Ground-Water Resources of the Bengási Area, Cyrenaica, United Kingdom of Libya

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1757-B

Prepared under the auspices of the United States Operations Mission to Libya, the United States Corps of Engineers, and the Government of Libya

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By W. W. DOYEL *and* F. J. MAGUIRE

CONTRIBUTIONS TO THE HYDROLOGY OF AFRICA AND THE MEDITERRANEAN REGION

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GROUND-WATER RESOURCES OF THE BENGÂSI AREA, CYRENAICA, UNITED KINGDOM OF LIBYA

By W. W. Doyel and F. J. Maguire

ABSTRACT

The Bengâsi area of Libya, in the northwestern part of the Province of Cyrenaica (Wilâyat Barqah), is semiarid, and available ground-water supplies in the area are relatively small. Potable ground water from known sources is reserved for the present and future needs of the city, and no surface-water supplies are available in the area. This investigation to evaluate known, as well as potential, water supplies in the area was undertaken as part of a larger program of ground-water investigations in Libya under the auspices of the U. S. Operations Mission to Libya and the Government of Libya.

A ground-water reservoir underlies the Bengâsi area, in which the water occurs in solution channels, cavities, and other openings in Miocene limestone. The reservoir is recharged directly by rainfall on the area and by infiltration from ephemeral streams (wadis) rising in Al Jabal al Akhḍar to the east. In the Banînah and Al Fuwayhât areas the ground-water reservoir yields water of fair quality and in sufficient quantity for the current (1959) needs of the Bengâsi city supply. The test-drilling program in the area south and southeast of Bengâsi indicates that water in sufficient quantity for additional public supply probably can be obtained in some localities from wells. The water, however, is moderately to highly mineralized and would require treatment or demineralization before it could be used for additional public supply. Much of the water could be used directly for irrigation, but careful attention would have to be given to cultivation, drainage, and cropping practices. The hazard of salt-water encroachment also exists if large-scale withdrawals are undertaken in the coastal zones.

INTRODUCTION

LOCATION AND EXTENT OF AREA

The city of Bengâsi[1] (Bãnghãzi), Libya, is on the southern Mediterranean coast and on the eastern side of the Gulf of Sidra (Sirte), 560 kilometers (airline distance) east of Tripoli (Tarābulas), Libya, and 800 kilometers west of Alexandria, Egypt (fig. 1).

[1] Geographical names used in this report conform to the usage of the U.S. Board on Geographic Names (1958).

