreds of dams, rock-walled terraces, small storage reservoirs, and wells. Until the Italian occupation (1911-1941) almost all wells in Libya were hand dug and shallow, most being less than fifteen meters deep. It was not until the Italian occupation that many deep wells were drilled in the area; several of these were more than 750 meters deep.

After World War II the French administration in Fezzan drilled several test holes and flowing wells. The British authorities also drilled several wells for public and military use in northeast Libya, notably near Bengasi. The United States Agency for International Development (U.S. AID) and its predecessor agencies (1952-1964) in cooperation with the Libyan government drilled more than sixteen kilometers of test and production wells averaging about 100 meters deep in several parts of the country. The Libyan government has continued drilling with its own equipment and by contracts. Drilling is primarily under the Ministries of Agriculture and Public Works. Recently, many wells have been drilled by oil companies in many parts of Libya.

The United States Geological Survey gathered information on the groundwater of Libya as a whole and especially of the Tripolitania area. (J. Jones, 1967, W. Ogilbee, 1962, D.J. Cederstrom, 1960, et. seq.)

The United Nations, with the cooperation of the Libyan government, made a study on groundwater of Garian area 1959.

The climatic data used in this thesis were recorded by the Libyan government, Ministry of Agriculture, and the Weather Administration.

II. GEOGRAPHY

A. Topography

The area described in this thesis is divided topographically into two parts: the coastal zone and the Jebel (plateau) zone. Each of these is described as follows:

1. Coastal Zone

The coastal zone, called the Jefara, is a sandy plain which rises gently from low sea cliffs (5-10 meters high) on the coast to about 200 meters above sea level at the base of the escarpment of the Jebel Nefusa, Figure 3. At some places west of Tripoli and east of Misurata the sea cliffs are very low or non-existent. Within the coastal Jefara there is higher rolling land about 50-100 meters in altitude, approaching the sea from Qarahbulli eastward to Homs.

Sabkhahs (salt-flats or marshes) are common along the coast. Farther inland the area has little local relief other than occasional sand dunes; the land surface rises gently upward to the base of the Jebel.

2. Jebel Zone

This zone consists of a large plateau (Jebel Nefusa) which has an altitude ranging from 400 to 900 meters. The Jebel reaches its maximum altitude about 20 kilometers southwest of the city of Garian. To the west of Wadi Al Majinin, the height of the northern front overlooking the Jefara generally exceeds 400 meters. Eastward from the wadi, the relief of the front declines from about 300 meters to as little as 50 meters. A few basalt-capped hills between Garian and Tarhuna increase the altitude of the plateau. To the south of the

Jebel zone, there is a land consisting of red sand dunes called Al-Hammedah, Al-Hamra.

B. Drainage

Runoff takes place along the wadis and sloping lands running from the highland in the Jebel region at the south to the sea at the north. This runoff occurs sometimes three to four times per year in the area along the eastern sea coast from Tripoli eastward to Wadi Caam near Zliten. Several wadis draining the Jebel Nefusa flow into the coastal plain and some of them discharge to the sea. Figure 2 shows the major wadis discharge to the sea in the area. In section V, the author has calculated the amount of fresh water loss to the sea through these wadis. Although other wadis cross the area for a short distance, discharge from them reaches the sea only when the rainfall is abundant.

C. Climate

The area under this investigation is affected by the Mediterranean Sea and a sahara (desert) climate. Overall, the climate is of general Mediterranean type with cool, wet winters and hot, dry summers.

The monthly maximum temperatures range from 18°C in December and January to 40°C in August. The monthly minimum temperatures range from as low as 5°C in December and January, to 19°C in August. During the winter, cold air crosses the Mediterranean from Europe toward the south bringing light snow to the Jebel Nefusa, and a good amount of rainfall to Tripoli and the coastal area. In Libya, because the occurrence of rain is closely related to the wind's direction, the principal rains take place when winds from the north bring moist air southward from the Mediterranean during the winter time. In the summer

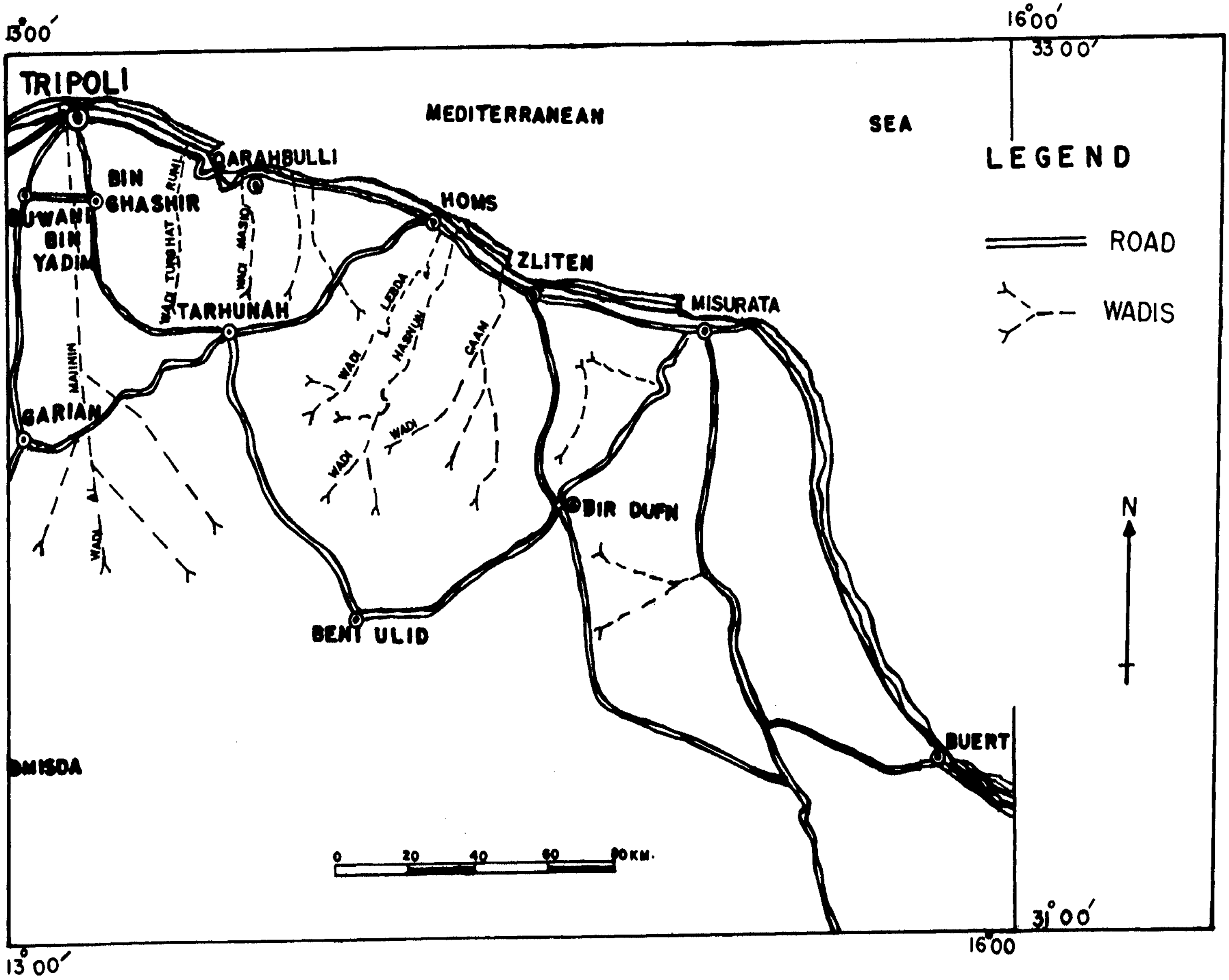


Figure 2. Map Showing the Major Wadis Discharge to the Sea

the wind direction is generally from the south. Extremely strong winds producing sand and dust storms known as Ghiblis occur at intervals. These are usually accompanied by temperature in excess of 37°C. Light winds blow throughout the year. At Tripoli, for example, the average wind (1925-1934) ranges from 5 to 10 meters per second or approximately 10-20 miles per hour.

The area receives an average annual precipitation from 380 millimeters at Tripoli, to less than 100 millimeters at the southern boundary of the area. The annual rainfall at Tripoli as given by D.J. Cederstrom and Mario Bertaiola (1960, p. 15) ranges from a maximum of 653.2 millimeters (1898-1899) to a minimum of 141.6 millimeters (1947-1948). They also suggest that there is a ten year cycle of drought. Table 6 in Appendix A shows the characteristics of the Mediterranean climate. The stations recording heaviest rainfalls are the ones near the sea; those which have the lowest rainfall are inland. Those stations show that rainfall of 150 millimeters or less occurs about one in ten years at Tarhunah which is not very far from the sea and has a high altitude, while it occurs in about nineteen in twenty years at Beni Ulid which is far from the sea.

III. GEOLOGY

A. Geological History

An uplift had begun along north Africa, particularly in Algeria and Tunisa, immediately after the Carboniferous period. While this uplift occurred, Permian and Carboniferous deposits were subjected to extensive erosion and much material of this age was removed.

The land then sank again. Triassic and Cretaceous strate were laid down successively on top of the earlier eroded formations. After their deposition, widespread uplift again occurred in the Jebel Nefusa region with east-west high-angle faulting through Azizia as shown in the Geological Map of the area, Figure 3. This fault system is of very large vertical displacement, so the Cretaceous materials are at depths of as much as 600 meters below sea level along the coast but the same materials reach altitudes on the south side of the fault line as high as 700 meters above sea level.

The uplift of Cretaceous material, acceompanied by volcanic activity, evidently occurred during the Tertiary period. The area contains three secondary faults that trend southeastward, normal to the escarpment between Garian and Tarhunah where mapped by Desio and his colleagues, 1963.

Some other secondary faults at the east part of the area were mentioned by many geologists. According to Hazen and Sawyer (1966) there is a parallel fault near Qusbat which was called the Msellata fault. They suggested another fault running through Zliten to the spring of Taourga. Though secondary faults have a very small displacement, they might have an importance in groundwater movement.

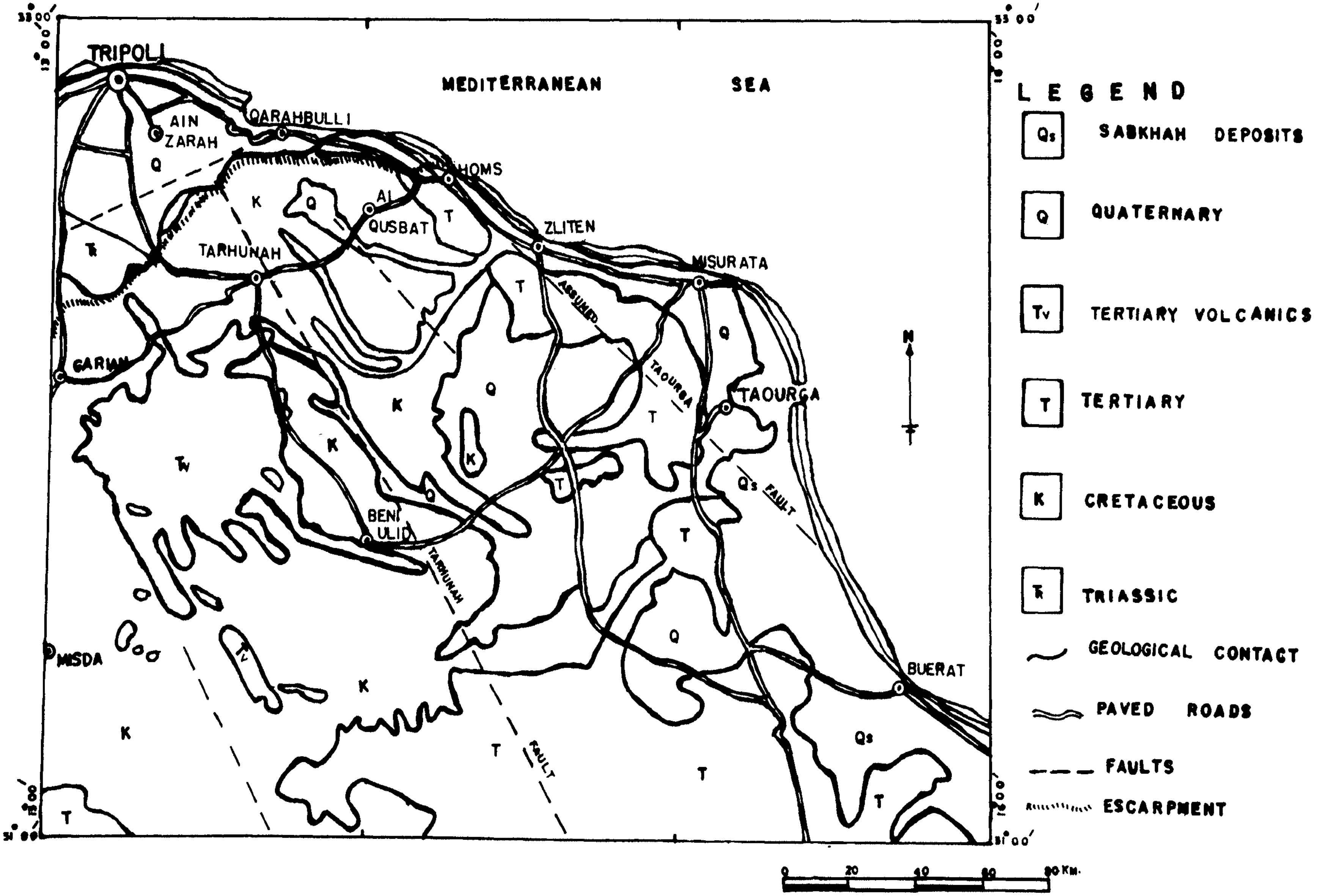


Figure 3. Generalized Geologic Map on the Area Under Study

The highest land is formed in the midst of Tertiary volcanic deposits southeast of Garian. The volcanic materials resulted from eruption of molten materials from great depths, through the Cretaceous formations to the surface.