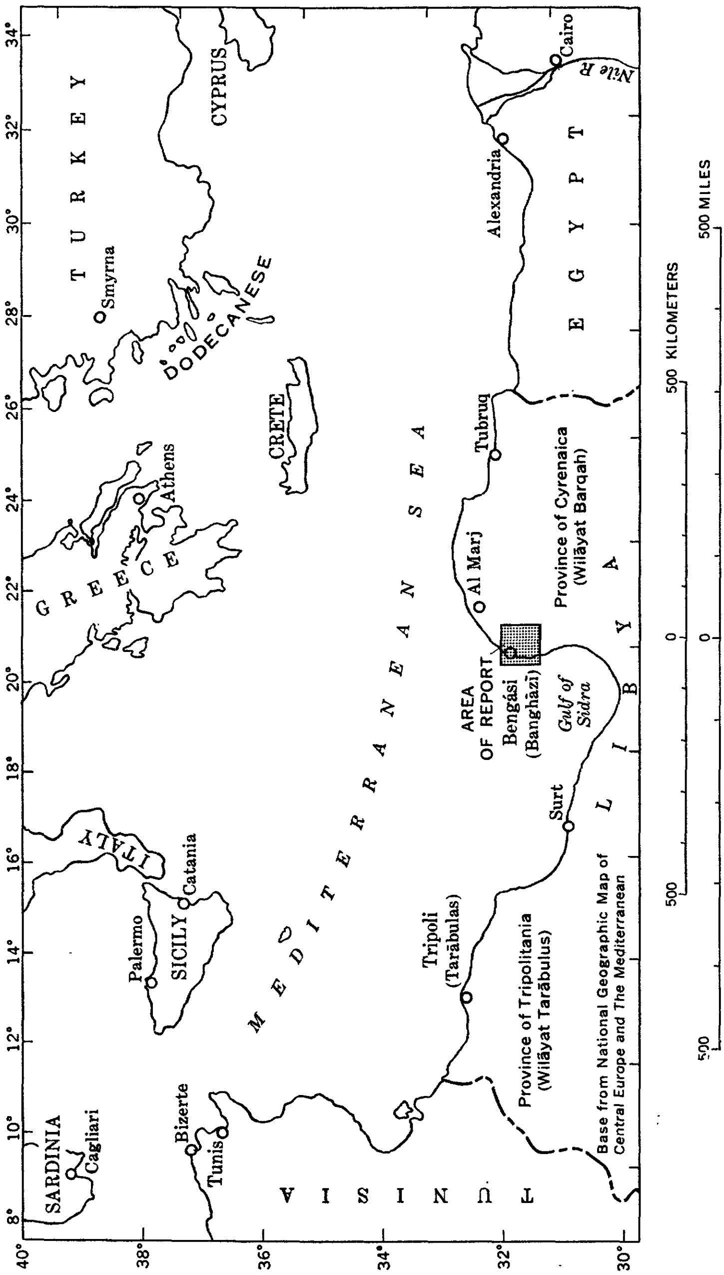

FIGURE 1.—Map of Mediterranean area showing location of area of investigation.

The Bengási area, as described in this report, consists of a part of the coastal plain that lies east and south of Bengási within an arc whose radius is approximately 35 kilometers. The report area consists of approximately 300 square kilometers (fig. 2).

PURPOSE AND SCOPE OF INVESTIGATION

This investigation of the Bengási area was undertaken to evaluate the ground-water resources of a part of the coastal plain in northwestern Cyrenaica (Wilāyat Barqah). It was part of a larger program of ground-water investigations in Libya, which have been in progress since 1952, by geologists of the U.S. Geological Survey assigned to the U.S. Operations Mission to Libya. The investigation was carried out between September 1957 and June 1958 through the joint work of the following workers: W. W. Doyel, geologist of the U.S. Geological Survey; F. J. Maguire, engineer of the U.S. Army Corps of Engineers; and M. J. Bessuni of the Government of Cyrenaica. The work included geological reconnaissance, collection of hydrologic data on existing supplies and previous ground-water exploration, and a test-drilling program which was financed by the U.S. Army Corps of Engineers because of interest in the area as a possible site for a U.S. military establishment.

ACKNOWLEDGMENTS

The writers wish to express their appreciation for the advice and assistance given by various staff members of the U.S. Operation Mission to Libya (USOM/L) and of the U.S. Embassy, including the following: Marcus J. Gordon, Country Director, USOM/L; Charles A. Wright, Provincial Director for Cyrenaica, Libyan-American Joint Service; Edwin L. Smith, Principal Officer, U.S. Embassy, Bengási; and Heywood H. Stackhouse, Acting Principal Officer, U.S. Embassy, Bengási. Acknowledgment is also made of the helpful assistance and support given by the Mudirs of the districts involved and by the following officials of the Cyrenaican Government: The Honorable Hussein Mazeg, Wali of Cyrenaica; Essayed Wanis Gaththafi, President of the Executive Council of Cyrenaica; Buseif Yaseen, Nazir of Interior; Mutawel Suleiman, former Nazir of Agriculture; Omar Jouda, Nazir of Agriculture; and Saad Obeidi, former Mutaṣarrif of Bengási. Mr. Harry Adam, Water-Supply Engineer, Nazarat of Public Works, gave valuable assistance by providing available information on the existing water supplies in the Bengási area. Parts of the investigation relating to the U.S. Army Corps of Engineers were carried out under the direction of Lt. Col. Artha D. Williams, Jr., District Engineer, U.S. Army Engineer District, Middle East.