B. Stratigraphy

Formations exposed in the area under study range in age from Triassic to Recent (Holocene). Many wells drilled near Qarahbulli, some at Misurata, and others in the Jefara plain penetrate formations older than the Miocene. The rocks of the region consist of a sequence of sedimentary formations that thicken toward the sea.

1. Mesozoic rocks

The oldest formation exposed in the area is the Ras Hamia formation of Middle Triassic age, exposed near Azizia. It consists of some 74 meters of dark red, fine grained, micaceous sandstone, red sand, green silty clay, claystone and vari-colored siltstone. Because only the upper part of the formation is exposed, the total thickness of the formation is not known. The thickness estimated by Menning and others (1963, p. 190) is about 633 meters. It has been suggested that the Ras Hamia near Azizia may be the aquifer that freely yields water to some wells. Well 3229-1301 probably taps this formation.

The Azizia limestone of Middle Triassic overlies the Ras Hamia formation. Christie (1955, p. 4-6) suggested that the Azizia formation has a thickness of 61 meters of light to dark gray compact fossiliferous limestone with bands and nodules of chert exposed. Ogilbee (1962, p. 47) suggested that the Azizia near Qarahbulli has a total thickness of 110 meters and is not an aquifer but does supply a few wells of low yield. Jones (1967, p. 87) suggested that the Azizia is not an aquifer.

The Bu Sheba formation has been described by Burollet(1960, p. 10) as late Triassic to early Jurassic. The formation comprises about 165 meters of red to brown sandstone pebble conglomerate, white sandstone, red and green clay and minor amounts of gypsum. According to Jones (1967, p. 87) the Bu Sheba formation ranges in age from late Triassic to early Jurassic.

The Bir el Ghnem Group of Jurassic overlies the Bu Sheba formation but is not considered a source of potable water. The Chcla formation is not considered a source of potable water either, and it is represented by about 65 meters of small pebble conglomerate, sandstone layers and clay, alternating with white to greenish sandstone layers.

The Nefusa Group (Jefern marl, Ain Topi limestone) of Lower and Middle Cretaceous consists of 79 meters of limestone, dolomite, marl, sandstone, clay and conglomerate that are exposed on the front of the Jebel Nefusa. These beds may also underlie the Miocene formations near the coast.

According to Hazen and Sawyer (1966) the Garian formation consists of massive fractured dolomite limestone beds with a thickness of about 100 meters. According to J. Curry (1965) the Garian formation is a gray, hard, microcystalline vuggy dolomite.

2. Tertiary Rocks

According to Christie (1955, p. 18) Miocene rocks consisting chiefly of limestone, clay, marl, quartz, sand and sandstone overlie the Mesozoic rocks in the coastal Jefara. According to Jones (1967),

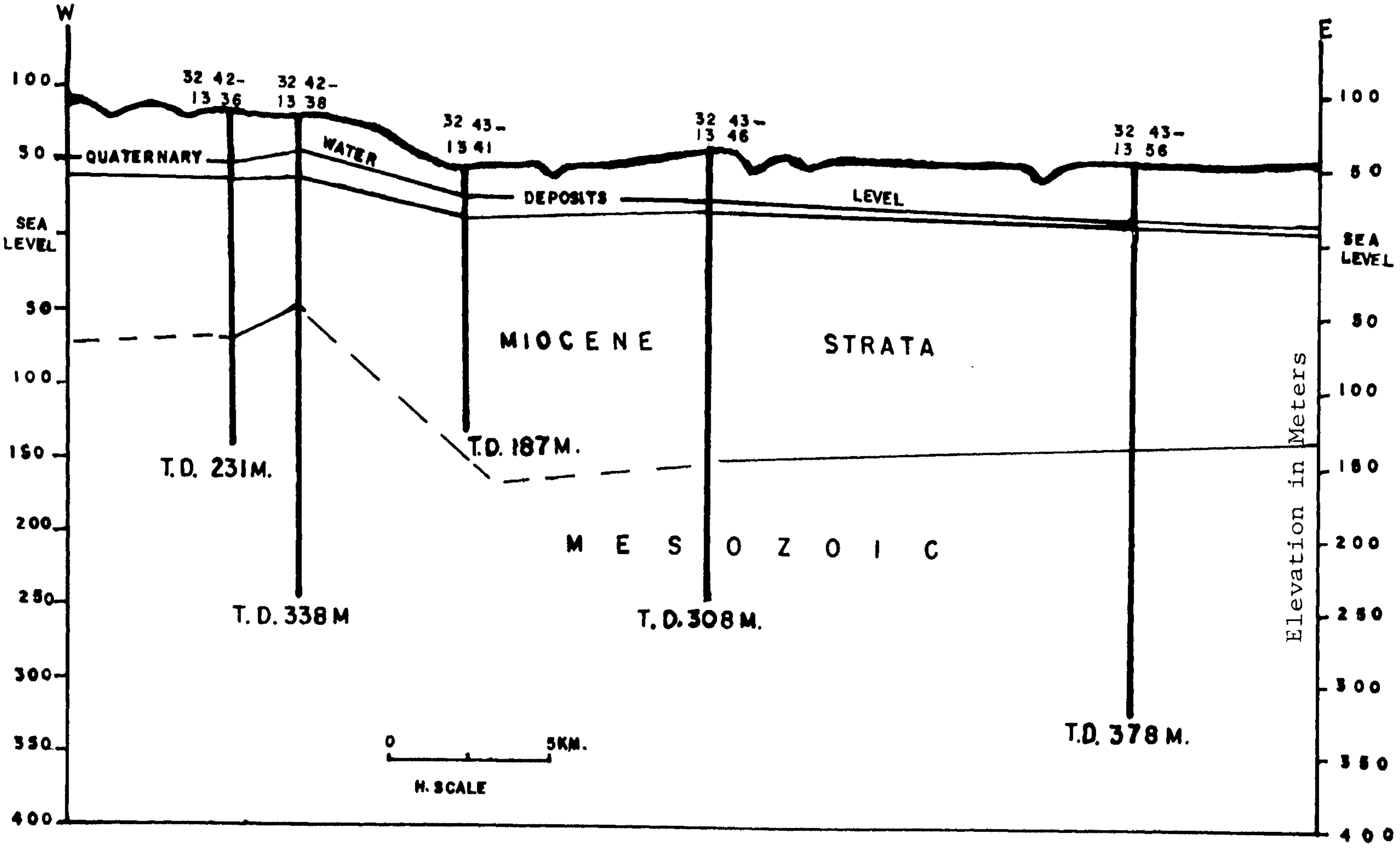


Figure 4. Cross Section Q_1Q_1' at Qarahbulli.
(Compiled from W. Ogilbee, 1962)

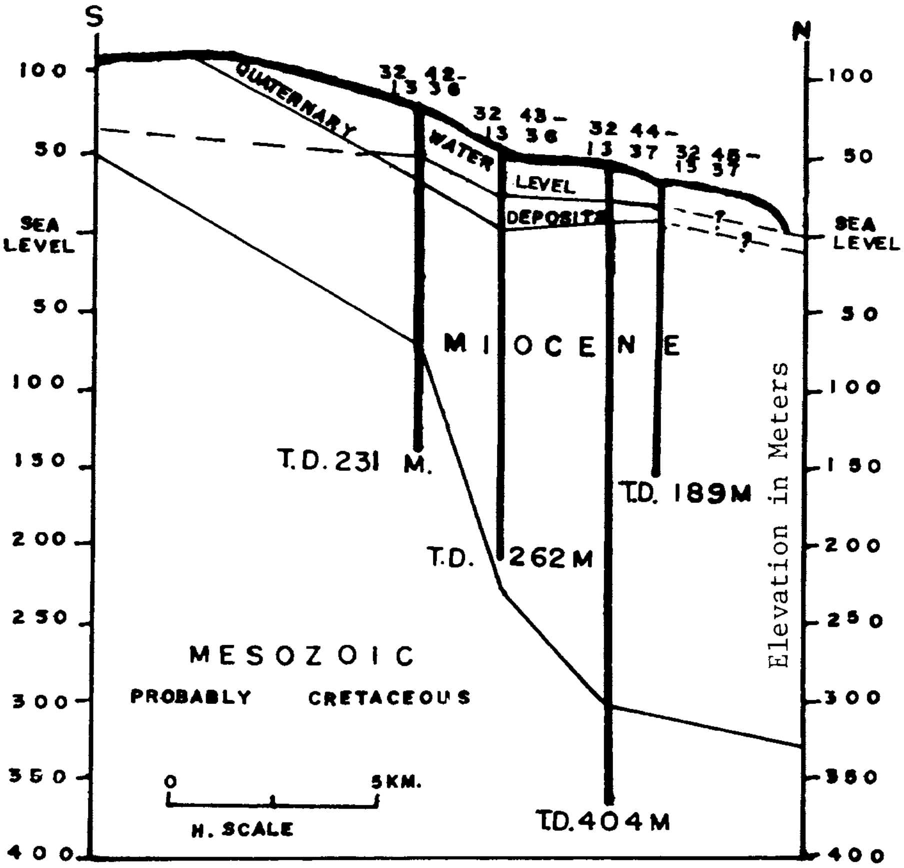


Figure 5. Cross Section Q_2Q_2' at Qarahbulli.
(Compiled from W. Ogilbee, 1962)

Desio (1940) suggested that there are more than 250 meters of Miocene rocks in the Qarahbulli area. Jones (1967) also described the Miocene as a siltstone, mudstone and marl which together form the principal aquifers for Misurata province and supply the deep wells in the area.

The Miocene generally dips northerly at about 15 meters per kilometers, Jones (1967), but near Misurata it dips southeastly. Miocene strata appear to thicken rapidly down dip as shown in the cross sections from near Qarahbulli, Figures 4 and 5.

3. Quaternary Deposits

Jones (1967, p. 91) describes the Quaternary deposits of the Gefara plain as continental and mostly of Pleistocene age; they contain alluvium and small amounts of colluvium from the erosion of the Jebel Nefusa. Streams and rivers fed by Pleistocene rain and snow carried silt, sand and gravel from Jebel Nefusa to the area. During Holocene time, streams have carried additional sediments into the area and wind has piled the available sand into dunes.

Near Qarahbulli the Quaternary deposits are of aeolian and marine origin and range in thickness from zero at the Miocene outcrop to more than forty meters of loosely cemented silty sand, and some limestone and clay. According to Gus H. Goudarzi (1970, p. 43) the Pleistocene deposits of Tripolitania consist of clayey sand locally cemented to sandstone and they occupy low basins separated by hills of Miocene rocks in the Homs-Zliten area. These deposits have an estimated thickness of about 50 meters and generally overlie the Miocene marly clays in the coastal area. Farther south they overlie the Mesozoic formation. The Pleistocene decrease in thickness eastward from Pisida along the Tunisian border to the Homs-Zliten area, where rocks of Miocene age crop out. From Zliten, Pleistocene thicken to the east toward Misurata and Taourga. Gondarzi added that in the coastal plains of Tripolitania the Holocene deposits are represented by a desert crust, sabkhah, soils, dunes and alluvium of variable thickness. They overlie the Pleistocene deposits which are visible along the coast to the Homs-Zliten area.

IV. GROUNDWATER HYDROLOGY

A. Occurrence and Movement of Groundwater

1. Occurrence of Groundwater

The area under study is underlain by a regional water table, which in most places lies in unconsolidated Quaternary sand. Deeper aquifers at many places in the Quaternary deposits yield water more freely than the uppermost sand, but all are in some degree interconnected.

The source of most fresh water in the area under investigation is precipitation. The sequence of evaporation, condensation, precipitation, and runoff known as the hydrologic cycle is continuous and has no beginning or end.

Jones (1967, p. 104) described groundwater in shallower rocks of the Jefara as occurring in the "Prima Falda," "Seconda Falda," and "Terza Falda." The terms describe successively deeper water yielding zones in Quaternary deposits. Confined water occurs in Miocene and older aquifers at Qarahbulli and Misurata under sufficient pressure to cause flow from wells at the land surface.

a. Quaternary Deposits

The author believes that the Quaternary deposits are the principal aquifers in the area. These deposits contain unconsolidated to loosely cemented sand, sandstone, limestone, and clay. The thickness of the Quaternary is not constant, it exceeds 50 meters in some places while it is only a few meters in others.

J. Jones (1967) considered the Quaternary deposits as the best aquifer in the area. They furnish most of the water for irrigation and public supply along the coastal plain. He also described the water bearing materials as a loosely cemented permeable sandstone and limestone intercolated with impermeable layers of clay. The overall permeability of the lower beds appears to be considerably greater than that of the upper beds which consitute the first or water table aquifer. The average depth of the wells penetrating the second aquifer in the lower beds of the Quaternary is about 40 meters at Qarahbulli, and increases somewhat to the west. The water table aquifer may go dry shortly after nearby deeper drilled wells begin pumping.

b. Tertiary Deposits

Miocene artesian aquifers supply a large part of the water used for irrigation in the area, especially near Tripoli. Artesian water has been reported at five different horizons in wells penetrating Miocene rocks at depths ranging from less than 100 meters to more than 400 meters. In well number 3244-1337-2 at El Guea, near Qarahbulli, Miocene aquifers were encountered at depths of 90, 182, 212, 236, and 340 meters. Flowing artesian water from the basal Miocene has been encountered in many wells in the area.

D.J. Cederstrom (1960) called the Miocene aquifer at Tripoli an intermediate zone containing very thick clay or marl beds in which limestones are less prominent and sandy beds are rare. Water well logs (Table 10-Appendix B) show that the Miocene strata contains sandy, fossiliferous clay and marl. In well 457, at Tagura the section from 80 meters to 427 meters is predominantly clay.

c. Mesozoic Rocks

The oldest water bearing formations known in the area are the Ras Hamia, Azizia and Bu Sheba formations of Triassic and Jurassic age.