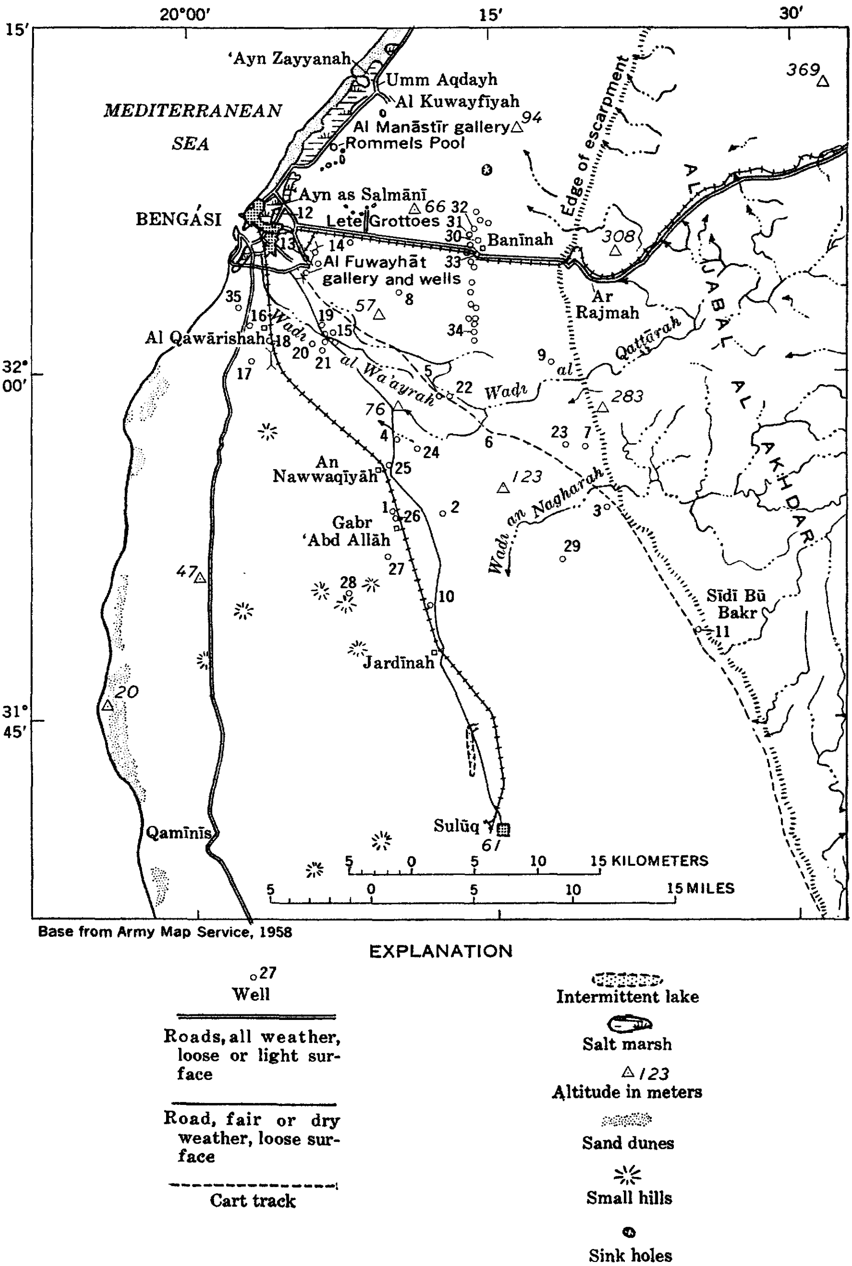

FIGURE 2.—Map showing locations of wells, galleries, and springs in Bengási area, Cyrenaica, United Kingdom of Libya.

GEOGRAPHY

GENERAL FEATURES

Bengási, which has a population of approximately 70,533 (1954), is the capital of the Province of Cyrenaica, the eastern province of the United Kingdom of Libya and, together with Tripoli, is also a cocapital of Libya. The city was almost completely destroyed during World War II, but it has since been rebuilt and is now (1959) expanding beyond the prewar limits as a result of increased governmental and commercial activity. The harbor facilities were destroyed during the war, and the one section that has been partly rebuilt is accessible only to ships of shallow draft. The depth of water in the harbor can vary by as much as 1.5 meters as a result of a combination of tides and strong northeasterly or southerly winds. A railroad, built during the Italian occupation, extends from Bengási eastward to Al Marj (Barce), a distance of about 100 kilometers. Another railroad, also constructed by the Italians, extends from Bengási southward to Sulūq, a distance of about 25 kilometers. The paved coastal highway that extends along the northern coast of Africa passes through Bengási. The only other paved road in the area connects Bengási with the airport located at Banīnah, 20 kilometers inland (fig. 2). There are numerous unsurfaced roads and trails in the area, many of which become impassable to vehicular traffic after heavy rains. Direct airline flights are scheduled from Bengási to Tripoli, Cairo, London, and Nairobi.

Besides Bengási and Banīnah, the report area contains scattered small villages and a sparse population belonging to the Auaghir tribe. Some of the people are nomadic, coming down from the plateau of Al Jabal al Akhḍar (The Green Mountain) during the rainy season to plant grain and to pasture herds of sheep, goats, and camels in temporary grasslands. During the dry season most of the stock is either driven back into the Jabal, slaughtered, or sold.

A thick soil cover is present in the Al Qawarishah area, immediately south of Bengási, and irrigation which utilizes shallow dug wells is practiced on a small scale. Cultivation by dry farming methods is carried on intermittently elsewhere in the report area, depending on the amount of rainfall and the thickness of the soil. When sufficient water is available, the soil, where tillable, is moderately productive. However, a considerable part of the coastal plain consists of rocky outcrops of limestone and is therefore unfit for cultivation. Barley is the principal crop in the area, and wheat is grown on a smaller scale. Groves of date palms are cultivated in the coastal dune areas, where small crops of grapes and melons are also produced.

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TOPOGRAPHY AND DRAINAGE

The Bengási area includes a gently undulating plain rising from the Mediterranean coast inland to the foot of an escarpment that trends parallel to the coastline. The plain widens toward the south as the coastline and escarpment gradually diverge. The escarpment is generally considered to be a wave-cut cliff and to represent a post-Miocene shoreline. The elevated plateau east of the escarpment is known as Al Jabal al Akhḑar.

The plain, which probably was formed as a wave-cut terrace, rises gradually from sea level to an elevation of about 120 to 150 meters at the base of the scarp. A narrow beach and a wide dune belt border the sea. A succession of sea-level salt flats is present between the dunes and a low coastal bluff, which marks the edge of the main terrace.

The plain, or terrace, has been dissected slightly by numerous ephemeral stream channels (wadis) that rise in the Jabal and drain westward to the sea. During the rainy season the wadis flow, but commonly little or none of the runoff reaches the sea. The two principal wadis in the area are Wadi al Qaţţārah, known as Wadi al Wa'ayrah in its lower reaches, and the Wadi an Nagharah. The Wadi al Qaţţārah drains a large area in the Jabal and, after heavy rains, discharges water onto the flatlands in the vicinity of Bengási. The Wadi an Nagharah drains a smaller area in the Jabal, and discharges water over a flat area 30 kilometers southeast of Bengási.

The plain in the Bengási area is underlain mostly by limestone mantled in places by red clay, sand, and gravel deposits. Karst (solution) features are conspicuous in the area, and solution channels probably are present to some depth below sea level. Solution features are most evident north of the Bengási-Banīnah road, where the surface of the plain is pitted with sinkholes. The underground river Lete, 6.5 kilometers east of Bengási, is marked by a chain of connected caverns formed by the solution of limestone. The roofs of these caverns have slumped, and the course of the river is now apparent from the air. Evidence of Karst topography decreases southward, and few sinkholes are present in the area south of the Bengási-Banīnah road.

CLIMATE

Rainfall is seasonal, occurring mostly in the winter months, and varies considerably from year to year in both quantity and intensity. The average annual rainfall at Bengási is 273 millimeters and at Banīnah 251 millimeters. The precipitation on Al Jabal al Akhḑar is greater on the average than on the coastal plain (fig. 3), but it, too, is seasonal in distribution.