Water in these formations is tapped at depths from 100 to 325 meters. Permeable beds of the Bu Sheba formation yield water rather freely to wells at Bir Al Ghanam west of the area under study. Potable water is also obtained from springs issuing from Cretaceous rocks. These Mesozoic formations underlie most of the northern and eastern part of the area at considerable depth, but the water contained in these formations is likely to be salty or brackish. In some places in Qarahbulli and Misurata water in rocks of presumed Cretaceous age immediately beneath the Miocene formation may be of chemical quality suitable for irrigation and industry. Appendix B, Table 11 shows that the Mesozoic formations contain quartz, sandstone and salty siliceous sand.

2. Movement of Groundwater

The cross sections of Figures 8, 9, 11, 12, and 13 show that the groundwater of the area under study almost everywhere moves generally from south to north; that is, toward the sea. The rate of movement of groundwater depends on its hydraulic gradient and the permeability of the aquifer. To compute the rate of movement of groundwater one may apply Darcy's Law:

$$V = P \frac{h}{L}$$

where

V is the velocity of water through a column of permeable material

h is the difference in head at the ends of the column

L is the length of column and

P is a constant known as the permeability of the material

Stuart (1960) made a rough calculation for the rate of groundwater movement in the Quaternary aquifer near Az Zahra just west of the area under study. He assumed that an approximate permeability can be computed by dividing the transmissibility, 35 cubic meter/hour, by the aquifer thickness of 15 meters. From this he determined that the permeability near Az Zahra is about 2.3 cubic meters/square meter. He assumed that the hydrologic gradient of the area is 4/1000. From Darcy's Law.

$$V = P \frac{h}{L} = 2.3 \times 4/1000 = 0.0092 \text{ meter/hour} = 75 \text{ meter/year}$$

This rate of movement is a maximum figure. Generally, in the coastal plain, groundwater movement in the quaternary rocks is less than this figure, because the saturated thickness of the aquifer is in most places more than 15 meters as shown in the well logs. According to J. Jones (1967) the groundwater movement near Misurata is north and east toward the sea.

B. Aquifer Characteristics

As defined to Todd (1963, p. 15), an aquifer is a permeable geologic formation having structures which permit appreciable water to move through them under ordinary field conditions. An aquiclude is an impermeable geologic formation which may contain groundwater but cannot transmit it. In order for a formation to transmit water, it must contain interconnected voids. These voids may be intergranular pore-spaces or they may be joints, fractures, bedding planes, or solution openings.

Aquifers may be classed as unconfined or confined. If a well is drilled into an unconfined aquifer, the static water level in the well will be at the same level at which the water is first encountered. However, when a well is drilled into a confined aquifer, the water will rise above the level at which it is first encountered. This rise occurs because the groundwater is confined under pressure greater than atmospheric pressure. A formation may contain local bodies of groundwater which lie above the main groundwater body and are called perched groundwater. According to Jones (1967) this kind of aquifer is common in the area under investigation.

When water is withdrawn from a well that penetrates aquifers, the direction of the flow of the water in the vicinity of the well is changed. The withdrawal causes a lowering of water level around the well in the form of an inverted cone. The well being at the center as the cone contracts and deepens, water flows toward the well from all directions. The rate of decline of the water level and the outward spread of the cone depend on the hydraulic characteristics of the formation as well as the rate of pumping. The hydraulic characteristics of water-bearing formations which have an effect on the rate of decline of water levels in wells are the ability of the formation to transmit water, and the capacity of the formation to yield water from storage. These factors are known as the coefficient of transmissibility and the coefficient of storage. The coefficient of transmissibility is the product of aquifer thickness and permeability, or conversely, permeability is transmissibility divided by aquifer thickness.

$$T = Kb \quad \text{or} \quad K = \frac{T}{b}$$

where

T is the coefficient of transmissibility

K is the coefficient of permeability and

b is the thickness of the water bearing formation

Permeability is a measure of the rate at which water flows through a porous medium. It can be obtained from Darcy's Law by:

$$K = \frac{V}{I} \quad \text{or} \quad K = \frac{Q}{IA}$$

where

K is the coefficient of permeability

V is the velocity

I is the hydraulic gradient

Q is the quantity of water flow and

A is the cross section of the area perpendicular to the flow

According to M. Nawrocki (M.S. Thesis, 1967, p. 6-7) the following equations are used to calculate aquifer characteristics:

Slichter (1898) assuming a well fully penetrating an artesian aquifer, developed the expression:

$$K = \frac{QL_n(1 + \frac{R}{r_w})}{2\pi DS_w}$$

where

K is the coefficient of permeability

Q is the discharge of the pumped well

R is the radius of influence of pumped well

r_w is the radius of the pumped well

S_w is the equilibrium drawdown in pumped well and

D is the total thickness of the aquifer

Thiem (1906) developed a similar equation assuming water table conditions. When modified by Wenzel (1942, p. 81) to use for both water table and artesian conditions his formula became

$$K = \frac{QL_n r_2/r_1}{2\pi D(s_1-s_2)}$$

where r_1 and r_2 are the distances of observation wells from the pumped well, s_1 and s_2 are the drawdowns respectively in the observation wells, and the other terms are as previously defined. The Thiem equation requires at least two observation wells in addition to the pumped well, while the Slichter equation needs only the drawdown of the pumped well plus a radius of influence measurement. Both equilibrium formulas assume full penetration.

The coefficient of transmissibility is defined as the rate at which water will flow through a vertical strip of the aquifer one foot wide and extending through the full saturated thickness, under a hydraulic gradient of 100 percent (M.A. Nawrocki, M.S. Thesis, 1967)

Theis (1935) used the following equation to calculate the coefficient of transmissibility

$$T = \frac{114.6\ QW(U)}{h_0 - h}$$

$$W(U) = \int_U^\infty \frac{e^{-U}}{U}\, dU$$

where

T is the coefficient of transmissibility

Q is the Well discharge

$h_0 - h$ is the drawdown and

W(U) is the Taylor infinite series expansion of the exponential integral

The coefficient of storage is defined as the volume of water an aquifer releases or takes into storage per unit of surface area of the aquifer per unit change in component of head normal to the surface. The coefficient of storage is given by Theis (1935) as

$$S = \frac{UTt}{1.87\ r^2}$$

where

S is the dimensionless storage coefficient

U is given from the table or from graphical method

T is the coefficient of transmissibility

t is the time in days since pumping started, and

r is the distance in feet from the discharging well to the observation well.

The only study dealing with aquifer characteristics that has been done on the area under investigation was the Stuart study (1960). He defined the coefficient of transmissibility to be the number of cubic meters of water per hour that would pass through a vertical strip of the aquifer one meter wide of a height equal to the saturated thickness of the formation and under hydraulic gradient of one meter of loss in head per meter of travel of the water. He found (Stuart, 1960, p. 9) that the transmissibility of Quaternary aquifers in the area under investigation ranged from 35 m^3/hour/m at Az Zahra to 398 m^3/hour/m at

Bin Ghashir. He also found the storage coefficient to range from 0.00003 at El Guea, near Qarahbulli, to 0.036 at Bin Ghashir.

At the eastern part of the area under investigation, the discharge of Ain Taourga, 15,000 m^3/hour, indicates an extraordinarily high transmissibility. Water wells in formations of such characteristics should easily yield 250 m^3/hour or more with little drawdown. There are a number of deep wells of this capacity in the area. The flowing wells at Gioda near Misurata had capacities of 200 to 300 m^3/hour when drilled in the 1930's. Their decline in yield is believed to be caused by collapse of open section and loss of deep water to shallow formations due to corrosion of the casing. The high capacity springs at Wadi Caam (1500-2000 m^3/hour) indicate good transmissibility in the area.

According to Hazen and Sawyer (1966, pp. 3-7), near Buerat in the southern part of the region studied, where conditions are less favorable, wells flow between 2.3 and 0.3 m^3/hour, from the Triassic formations. These flow rates indicate low permeability. Water wells drilled in the Garian Formation at Bin Ulid in 1965 by the Ministry of agriculture produced about 23 m^3/hour with substantial drawdown indicating low transmissibility.

The indications are that north of latitude 32°00', transmissibilities are adequate to permit development of wells of 150 m^3/hour or more.

C. Groundwater Recharge and Discharge

The groundwater reservoir underlying most of the area under investigation is recharged by direct infiltration from precipitation, by infiltration from surface runoff in wadis, by return circulation of excess irrigation water, and by underflow from the Jebel to the south. The generally sandy surface of the dunes in the Jefara Plain is particularly receptive to direct infiltration, but most of the water goes to satisfy soil moisture deficiencies or evaporates before reaching the water table. Near Misurata and Qarahbulli, water discharging to the land surface by flowing wells or escaping underground through leaking well casings also contributes some recharge. In most years, recharge is nil, especially in the western and southern part of the area.

Definite statements as to the amount of recharge or details of its regimen cannot be made until quantitative studies provide the basis for sound estimate. However, several estimates of rainfall disposition and recharge have been made.

Cederstrom (1960, p. 33) made a rough empirical estimate that recharge in Bin Ghashir and Swani Bin Yadim is equal to about 2/3 of the pumping from the period 1920-1957.

J.H. Stewart (1960) estimated an average disposition of water as follows:

Disposition	Millimeters per year	%
Evaporation from soils	167	77.5%
Transpired by vegetation	30	14.2%
Runoff into deltas	4.5	2.1%
Runoff into sea	3.5	1.6%
Groundwater recharge	10	4.6%
TOTAL	215	100%

According to Hazen and Sawyer (1966), the amount of recharge from rainfall is probably between 4 and 6 percent of the precipitation, as shown in Table 1.

Table 1. Disposition of Rainfall mm/yr*

Annual Rainfall in mm	Annual Runoff	%	Evaporation From Soil	%	Transpired Vegetation	%	Groundwater Recharge	%
350	29	8.3	210	60.0	91	26.0	20	5.7
300	21	7.0	200	66.7	44	14.7	15	5.0
250	13	5.2	190	76.0	35	14	12	4.8
215	8	3.7	167	77.8	30	14	10	4.7
200	6	3.0	157	78.5	28	14	9	4.8
150	3	2.0	120	80.0	20	13	7	4.7
100	1	1.0	82	82.0	12	12	5	5.0

* (After Hazen and Sawyer, 1966)

Groundwater discharge occurs both by natural and artificial means. Water is discharged naturally from a groundwater reservoir by submarine outflow, spring flow and by evapotranspiration.

The total discharge of groundwater from wells in the area is about 400 million meter^3 per year (J. Jones, 1967). This is about 8 percent of the estimated precipitation of the area. At Misurata, the major discharge is from Ain Taourga which flows between 100-150 million meter^3 per year. Another major visible natural discharge is from springs in Wadi Caam between Homs and Zileten and from a few which lie near the foot of the Jebel Nefusa. These springs discharge about 20 million meter^3 per year.

According to William Ogilbee (1962) the total discharge from the Quaternary aquifer near Qarahbulli was estimated to be 7 million cubic meter per year. The annual withdrawal from the Miocene aquifers was computed to be about 2 million cubic meters per year, making the total annual discharge some 9 million meter^3 per year.

D. Well Yields

The yield of individual wells in the area under investigation ranges from about one cubic meter per hour (1 m^3/hr) to as much as 300 cubic meters per hour (m^3/hr). Thousands of shallow dug wells yield only one or two cubic meters per hour and many of them can be pumped dry within a few hours. Wells tapping the Quaternary or Miocene aquifers, most of which were drilled in the Qarahbulli or Misurata area, yield an average of about 30 cubic meters per hour (30 m^3/hr).

Mario Bertaiola (1960) has reported that some wells drilled in the early 1930's near Bin Ghashir, yielded in 1958 only about a quarter of their original production rate. He also added that yield from wells that tap pre-Quaternary aquifers is generally higher than those that yield from the Quaternary aquifer. The yields of many wells in the Qarahbulli area could be increased if they were developed properly by modern water well construction methods.

V. RESULTS AND RECOMMENDATIONS

Quantitative results were obtained in this investigation for the estimation of freshwater losses to the sea, and for local water level declines near Aqaba Air Force Base, and Qarahbulli. The methods used to calculate the results are discussed in section II. The data used in the calculations are discussed in section IV. The results are described separately in this section.

A. Fresh Water Loss to the Sea

1. By Surface Runoff to the Sea

The wadis in the area under study shown in Figure 2 are grouped for computation, the runoff computation for each group from west to east is given below and summarized in Table 2. A single figure followed by the correct number of zeros is about as close as this can be estimated from present knowledge.

a. Wadi AL Majinin

This wadi is the major wadi in the area, occupying about 1200 square kilometers and receiving between 200-300 millimeters of rainfall. The rate of runoff of this wadi is about 45 millimeters per year. The total fresh water flow to the sea through this wadi is estimated as follows:

Area x Rate of Runoff = Volume of flow per year

$$A \times R = V$$

where

A is the area occupied by the wadi

R is the runoff

V is the amount of fresh water loss to the sea

$1200 \text{ sq. km.} \times 45 \text{ mm.} = 54 \times 10^6 \text{ m}^3/\text{yr}$

b. Wadi Turghat (Ruml) Near Qarahbulli, Through Wadi Lebda Near Homs

These wadis receive an average rainfall of about 275 millimeters per year and have an average runoff of 45 millimeters. The total area of the wadis is about 1100 square kilometers; therefore, the average annual yield of fresh water that reached the sea as a surface runoff is:

$$A \times R = V$$

$1100 \text{ sq. km.} \times 45 \text{mm.} = 50 \times 10^6 \text{ m}^3/\text{yr}$

c. Wadi Hasnun (East of Homs)

This wadi receives an average rainfall of 225 millimeters per year and an average runoff of 35 millimeters. The total area is about 115 square kilometers (using the above equation)

$$A \times R = V$$

$115 \text{ sq. km.} \times 35 \text{ mm.} = 4 \times 10^6 \text{ m}^3/\text{yr}$

d. Wadi Caam Between Homs and Zliten

This wadi is divided into two parts. The first part, with an area of about 1000 square kilometers, receives an average rainfall of about 150 millimeters. Runoff is estimated at 40 millimeters. Therefore the average annual yield of fresh water loss to the sea is:

$$A \times R = V$$

$1000 \text{ sq. km.} \times 40 \text{ mm.} = 20 \times 10^6 \text{ m}^3/\text{yr}$

Another 500 square kilometer area of rough rocky land has low relief possessing slightly lower runoff characteristics. It lies in the 200 millimeter rainfall area and the runoff is estimated to average 20 millimeters annually. Runoff volume from the area is:

$$A \times R = V$$

$500 \text{ sq. km.} \times 20 \text{ mm.} = 10 \times 10^6 \text{ m}^3/\text{yr}$

This simplified analysis indicates an annual yield from the wadi Caam of about $30 \times 10^6 \text{m}^3$.