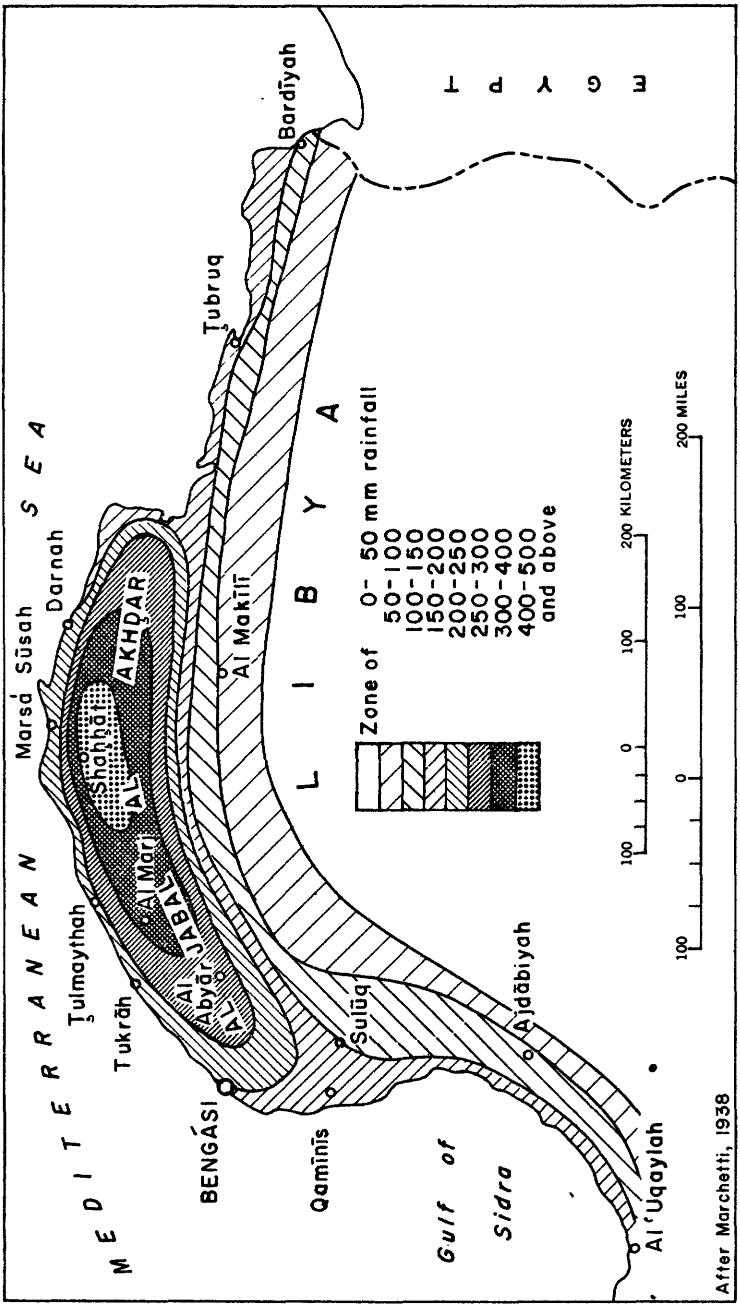

FIGURE 3.—Map showing distribution of average annual rainfall, northern Cyrenaica.

Prevailing winds are from the north-northwest through north. Hot south winds (ghiblis) occur infrequently, and are sometimes accompanied by sand and dust.

GEOLOGY

The coastal plain in the Bengási area is underlain chiefly by stratified rocks belonging to the Helvetian Group of middle Miocene age (Desio, 1935) (fig. 4). The group consists largely of limestones, which range in character from soft and amorphous to medium hard and crystalline and which contain some thin interbedded clays and marls. Some fragmented and disintegrated limestone (partially cemented limestone "sand") was found in test wells. For example, in well 11, the deepest test well drilled during this investigation, sand of probable Miocene age was found at a depth of 231 meters. The limestones, which were apparently deposited under near-shore conditions, are continuous throughout the area. They have undergone solution following deposition, and now contain numerous solution channels and caverns.

Rocks of the Helvetian Group are also exposed in the escarpment forming the inland margin of the coastal plain and in Al Jabal Akhḍar, where they are in contact with the younger rocks of the Tortonian Group of middle Miocene age (fig. 4). No Tortonian rocks have been identified in the coastal plain.

Rocks of the Helvetian Group in the Bengási area dip generally less than 1°, and no regional structures are apparent. However, several faults have been postulated. Marchetti (1938) described a fault at Al Fuwayhāt that strikes northeastward. Faults also have been postulated by other geologists at 'Ayn Zayyanah and Lete and in an area extending along the coast for more than 100 kilometers from Bengási to near Tulmaythah. According to Cotterell,[2] resistivity work in the Banīnah area has indicated a north-south fault in the vicinity of the 100-meter contour. The writers noted no marked surface evidences of faulting in the Bengási area, and beds exposed in the wadi channels and in the escarpment appear to be virtually continuous. Evidence of structural deformation in the older Tertiary rocks of the Jabal suggests that the formations underlying the Miocene rocks of the coastal plain are probably folded and faulted.