The total flow of fresh water to the sea by surface runoff from an area of 3915 square kilometers is estimated at $138 \times 10^6 \text{m}^3/\text{yr}$. The figure above of fresh water loss to the sea is not necessarily very accurate because of the incomplete data on the whole area. But it gives an idea about what has been unknown for a long period of time.

2. By Subsurface Flow to the Sea

a. Introduction

Because the data available are not sufficient to calculate subsurface fresh water loss for the entire area under study, the author concentrated on two locations for which data are available. Therefore the author's conclusions are based on the information available from water well logs and his interpretation of the geology of the area. The cross sections AA', BB', CC' near Qarahbulli and TT' and T_1T_1' near Aqaba Air Force Base, have been used to estimate the hydraulic gradient within the aquifers and the direction of groundwater movement, the permeability of the aquifers estimated from previous published data or estimated by the author. To compute the rate of movement and amount of fresh water loss to the sea by subsurface flow, one may apply Darcy's Law and the flow equation.

Table 2. Estimation of Fresh Water Loss to the Sea by Surface Runoff

Wadi Name	Location	Total Area Sq. km.	Annual Rainfall mm.	Annual Runoff mm.	Average of Fresh Water Loss to the sea m^3/yr	Remarks
AL Majinin	West of City of Tripoli	1,200	300-200	45	54×10^6	
Turghat and Lebda	Near Homs	1,100	275	45	50×10^6	
Hasnun	East of Homs	115	225	35	4×10^6	
Caam	Between Homs and Zliten	1,000 500	150 200	40 20	20×10^6 10×10^6	Total runoff to the sea at Wadi Caam is about $30 \times 10^6 m^3$

$$V = P \frac{h}{L}$$

where

V is the velocity of the groundwater through a section of permeable material

P is the permeability

$\frac{h}{L}$ is the hydraulic gradient

b. Fresh Water Loss to the Sea by Subsurface Flow Near Aqaba Air Force Base

Near this area the hydraulic gradient obtained from the cross sections TT' and T_1T_1' Figures 8 and 9, are equal to two meters per each kilometer, the width of the area obtained from the location map, and equal to seven kilometers, the aquifer thickness which obtained from well logs found to be equal 15 meters. The permeability is estimated by the author at about 3 $m^3/hr/m^2$.

$$V = P \frac{h}{L} = 3 \times \frac{2}{1000} = 0.006 \text{ m/hr}$$

$$= 53 \text{ m/yr (Approx.)}$$

$$Q = w \times h \times v$$

where

Q is the amount of flow to the sea

W is the width of the area

h is the thickness of the aquifer

v is the velocity of the water

$Q = 7500 \times 15 \times 53 = 6 \times 10^6 \text{ m}^3/\text{yr}$

c. Fresh Water Loss to the Sea by Subsurface Flow Near Qarahbulli

The author assumed that the hydraulic gradient is increasing to the east so it is greater than that at Aqaba Air Force Base and estimated at about three meters per kilometer; the thickness of water bearing formation is obtained from well logs at 15 meters, the width of the area measured from the location map of Qarahbulli Figure 10 at 17.5 kilometers, the permeability estimated by the author at 2 $m^3/hr/m^2$.

$$V = P\frac{h}{L} = 2 \times \frac{3}{1000} = 0.006 \text{ m/hr.}$$

$$= 53 \text{ m/yr}$$

$$Q = w \times h \times v$$

$$= 17{,}500 \times 15 \times 53 = 9 \times 10^6 m^3$$

Therefore, the total amount of fresh water loss to the sea by subsurface flow in Aqaba Air Force Base and Qarahbulli area is estimated at 15 x $10^6 m^3$.

B. Water Levels

Considerable attention was given to water levels in wells because these levels are an important factor in evaluating the future of groundwater development and the cost of pumping.

The area under this investigation has a depth to water table ranging from land surface in some sabkhah to more than 100 meters below the surface as shown in Figure 6.

Data from unpublished records (J. Jones, 1967) indicates that in the cicinity of Bin Ghashir, the depths to water levels were commonly less than 5 meters below land surface. This was observed when the area was first being developed before 1920. However, by 1956 water levels

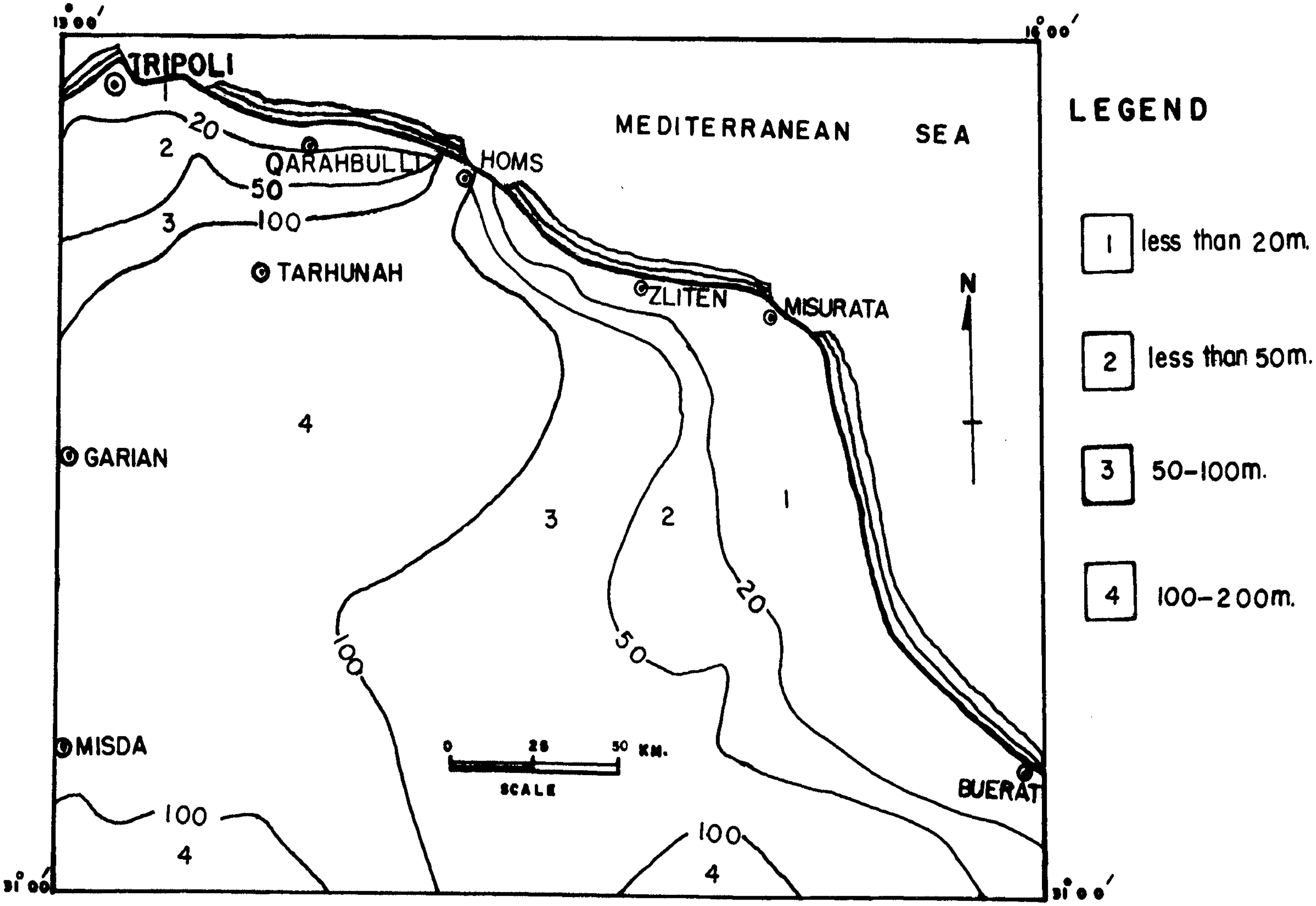


Figure 6. Map Showing Approximate Depth Below Land Surface to the Groundwater Bodies

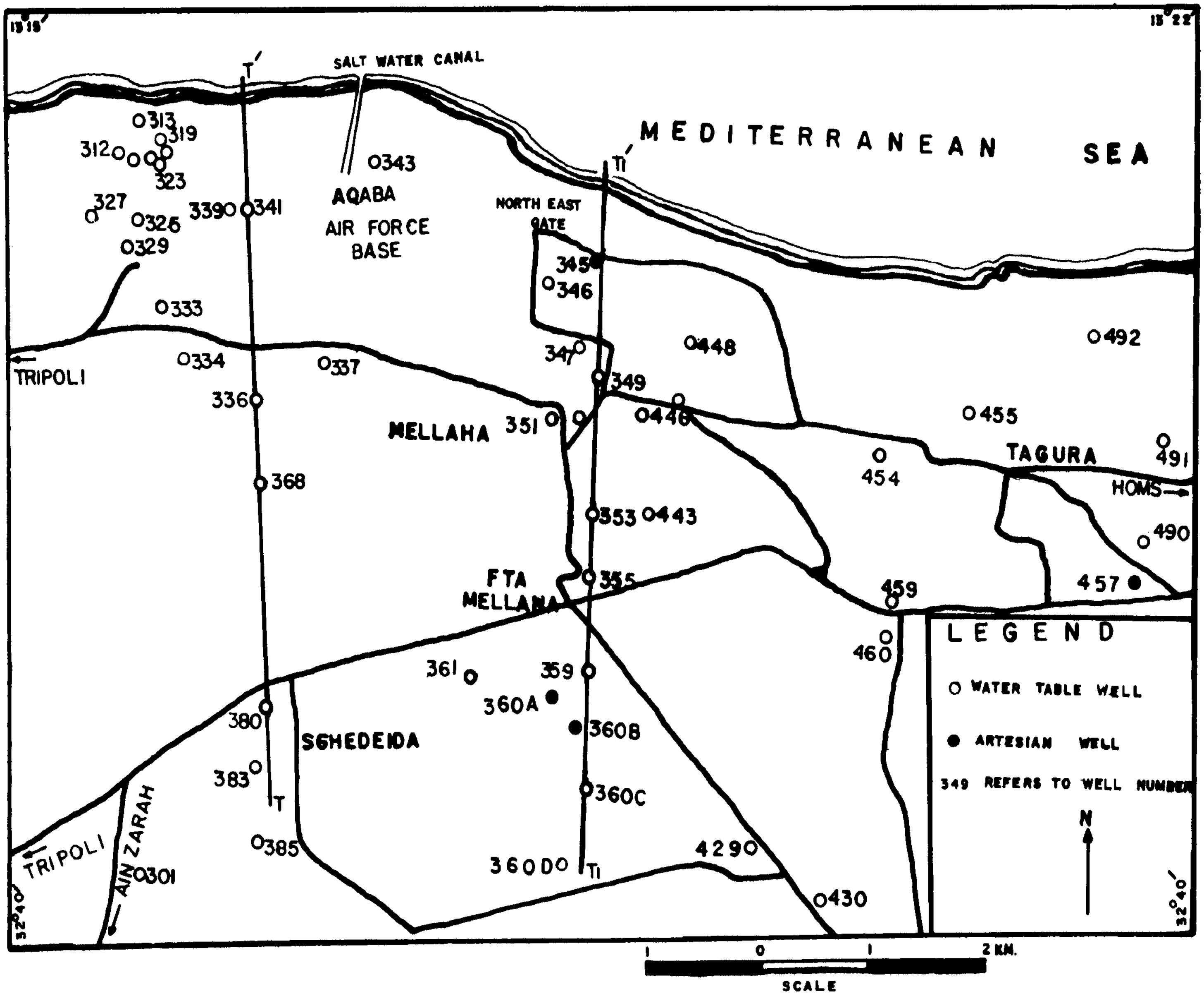


Figure 7. Map of Well Location and Cross Section Near Aqaba Air Force Base

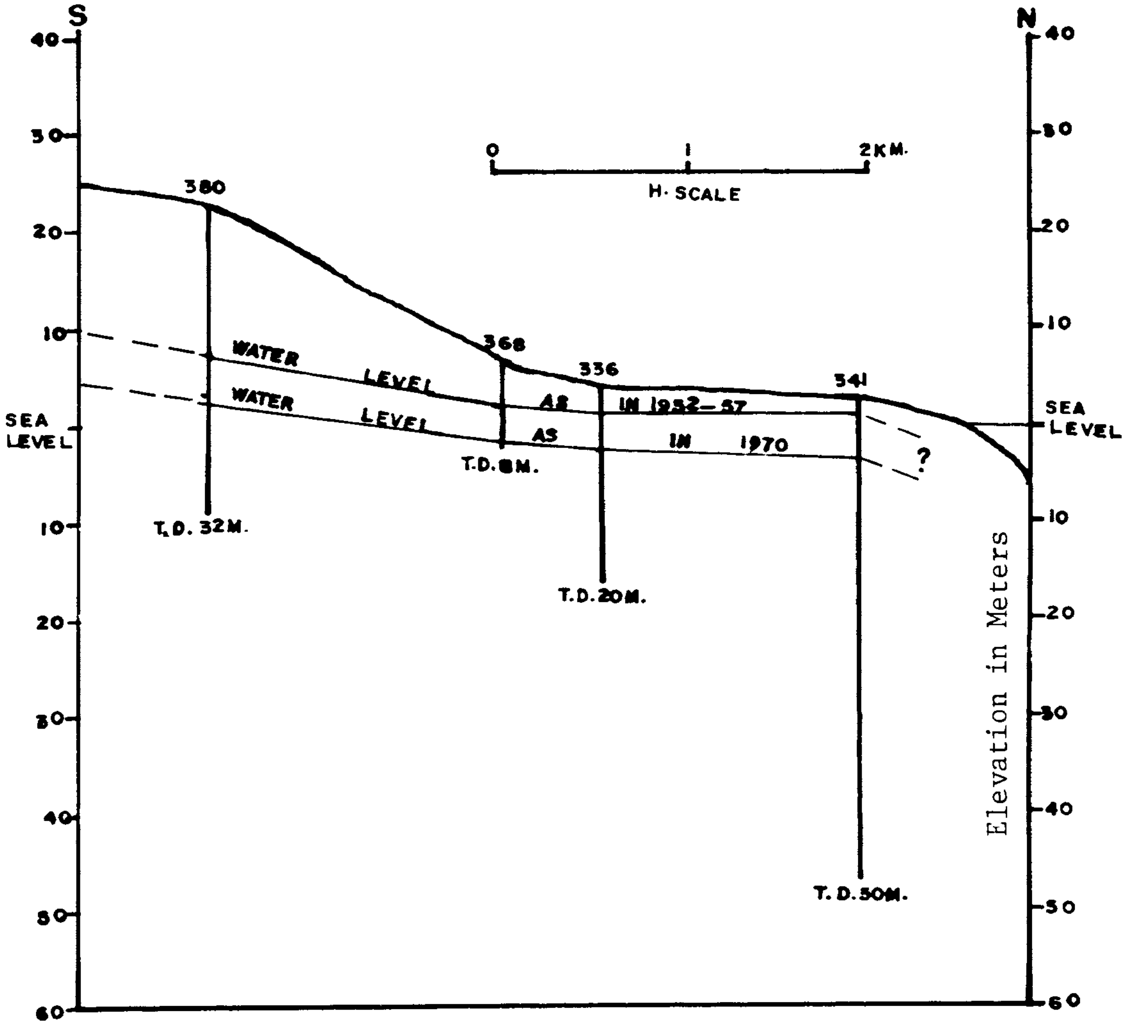


Figure 8. Cross Section TT' Near Aqaba Air Force Base Showing the Decline of Water Levels

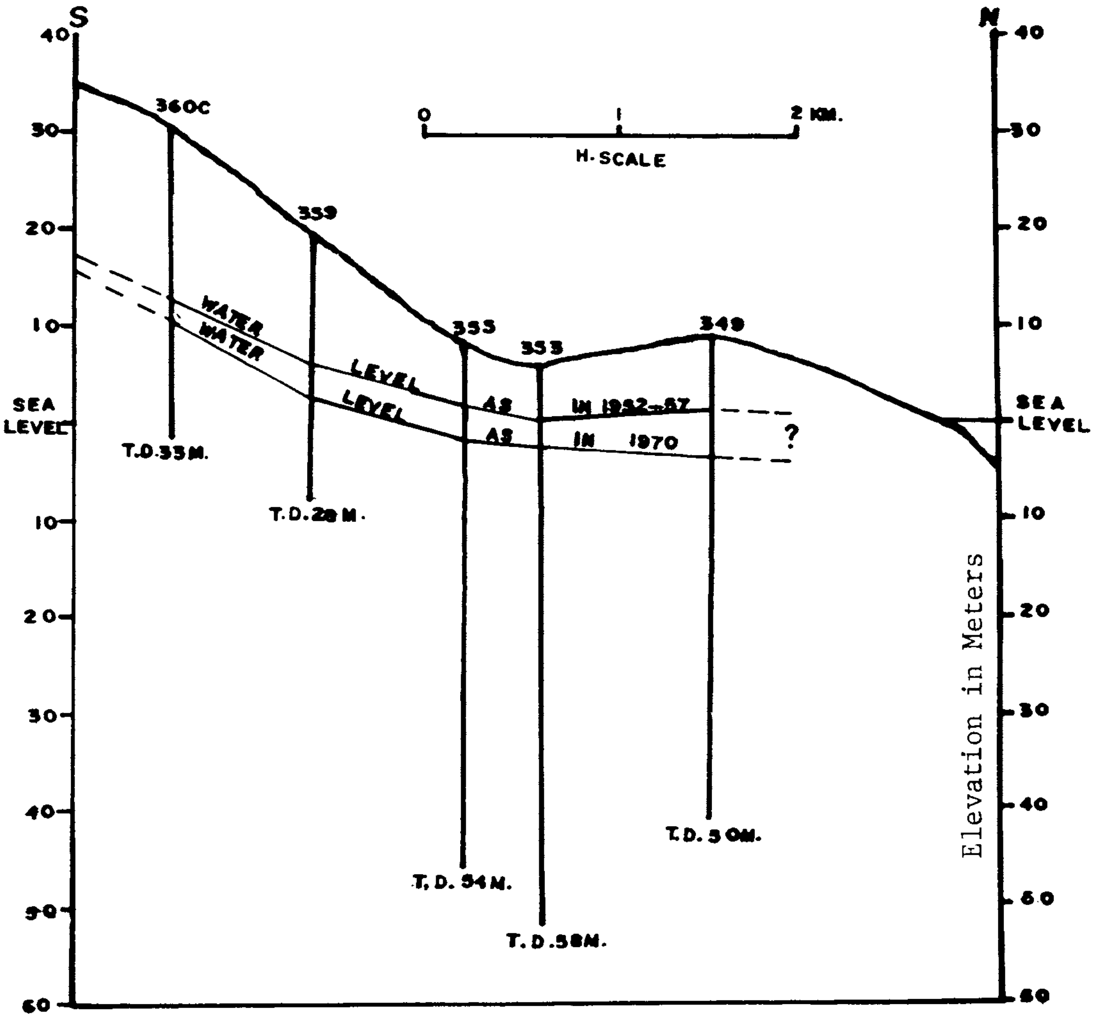


Figure 9. Cross Section T_1T_1' Near Aqaba Air Force Base Showing the Decline of Water Levels

around Bin Ghashir and westward (almost to the town of Sawani Bin Yadim) had declined to more than 16 meters below land surface.

1. Water Levels Near Aqaba Air Force Base

The depth of water below the land surface in 1956 ranges from 2 meters at well 341, near the sea, to about 17 meters at well 360c, near the southern boundary of the area.

The author constructed the two cross sections TT' and T_1T_1', Figures 8 and 9 to find the rate of water level decline in the area from 1952-1957 to 1970. Theoretically the decline is not constant but is different from one place to another depending on the rate of withdrawal from the wells, and the permeability, transmissibility, and storage coefficient of the aquifers.

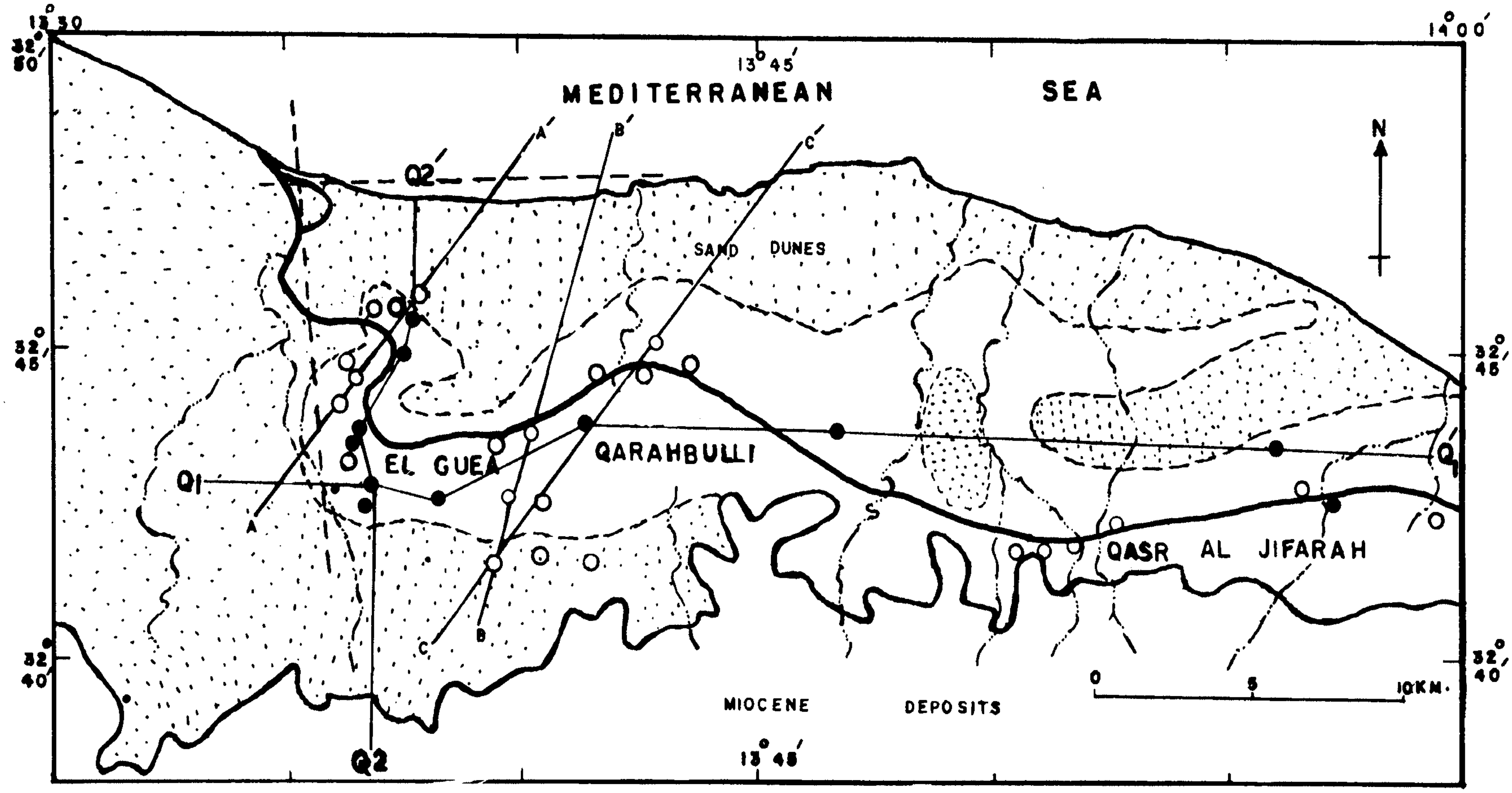
In this investigation at Aqaba Air Force Base the author assumed that the decline was constant. It is 0.25 meters per year for the water table wells and 0.5 meters per year for the flowing wells. It is known from Figure 9 and Table 7 that the water table at well 360c was at depth 17 meters in December 1956, and at 20.5 meters in December 1970, with a decline of 3.5 meters. From the same figure well 349 had a water table depth at 8 meters in 1952 and 12.5 meters in 1970. In Figure 8 well 368 had a water table depth at 4 meters in January 1957 but in 1970 it reached 7.5 meters. This rate of decline is considered very high in comparison with some wells in the west of the area where the decline is only 0.01 meters per year. At wells 335, 333 and 349, Figure 9 shows that the water level was below sea level in 1970. This could cause the sea water to enter the aquifer in the area. Figure 8 shows the same situation for wells 368, 336, and 341.

According to D.J. Cederstrom and Mario Bertaiola, (May, 1960), water level in well 303 (just southwest of the area) declined 2.6 meters in the period 1948-1956. A one meter decline in the period of four years is noted by them in the wells between Sghedeido and Mellaha. This agrees with the author's estimation. A decline of one half meter is reported in well 429 in the period 1953-1957.

2. Water Levels Near Qarahbulli

Because this investigation is dealing with the rate of water level decline and the results of this decline, the author constructed three cross sections AA', BB', and CC', Figures 11, 12 and 13 and estimated the position of the water table from 1960-1970. Cross section AA', Figure 11, shows that the well 3244-1336-1 has a decline of about 2.2 meters in the period 1960-1970, while well 3243-1336-2 has a decline of 0.9 meters for the same period of time. Well 3245-1377-3 has 2.4 meter decline for the same period, 1960-1970. Cross section BB', Figure 12, contains wells having different rates of decline, well 3241-1300-1 has a decline of 2.5 meters, well 3242-1339-2 has a decline only of 0.6 meters while well 3243-1340-1 has a decline of 1.1 meter, these descriptions of the wells were obtained from 1960-1970. Cross section CC', Figure 13, has wells of different rate of decline too all representing the same interval of time 1960-1970. Well 3241-1339-1 has a decline of 2.5 meters, well 3243-1340 has a decline of 2 meters and well 3245-1342 (north of the town of Qarahbulli) has a decline of 0.5 meters.