Quaternary deposits in the Bengási area range in thickness from a few centimeters to several tens of meters. A thick clay in the subsurface in the Jardīnah-Sulūq area has been placed n the Quaternary by Marchetti (1938). Marchetti also placed in the Quaternary the shelly, sandy limestone used for building in the Bengási area. The

[2] Cotterell, A. P. I., and Son, 1949, Cyrenaica water resources: London, 4 pts. [Unpublished consulting report for British Military Government]

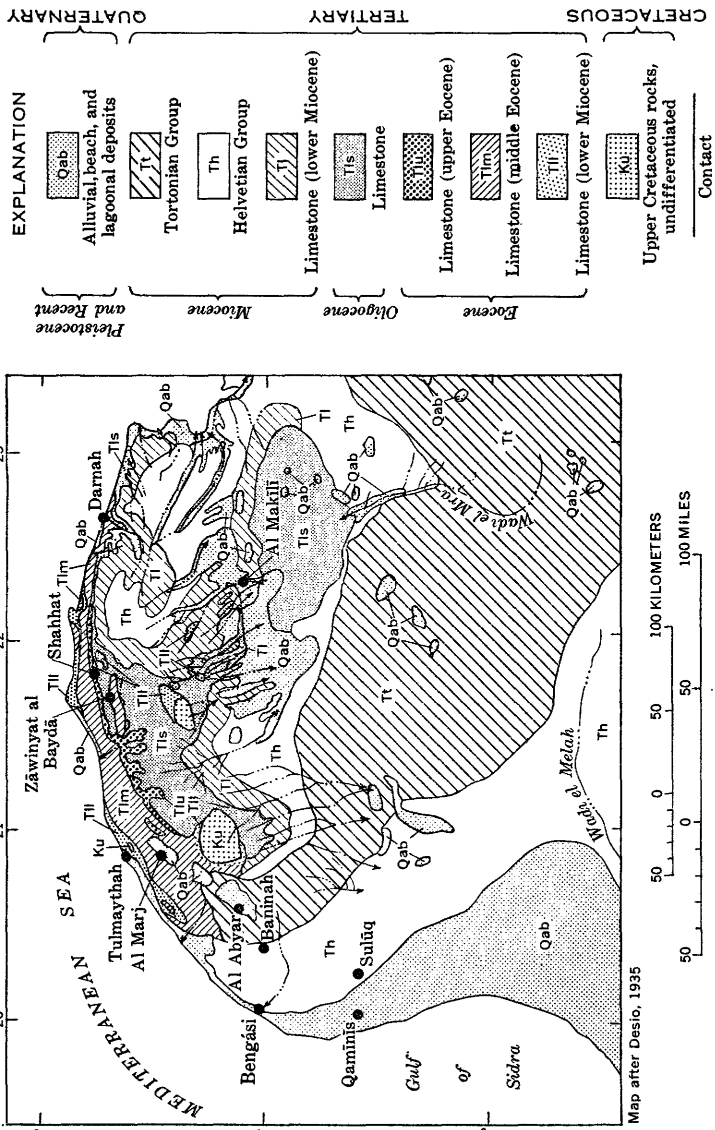

FIGURE 4.—Geologic map of northwestern Cyrenaica, United Kingdom of Libya.

red clay that covers much of the surface in the Bengási area is probably also of Quaternary age and may, in considerable part, be a residual from solution of the limestone.

Recent deposits found along the coast are mostly in the form of unconsolidated, semiconsolidated, and consolidated sand dunes. Recent deposits of sand, silt, and gravel are also present in the wadi channels.

GROUND WATER

Except for bodies of water in the coastal dunes and some locally perched water in the coastal plain, the principal ground-water reservoir in the Bengási area occurs in solution cavities, joints, and bedding planes in the limestone that underlies the coastal plain as well as Al Jabal al Akhḏar. The upper surface of the ground-water reservoir is marked by a water table that lies near sea level at the shore but that gradually rises to altitudes of 5 meters or more near the escarpment marking the inland edge of the coastal plain. Farther inland in the Jabal the water table is at still higher altitudes. The depth to the water in a well in the area depends on the difference in altitude between the land surface and the water table. This difference in the coastal plain ranges from a meter or two near the shore to 175 meters or more in deep wells near the escarpment. The greatest depth to water observed in the area was 172.1 meters in well 7.

The yield of wells in limestone generally depends on the number and size of water-filled openings below the water table and on the degree of interconnection of these openings in the zone of saturation. Thus, wells drilled only a few meters or few tens of meters apart may have considerable differences in individual yields. For example among 10 test wells drilled by the U.S. Army Corps of Engineers, 3 wells (Nos. 3, 7, and 9) had yields of less than 0.4 liter per second, and 2 wells (Nos. 1 and 10) produced yields of 11.3 and 12.6 liters per second, respectively.