The average decline of the water level all over the area of Qarahbulli was about 0.16 meters per year for the shallow wells, but



LEGEND

○ **QUATERNARY WELL**

● **MIOCENE WELL**

Figure 10. Map of Well Location and Cross Sections Near Qarahbulli. (After W. Ogilbee, 1962)

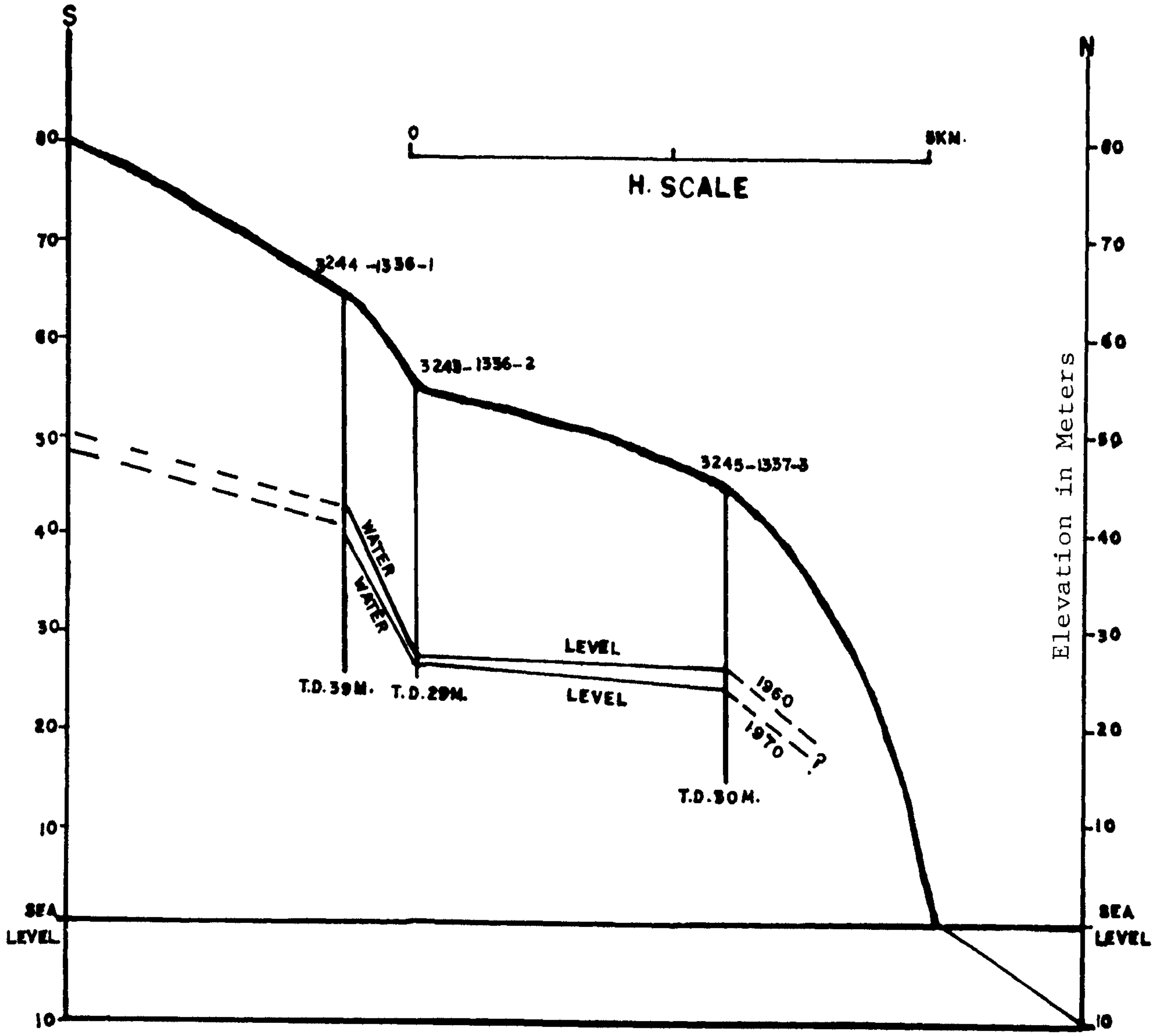


Figure 11. Cross Section AA' at Qarahbulli Showing the Decline of Water Levels

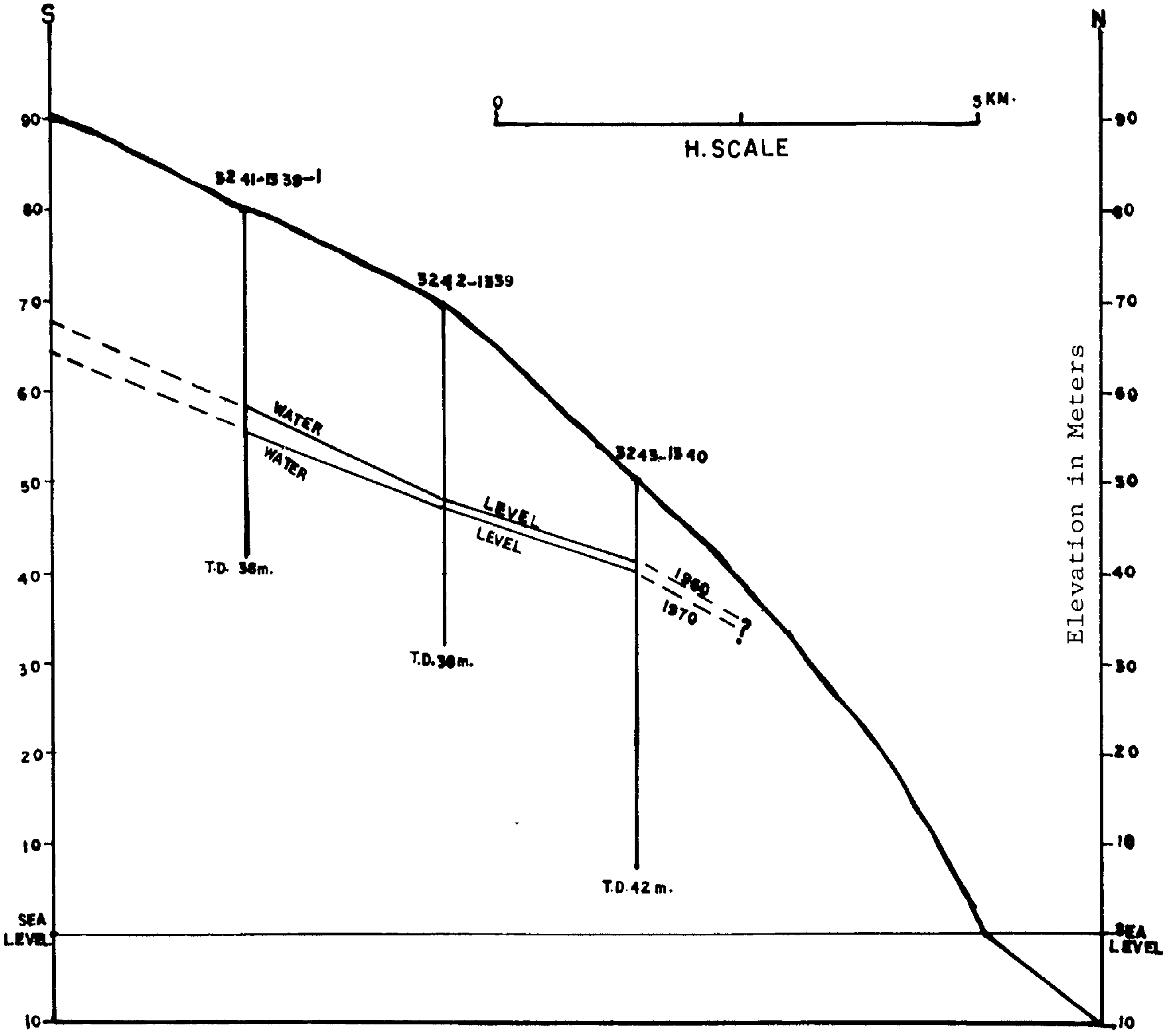


Figure 12. Cross Section BB' at Qarahbulli Showing the Decline of Water Levels

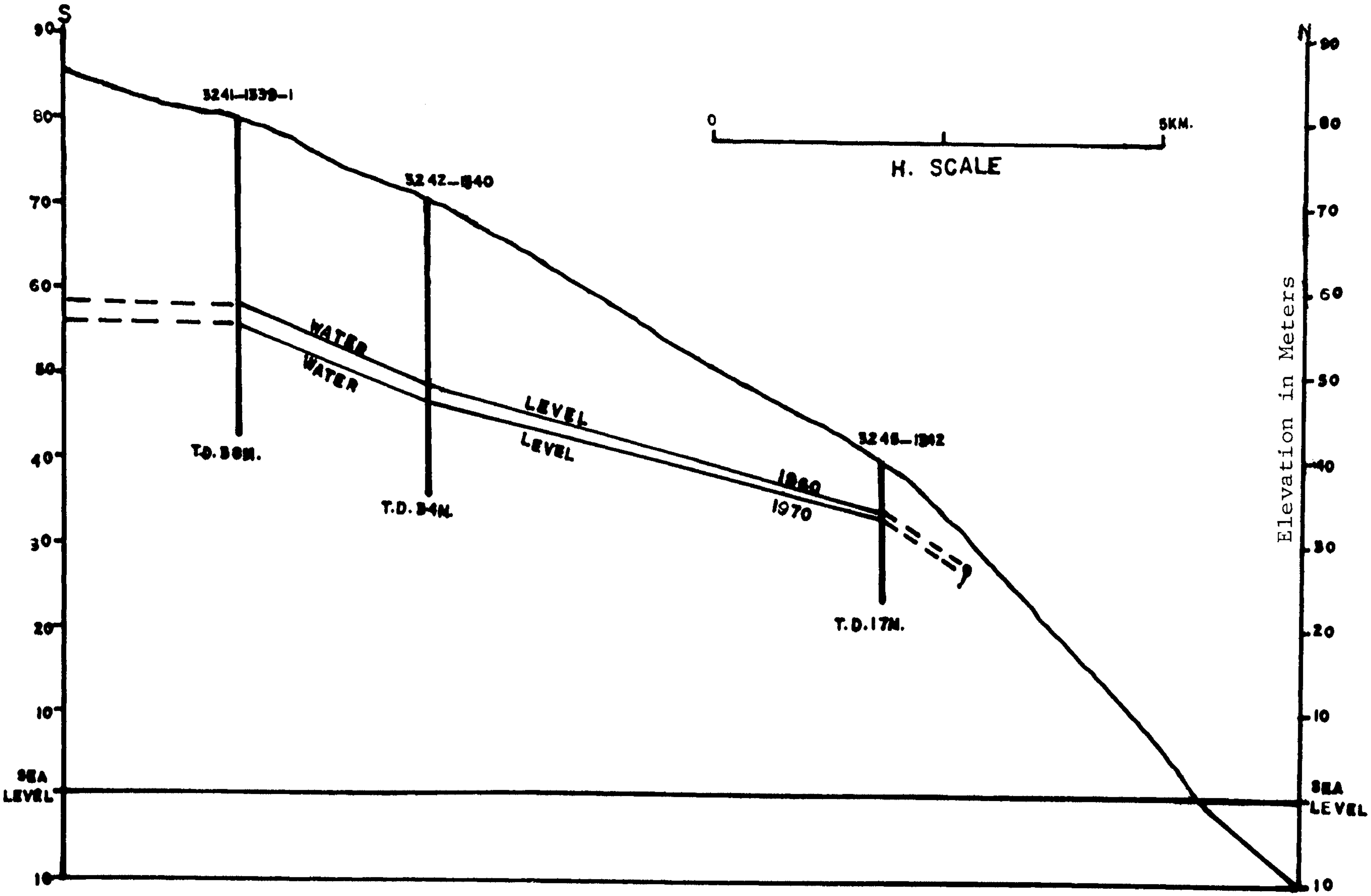


Figure 13. Cross Section CC' at Qarahbulli Showing the Decline of Water Levels

this figure may not be necessarily correct inasmuch as the data available on them indicated that the rate of decline may have accelerated in the last few years because the rate of decline for 1950-1960 exceeds that of 1940-1950.

Cross section AA' is drawn at the northwest of El Guea and the cross sections BB' and CC' are at the northwest of the town of Qarahbulli as shown in Figure 10.

William Ogilbee (November, 1962, p. 40) shows that the average of water level decline per year was 0.2 meters for shallow wells and 0.5 meters for deep wells. Near Qasr al Jifarah, he reported that a maximum head of 14 meters above land surface was reported in well 3245-1337-2 when drilled in 1939. In 1960 prior to the pumping test by Stuart the maximum head in the same well was reported to be 5 meters above land surface. Well 3243-1341-1 had a reported head of 8 meters above land surface when drilled in 1937. By 1961, the water level was 0.70 meters below land surface. He also reported that the water level in well 3243-1336-4 was 8.2 meters below land surface when drilled in 1956, but by 1959 it had dropped to 10.6 meters.

If this rate of decline continues, pumps will eventually have to be installed in all of the artesian wells in the area. Under the above conditions, water levels will continue to fall, therefore cost of pumping will rise and consequently it will not be possible for some farmers to irrigate certain crops because the cost of water consumed will be too great.

C. Groundwater Contamination in the Area

1. Introduction

Coastal aquifers come in contact with the sea at or seaward from the coast and, under conditions, have discharged fresh groundwater into the sea. At the same time there have been increased demands for groundwater for domestic or industrial purposes in many coastal areas. However, the seaward flow of fresh groundwater has been decreased or even reversed causing sea water to enter and to penetrate inland. This phenomenon is called sea water intrusion.

If the salt water travels inland to well fields the groundwater supplies become useless. Moreover the aquifer becomes contaminated with salt water which may take years to remove even with adequate fresh groundwater available to flush out the saline water. Many theories describe the shape of the salt water-freshwater interface. One of the earliest studies was published in 1855, by Braithwaite, who described the increasing salinity of water pumped from wells in London and Liverpool, England. This problem occurred in many other places such as Germany, Japan, Italy, the Middle East, and the U.S.A.

Many other investigators have worked on this problem since the early nineteenth century. One of the most widely known relations describing salt water intrusion is the Ghyben-Herzberg relation (1889-1901) which discovered that fresh water occurred underground not at sea level but rather at a depth below sea level of about 40 times the height of fresh water above sea level.

2. Groundwater Contamination Near Aqaba Air Force Base

From the present investigation there is no indication that a major sea water intrusion is taking place in the area. The cross sections TT' and T_1T_1' show that the hydraulic gradient is toward the sea in most places in the area. However, the continuous decline of the water level in the area may reverse the hydraulic gradient toward the land, as is shown in cross section T_1T_1', here the hydraulic gradient is toward the land from well 349 to well 353, which gives a little indication of the possibility of contamination to the water yield from the well 353, which has 92 ppm of chloride in comparison to well 355 which is one hundred meters south of well 353 and yields only 36 ppm of chloride. The water wells in the northwest part of the area has a high chloride content: it reached 32,750 ppm in well 339 and 30,300 ppm in well 341. Both wells have a distance of about one kilometer from the sea. But well 313 has only 2440 ppm. and is located just 100 meters from the sea. At the northeast side of the well location map, Figure 7, well 492 has only 1510 ppm. of chloride and is located just one half kilometer from the sea.

The origin or source from which the chloride comes is of special interest because if the origin is known it may be possible to prevent future increases in the salinity of the water and it may, indeed, be possible to take steps to decrease the chloride content of the water in certain areas.

D.J. Cederstrom and Bertaiola (1960) suggested that a higher than normal chloride content of some shallow groundwater may originate in several ways:

a. Along the coast heavy pumping may cause the sea water to enter the aquifers.

b. Salt spray may be driven inland by storms.

c. The concentration of salts in normal groundwater of low mineral content will increase.

1. As water is lost by evaporation through the capillary fringe above the water table.
2. Due to evaporation during irrigation.

In both cases, salts may be deposited, the soluble portion of which is later redissolved and carried down to water table.

d. From contamination by artesian water of high chloride content.

e. By contamination from organic waste.

They also indicated that near Aqaba Air Force Base there is no indication of any contamination by artesian wells because well 345 at the northeast gate of the base flowed freely in 1956 which might be thought of as contaminated, or having contaminated adjacent shallow wells that yield chloride water. However, both wells 346 (one half kilometer to the southwest) and well 448 (three fourth kilometer to the southeast of well 345) yield water containing much more chloride than 936 ppm. found in the artesian water of well 345. Also artesian well 457 at Tagiura does not appear to contaminate the shallow water zone. Well 490 to the north yields water containing only 111 ppm. of chloride, an amount only slightly in excess of normal in the shallow water zone in the area of Tagiura.

The evaporation of capillary water may cause increase in the salt water content of groundwater. What water rises by capillary action, salt is deposited upon evaporation, and is later dissolved by rain or other water and carried down to the water table. The groundwater may then become slightly more saline than it was previously. As this process continues the salinity of the zone of saturation will continue to increase. If the groundwater moves seaward old water (saline water) may be removed by the new fresh water. However, in a heavily irrigated area, like Tagiura and its vicinity, where the amount of water lost by evaporation and plant use (transpiration) is large, this is in comparison to the amount of water added from rainfall or that percolating into the area by underground flow, make the water more contaminated. Another factor that should be discussed is the sabkhahs (playas) which cause the salinity in groundwater in wells or farm lands adjacent to the sabkhahs. For example, there exists one near Aqaba Air Force Base where heavy pumping in the vicinity may draw heavy brines from the sabkhah into the well area and the water will gradually become useless for irrigation or any other purpose. The data tend to show that sea water is not the contaminant in the area near Aqaba Air Force Base. The conclusion is that the water from wells at the west of Aqaba Air Force Base are pumping from ancient salt flats on which the runway of the Aqaba Air Force Base was built. This is known because of extremely saline water from well 339, 341 and 343 adjacent to the salt water canal. These wells contain chloride ranging from 29,400 to 32,750 ppm. It may explain that the contamination is from the salt brines, where as the Mediterranean sea water contains less than 22,000 ppm. of chloride. The author believes that there is more than one process causing the increase of the salinity along the coastal area of Tripoli.

3. Groundwater Contamination Near Qarahbulli

There is no indication of any sea water intrusion in the area at the present time. The three cross sections AA', BB' and CC', Figures 11, 12 and 13, show that the hydraulic gradient is toward the sea, which means that the fresh water is discharging into the sea. However, the decline of water level in the area is increasing. This eventually may change the direction of the gradient and cause sea water to enter the aquifers in the area.

Many other factors (similar to those at Aqaba Air Force Base near Tripoli) increase the salinity of the groundwater in the area.

D. Recommendations

The author recommends the following:

1. Capture and use some of the freshwater flow to the sea, whether by building dams and irrigation projects or by many small dikes and dams distributed on water courses of minor tributaries throughout the area.

2. Select observation wells near both Aqaba Air Force Base and Qarahbulli for regular measurement of water levels, and drill new wells for this purpose where necessary.

3. In areas of rapidly declining water levels like Aqaba Air Force Base and Qarahbulli, prohibit both construction of new wells and any change to higher production from existing wells.

4. In areas subject to sea water intrusion like Aqaba Air Force Base:

a. Control pumping patterns, either by reducing extractions, by rearrangement of areal pattern of pumping, or both, so that groundwater levels will rise to or above sea level.

b. Maintain the groundwater levels above sea level by artificial recharge. Utilizing surface spreading, injection wells, or both.

c. Establish a subsurface barrier to reduce the permeability of the water-bearing deposits sufficiently to prevent the inflow of sea water into the freshwater aquifers.

5. Control the wells adjacent to the sabkhah underlain by highly mineralized water as near Aqaba Air Force Base and Qarahbulli, there is the danger of contaminating the water supply by heavy pumping. Here regulation may:

a. Provide for a reasonable apportionment of available water.

b. Restrict the total pumpage to an amount less than which caused the inflow of salty water.

c. Secure the complete shutdown of wells already contaminated or beginning to show contamination.

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VITA

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APPENDICES

APPENDIX A

Climatic Data Tables

Appendix A shows the maximum and minimum temperature of the area by using records of several years. It also shows the average monthly and annual rainfall of ten stations. Some of them are on the coast, others are far inland; percent of years when rainfall is less than stated amounts is shown in the last table of this appendix.

Table 3. Average Maximum and Minimum Temperature (°C)

Tripoli (20 years records)

Month	J.	F.	M.	A.	M.	J.	J.	A.	S.	O.	N.	D.
Maximum	16.9	18.6	20.4	23.4	26.2	29.3	30.8	31.8	30.6	28.4	23.2	19.1
Minimum	7.3	8.5	10.0	12.8	15.8	18.8	20.8	21.7	20.5	17.7	13.0	8.8

Al Azizia (19 year record)

Maximum	17.4	19.8	23.3	28.0	31.2	35.8	37.5	37.9	36.4	31.9	24.3	19.1
Minimum	5.9	7.1	9.4	12.4	15.4	19.0	20.3	20.6	19.8	16.9	17.1	7.3

Homs (15 year record)

Maximum	16.7	18.9	21.0	22.0	25.5	29.0	31.0	32.0	30.5	28.0	22.0	18.6
Minimum	7.2	8.3	9.5	11.9	15.2	17.9	20.7	21.5	20.3	17.5	12.8	7.6

Misurata (15 year record)

Maximum	17.2	19.5	23.0	27.0	31.0	34.9	37.0	37.9	35.8	30.8	25.0	19.3
Minimum	5.2	7.4	9.3	11.9	15.0	18.6	20.1	20.4	19.6	16.2	12.4	7.1

Groundwater Resources of Tripoli area Libya. D.J. Cederstrom and Marie Bertaiola, May 1960

Table 4. Climatic Means for Selected Stations in Area Under Study

Tripoli

Month	J.	F.	M.	A.	M.	J.	J.	A.	S.	O.	N.	D.	Average Year
Temperature °C	12.0	13.3	15.2	18.2	20.6	23.9	25.6	26.3	25.6	22.7	18.1	13.6	19.6
Rainfall mm.	79.9	42.9	24.6	9.3	5.3	1.3	0.5	0.8	10.2	36.5	65.9	93.8	368.0
Relt. Humidity	62	61	60	59	62	63	65	65	63	60	64	62	62

Homs

Temperature °C	13.2	14.0	15.6	18.5	20.5	24.3	26.2	26.9	25.8	23.5	19.0	14.7	20.7
Rainfall mm.	57.1	39.1	19.6	9.3	5.7	1.3	0.0	0.8	7.3	24.9	48.9	52.3	271.9
Relt. Humidity	66	65	62	65	64	65	67	67	65	66	66	66	65

Azizia

Temperature °C	11.3	13.0	15.7	19.6	23.1	27.0	28.7	28.8	27.5	23.6	17.7	13.0	20.8
Rainfall mm.	47.5	33.2	21.1	9.6	1.2	4.6	0.1	0.1	6.6	16.0	27.1	50.5	217.0
Relt. Humidity	62	58	54	46	42	37	41	45	44	50	57	60	50

Table 4. (continued)

Garian

Month	J.	F.	M.	A.	M.	J.	J.	A.	S.	O.	N.	D.	Average Year
Temperature °C	8.3	10.0	12.7	17.0	20.7	24.7	26.5	26.8	24.1	20.4	15.3	9.9	18.0
Rainfall mm.	74.1	51.5	39.9	16.0	12.7	2.1	0.5	0.7	11.4	23.8	39.5	54.0	326
Relt. Humidity	57	54	48	40	36	28	30	30	39	43	53	58	43

Misurata

Temperature	13.0	14.2	15.4	18.3	21.0	23.9	26.4	26.1	25.3	23.1	19.2	14.2	19.8
Rainfall mm.	60.2	42.1	20.2	10.0	6.2	2.1	0.1	0.9	8.2	29.8	50.1	56.9	281.2
Relt. Humidity	62	63	66	64	66	65	67	67	65	66	66	66	65

Compiled by the author from previous data

Table 5. Average Monthly and Annual Rainfall

Station	Code #	Alt	J.	F.	M.	A.	M.	J.	J.	A.	S.	O.	N.	D.	Year	# years record
Tripoli	3254-1311	17	77.1	42.2	24.8	9.7	5.1	1.4	0.5	0.8	10.1	36.0	67.5	95.6	370.8	70
Homs	3239-1417	11	52.8	41.2	19.2	9.2	4.5	1.8	0.0	0.4	6.5	27.0	51.0	54.0	268.7	30
Zliten	3230-1435	8	49.7	28.5	19.9	6.7	3.1	1.4	0.0	0.0	8.7	26.0	33.0	40.5	215.7	17
Misurata	3122-1512	8	52.6	31.5	13.0	6.6	4.3	1.3	0.0	0.6	11.8	34.0	41.0	49.8	247.4	29
Azizia	3232-1301	116	45.5	33.6	20.9	11.1	3.8	1.4	0.2	0.1	6.9	11.5	27.1	48.3	214.4	34
Qarahbulli	3244-1343	42	78.8	47.5	29.2	8.4	3.1	1.8	0.0	0.0	11.3	48.5	26.1	72.2	371	20
Tarhunah	3226-1338	430	57.3	50.8	31.8	11.4	4.6	3.0	0.2	0.8	7.2	21.4	26.8	44.0	259	15
Garian	3200-1301	725	74.6	49.6	40.4	11.8	8.7	2.2	0.6	0.8	12.1	23.8	39.4	53.1	322	30
Beni Ulid	3145-1401	220	14.3	8.7	5.7	7.4	5.6	0.0	0.0	0.0	6.4	8.2	4.8	12.1	75.4	15

Development of groundwater in Gebel Tarhunah Tripolitania Libya (Hazen and Sawyer, 1966)

Table 6. Percent of Years when Rainfall is Less than Stated Amounts

Station	Annual Rainfall mm/year	Percent of Years when Rainfall is Less than 150 mm.	200 mm.	250 mm.	300 mm.
Tripoli	370.8	1	8	23	42
Homs	268.7	12	36	61	80
Zliten	215.7	1	14	32	61
Misurata	247.4	1	13	37	63
Tarhunah	259.0	7	24	44	61
Beni Ulid	75.4	95	99	--	--

Development of groundwater in the Gebel Tarhunab Tripolitania Libya (Hazen and Sawyer, 1966)

APPENDIX B

Water Well Data Tables

Most of the well records have been obtained from selected records assembled by J. R. Jones of the U.S. Geological Survey International Activities Revision, Washington, D.C.

Mr. Jones compiled these data during a number of years of work on groundwater problems in Libya, and from previous investigations by the Libyan government and other foreign agencies. Additional records were secured from Italian maps and well logs and from the files of the U.S. Geological Survey International Activities in Washington, D.C. and from personal interview.

Most of the wells were selected because they are representative of the area in which they are located. Some were chosen because they illustrate uncommon conditions. If a choice was available, wells with the more complete data were selected over those with incomplete data. The groundwater sources data used in this thesis are shown in the bibliography.

Table 7. Records of Water Wells in Sections TT' and T_1T_1' Near Aqaba Air Force Base

Well Number	Location and Owner	Elevation (m)	Depth (m)	Type	Year	Water Level Depth (m)	Date of Measurement	Calculated Depth (m)	Yield m^3/hr
360c	1.5 km. S of km. 11.5 on Tripoli-Homs Road	31.0	33	Dr.	--	17	Dec. 1956	17(1956)- 20.5(1970)	150
359	1 km. SE of Fattarin Mellaha	20	28	Dr.	--	14	Dec. 1957	14(1957)- 17.5(1970)	--
355	Mellah Well Field Aqaba Air Force Base	8	54	Dr.	--	6	Aug. 1955	6(1955)- 9.5(1970)	--
353	Mellaha Well Field Aqaba Air Force Base	6	58	Dr.	--	6	1956	6(1956)- 9.5(1970)	--
349	Guastalla Well Field Aqaba Air Force Base	9	50	Dr.	--	8	Jan. 1952	8(1952)- 12.5(1970)	80
380	Sghedeida Well Field Aqaba Air Force Base	23	32	Dr.	--	16	Mar. 1953	16(1953)- 20.5(1970)	21

Table 7. (continued)

Well Number	Location and Owner	Elevation (m)	Depth (m)	Type	Year	Water level Depth (m)	Date of measurement	Calculated Depth (m)	Yield m^3/hr
368	1.35 km N. of km 9 on Tripoli-Homs Road	6	8	Dg.	--	4	Jan. 1957	4(1957)- 7.5(1970)	25
336	1.5 km SE of West Gate of Aqaba Air Force Base	4	20	Dr.	1953	3	Dec. 1956	3(1956)- 6.5(1970)	20
341	1.4 km E. NE. of west gate of Aqaba Air Force Base	3	50	Dr.	--	2	Dec. 1952	2(1952)- 6.5(1970)	39

* (After D.J. Cederstrom, May 1960)

Table 8. Records of Water Wells Near Qarahbulli

Well Number	Location	Elevation (m)	Depth (m)	Type	Year	Water Level Depth (m)	Date of Measurement	Calculated Depth (m)	Yield m^3/hr
3242-1336	Qarahbulli	85	231	Dr.	--	30	1940	40(1960) 45(1970)	-
3242-1338	El Guea	85	338	Dr.	--	30.5	1940	40.5(1960) 45.5(1970)	-
3243-1341	Qarahbulli	50	187	Dr.	--	0.7	1962	+1.6*(1960) -1.4*(1970)	60
3243-1346	Qarahbulli	60	308	Dr.	--	14.50 17.43 17.40 17.48	1937 1960 1961 1962	17.43(1960) 22.43(1970)	78
3243-1356	Qasr Al Jifarah	60	378	Dr.	--	22.0	1938	33(1960) 38(1970)	-
3243-1336	Qarahbulli	50±	262	Dr.	--	--	--	--	-
3244-1337	El Guea	45	404	Dr.	--	+12*	1956	+11(1960)* +6(1970)*	140
3245-1337	---	35	189	Dr.	--	+14*	1939	+5(1960)* +0.5(1970)*	70
3243-1339	El Guea	52.5	193	Dr.	--	+6.5*	1939	-4(1960)* -9(1970)*	-
3242-1336	El Guea	--	28.8	Dg.	--	23.4 23.35** 23.27	1960 1961 1962	23.4(1960) ? (1970)	-
3244-1366	El Guea	--	41	Dr.	--	24.62 25.35 25.13	1960 1961 1962	24.62(1960) 26.62(1970)	37

Table 8. (continued)

Wall Number	Location	Elevation (m)	Depth (m)	Type	Year	Water Level Depth (m)	Date of Measurement	Calculated Depth (m)	Yield m^3/hr
3244-1341	Qarahbulli	--	32	Dr.	--	17.96 19.00	1953 1962	18.76(1960) 19.96(1970)	60
3244-1336	El Guea	--	38.5	Dr.	--	21.75 22.07 21.60**	1960 1961 1962	21.75(1960) 23.95(1970)	60
3245-1343	Qarahbulli	--	26.6	Dr.	--	20.00 15.73** 15.85	1960 1961 1962	20.00(1960) 21.2(1970)	-
3245-1343	Qarahbulli	--	21.5	Dr.	--	13.00 13.00 13.00	1960 1961 1962	13.00(1960) 13.00(1970	-
3241-1350	Qasr Al Jifarah	--	47.6	Dg.	--	43.96 43.79** 44.00	1953 1961 1962	43.58(1960) 45.68(1970)	-

*+ indicates that the well flows above ground surface

*- indicates that the water level is below surface

** indicates that the rise in water level is because of the rainfall during winter time

Table 9. Well Log Near Tripoli
(Well 338 1.3 km. East Southeast
of Main Gate Aqaba Air Force Base*)

Altitude 11.2 meters

Lithologic description	Thickness meters	Depth meters
Fine sand	4.1	4.1
Soft gray limestone	1.1	5.2
Hard packed fine sand	3.6	8.8
Light gray limestone	2.2	11.0
Soft yellow to brown sand clay	13.1	24.1
Soft light brown limestone, water	3.6	27.7
Soft light gray limestone	0.6	28.3
Stiff light blue sand clay	2.4	30.7
Soft light gray limestone	7.0	37.7
Soft light gray sandy clay	4.5	42.2
Soft white chalky clay	2.7	44.9
Soft light yellow clay	6.1	51.0
Soft light gray limestone, salt water	7.4	58.4
Soft white limestone	10.3	68.7
Soft light blue sandy clay	0.1	68.8
Gray shell rock	5.7	74.5
Stiff yellow clay	1.2	75.7

* (After D.J. Cederstrom, May 1960)

Table 10. Well Log Near Tripoli (Well 457 O.P.D.L., Servizio Perforazioni 14) Conc. Cagno. Km. 17, Tripoli-Homs Road, Tagiura.

Altitude 7.5 meters

Lithologic Descriptions	Thickness meters	Depth meters
Soft red sandstone, water static level 3 meters below surface......................	7.5	7.5
Friable quartz sandstone, compact at base...	10.5	18
Sandy limestone............................	4	22
Quartz sandstone...........................	1	23
Limey quartz sand, water static level 3 meters below surface......................	3	26
Limey quartz sand..........................	18	44
Fossiliferous sandy limestone..............	30	74
Green clay sand............................	6	80
Sandy clay, fossiliferous in upper portion..	25	105
Fossiliferous clayey limestone.............	24	129
Green slightly sandy clay..................	15	144
Clayey limestone...........................	6	150
Plastic green clay.........................	18	168
Fossiliferous green limey sand.............	7	175
Clay, largely plastic clay; a fossiliferous limestone stratum at 204-206 meters and thin streaks in the basal portion sandstone at 235-238 and 239-241 meters clayey sand at 241-241.5 and 364-370.5 meters static level 72 meter above surface flow.................	252	427
Quartz sandstone. Salty(?) water static level 57 meter above surface flow 50 cu. m/hr. siliceous sand salty(?) water static.......	36	463
Level 57 meters above surface flow 225 cu. m/hr.	17	480

Table 11. Well Log Near Tripoli (Well 345 O.P.D.L., Servizio Perforazione 25) Conc. Bigiorno. Opposite Northeast Gate of Aqaba Air Force Base, Mellaha.

Altitude 6 meters

Lithologic Description	Thickness meters	Depth meters
Slightly clay sand............................	4.5	4.5
Soft reddish limestone, water at 6 meters Static level 5.5 meter below surface.................	12.5	17
Friable sandy marl............................	5	23
White and gray limestone......................	12	35
White to yellow spongy-textured limestone water at 37-55 meters.........................	39	74
Somewhat sandy blue clay......................	27	101
Fossiliferous gray marly limestone............	3	104
Plastic clay, water in spongy limestone at 259-260 meters (slight flow) and at 308-310 meter (slight flow)................................	338	442
Compact fossiliferous limestone...............	5.5	447.5
Somewhat friable white quartz sandstone water, static level 57 meters above, surface, flow 100 cu. m/hr.................................	45	482.5
Quartz sand and gravel with large oyster shells, water static as above flow 300 cu. m/hr........	1.5	484

Table 12. Well Log Near Tripoli (Well 348 Guastella Well Field at East End of Field, Aqaba Air Force Base)

Altitude 11 meters

Lithologic Description	Thickness meters	Depth meters
Fine sand	1.8	1.8
Light gray clay with pieces of limestone	5.2	7.0
Hard light brown limestone	1.3	8.3
Light gray to brown sandy clay with pieces of limestone	5.4	13.8
Stiff light brown sandy clay	4.8	18.6
Soft gray sandstone, Water	11.0	29.6
Dark gray sandy clay	4.5	34.1
Soft light gray limestone	14.7	48.8
Soft light limestone	.082	49.0

Table 13. Well Log Near Tripoli (Well 360A 1 Km. South of Km. 11.2 on Tripoli-Homs Road)

Altitude 27.5 meters

Lithologic Description	Thickness meters	Depth meters
Friable red sandy limestone....................	4	4
Soft yellow limey quartz limestone.............	14	18
Soft white sandstone, water static at 18 meters below surface.................................	6.5	24.5
Compact yellow limestone, water at 32-34 meters static level at 15 meters below surface.........	9.5	34
Very sandy maral...............................	10	44
Compact quartz sandstone.......................	4	48
Spongy-textured limestone......................	4	52
Fossiliferous green sandy clay.................	7	59
Fossiliferous white spongy-textured limestone...	18.5	77.5
Fossiliferous green clay.......................	11.5	89
Sandy limestone................................	2	91
Fossiliferous sandy clay.......................	15	106
Green clay, sandy in lower portion limestone strata at 147-151, 160.5-163 and 182-187m. Water at 206 meters salty static level 8.5 meters below surface.................................	130	236
Fossiliferous clayey limestone breccia..........	16.5	252.5
Green sandy clay...............................	7	259.5
Pebbly sand and clay salty water small flow.....	10.5	270
Clay with fossiliferous nodules................	7	277
Gray clay......................................	15	292

Table 13. (continued)

Lithologic Description	Thickness meters	Depth meters
Spongy-textured fine sandy limestone-salt water static level 12 meters above surface flow 8m^3/hr..........................	4	296
Fossiliferous very sandy marl.................	10	306
Fossiliferous sand and clay...................	3	309
Very sandy marl...............................	18	327

Table 14. Well Log Near Qarahbulli (Well 3242-1336-1)*

Altitude 85m

Lithologic Description	Thickness meters	Depth meters
Quaternary deposits		
Sand, yellowish-red	8	8
Clay, sandy (tin)	9	17
Clay, sandy, with gravel	3	20
Clay, yellow, with sandy clay	7	27
Clay, plastic, yellow	5	32
Gravel with fossils	5	37
Clay, scaly, yellow	4	41
Limestone, clayey, water bearing	1	42
Clay, yellow	6	48
Conglomerate	1	49
Miocene strata		
Clay, grayish-green	9	58
Limestone, grayish-white, fossiliferous	3	61
Clay, green	12	73
Clay, slightly scaly, green	9	82
Limestone, white	6	88
Clay, green	13	101
Limestone, hard	4	105
Clay, green, with limestone beds	13	118
Limestone	3	121
Clay, green	5	126

Table 14. (continued)

Lithologic Description	Thickness meters	Depth meters
Limestone	4	130
Clay, green	22	152
<u>Mesozoic rocks</u>		
Limestone, white	30	182
Sand loose	1	183
Limestone, avenaceons, white	14	197
Sand, loose, salty water	2	199
Sandstone, with sand and gravel	24	223
Clay, reddish	8	231

* (After William Ogilbee, 1962)

Table 15. Well Log Near Qarahbulli
(Well 3243-1341-1)

Altitude 50 m.

Lithologic Description	Thickness meters	Depth meters
Quaternary deposits		
Sand, surficial	2	2
Sand, quartz, limy, soft	20	22
Limestone and sandstone strata water at 22 to 25 meters	8	30
Clay, Sandy, greenish with fossils	5	35
Limestone, fossiliferous water from 35 to 41 meters	6	41
Miocene strata		
Clay, very sandy, fossiliferous	19	60
Limestone, clayey, green, gray, fossils	9	69
Clay, sandy, green	24	93
Sand, limy water bearing	2	95
Limestone, sandy, water bearing	2	97
Sand, limy, thin-bedded, water bearing	5	102
Sandstone, quartz, soft water from 102 to 112 meters	18	120
Clay, green	5	125
Limestone, marly, and clay	5	130
Limestone	3	133
Clay, scaly	2	135
Sandstone and quartz sand strate water from 135 to 187 meters	32	187

Table 16. Well Log Near Qarahbulli
(Well 3244-1337-3)

Altitude 45m±

Lithologic Deposition	Thickness meters	Depth meters
Quaternary deposits		
Sand, dune..................................	3	3
Sandstone..................................	16	19
Sandstone, calcareous, thin-bedded water bearing..................................	19	38
Sandstone, clayey, green....................	4	42
Miocene strata		
Clay, yellow..............................	15	57
Clay, plastic..............................	25	82
Clay with thin limestone and sandstone layers, water at 90 m............................	67	149
Limestone, siliceous, hard, with strata of plastic, Clay water at 182 m................	41	190
Clay, scaly, and hard rock.................	10	200
Limestone, hard with beds of clay...........	20	220
Clay, calcareans...........................	62	282
Limestone, siliceous, and scaly clay........	6	288
Clay, calcareans, plastic, scaly...........	25	313
Rock, Siliceous............................	9	322
Limestone, with strata of scaly clay........	16	338
Limestone, hard with scaly clay water at 340m..	51	389
Mesozoic rocks		
Rock, siliceous, hard......................	3	392
Clay, scaly, and siliceous limestone........	2	394
Rock, siliceous............................	10	404

Table 17. Well Log Near Qarahbulli (Well 3243-1336-3)

Altitude 50m±

Lithologic Description	Thickness meters	Depth meters
Quaternary deposits		
Sand, red..............................	5	5
Sand, fine, with limy pebbles...........	3	8
Sandy, limy............................	10	18
Limestone, sandy, stratified............	3	21
Sandstone, bedded......................	11	32
Clay green, with sandy beds.............	14	46
Limestone..............................	1	47
Miocene strata		
Clay, plastic, green, with sand layers...	39	85
Sand, gray.............................	1	86
Clay, plastic, blue.....................	3	89
Sand, gray.............................	4	93
Clay, scaly, white, with sandy layers....	5	98
Conglomerate...........................	4	102
Clay, scaly, dark blue..................	6	108
Sand, gray.............................	4	112
Clay, scaly, dark blue, with sandy layers..	16	128
Conglomerate...........................	6	134
Sandstone, gray, with white siliceous sand layers water bearing....................	10	144
Sandstone, gray........................	3	147
Clay, scaly, blue......................	7	154

Table 17. (continued)

Lithologic Description	Thickness meters	Depth meters
Sandstone, fossiliferous, with sandy layers..............................	7	161
No record water from 134 to 144 meters..	6	167
Clay, gray...........................	7	174
Sandstone, gray water bearing.........	4	178
Clay, yellow.........................	3	181
Limestone, yellowish.................	5	186
Clay, scaly, red......................	7	193
Sandstone, gray, and white quartz sand water from 199 to 211 meters..........	19	212
Clay greenish........................	1	213
Limestone, gray, fossiliferous, water from 234 to 244 meters................	31	244
Sandstone, spongy, white water from 244 to 250 meters.....................	18	262

APPENDIX C

Definition of Arabic Terms

The following are definitions of Arabic words frequently used in the text.

Term	English meaning
Ain	spring
Bir	well
Jebel	mountain
Jefara	coastal plain
Ghibli	hot wind from south
Qasr	castle or ruin
Ra's	hill or peak
Wadi	valley bottom
Sabkhah	salt flats or marshes