The ground-water reservoir is sustained and recharged by infiltration from rainfall and also by runoff in wadis that rise on the Jabal and disgorge onto the coastal plain. Such recharge probably takes place chiefly during the winter months when most of the precipitation falls. Recharge probably does not occur during every year or after every storm, but only after relatively intense and prolonged rainfall.

Water in the ground-water reservoir moves down the slope of the water table from areas of higher hydrostatic head, as from the inland part of the coastal plain and Al Jabal al Akhḏar, toward points of natural discharge near the shoreline. Most of the movement noted occurs through the more permeable zones of the limestone, particularly where solution openings are well developed. Sinkholes are relatively common in the northern part of the coastal plain in the Bengási, Banīnah, and Al Kuwayfīyah areas, but are not particularly common in the central and southern parts of the report area.

Discharge from the ground-water reservoir takes place naturally through springs, submarine outflow, and evapotranspiration in salt marshes near the shore and artificially by withdrawals from wells and galleries for municipal, domestic, stock, and irrigation purposes. Perennial springs and ground-water pools in sinkholes are common in the coastal zone between Bengási and Al Kuwayfīyah. 'Ayn es Salmānī, Rommel's Pool, 'Ayn Zayyanah, and Lete Grottoes are typical. Discharge of ground water by submarine outflow is also probably considerable. Evapotranspiration of ground water is active in all the salt marshes, which extend discontinuously along the coast. The largest artificial withdrawals of ground water from wells and galleries in the area are for the Bengási municipal supply, which is currently (1959) about 4,545 cubic meters per day. Small-scale withdrawals for irrigation, domestic and stock use also are made from dug wells scattered over the coastal plain.

Virtually all the ground water in the coastal plain at depths more than 10 meters below the water table is moderately to highly mineralized, containing in most places from 900 to 6,000 ppm (parts per million) of total dissolved solids. This condition may be due to several factors. First, the Miocene rocks were deposited in salt water and have undoubtedly been filled with salt water from time to time since their deposition. As a result, they may contain residual salt both in the limestone and in the associated clays. Because of insufficient circulation of fresh water through the rocks, the residual salt may not have been flushed out completely. Second, wind-blown salt spray and salt accumulated in the soil by evapotranspiration may contribute salt to recharging fresh water in some areas. Third, the ground-water reservoir in the coastal plain receives inflow of ground water from Al Jabal al Akhḍar that already contains a considerable content of dissolved solids. In most places, only the very shallow ground water—that is, a skim a few meters thick below the water table—is relatively fresh and low in dissolved solids. For example, in shallow well 26 at a depth of 64.5 meters the water contains a total of about 360 ppm of dissolved solids, whereas in well 1 in the same vicinity water at 73.5 meters contains a total of 3,500 ppm of solids. In other shallow wells the dissolved-solids content is low. For example in wells 19, 21 and 27, the water contains a total of only 580, 300, and 250 ppm, respectively, of dissolved solids. Elsewhere, both the shallow and the deep water is moderately to highly mineralized.

In the coastal zone of the Bengási area, the nominally fresh water in the ground-water reservoir is inferred to be in contact with salty water along an interface, or zone of diffusion. The relationship between the fresh water and the salty water is probably similar to that expressed by the Ghyben-Herzberg principle (Brown, 1925, p. 16). This principle states that the approximate depth to which fresh water extends below sea level is determined by the head of the fresh water above sea level and by the difference in specific gravities of fresh and salty waters on opposite sides of the interface. Under conditions of static equilibrium, 1 meter of fresh-water head above sea level will balance about 40 meters of fresh water below sea level. Thus, a small change in fresh-water head above sea level may result in a large change in the amount of fresh water available below sea level. For this reason a ground-water supply in a coastal zone is exposed to the potential danger of salt-water contamination. Therefore, it is important to know the altitude above sea level of water levels in wells in the area, and a system of water-level measurements and quality control is essential.

BENGÁSI MUNICIPAL SUPPLY

Prior to World War II the water supply for Bengási was derived from two sources: a system of galleries and wells at Al Fuwayhāt, at the southern edge of the city, and a collecting gallery at Al Manāstīr, on the coast 5 kilometers northeast from the city. The combined sources yielded less than 4,540 cubic meters a day, and the water contained approximately 610 ppm of chloride. This supply was inadequate, and in an attempt to locate additional sources, the Italian Administration put down numerous test borings in the vicinity of Bengási. The results, which were tabulated by Romano (1933) and commented on by Marchetti (1938), proved that a zone of saturation is present. Furthermore, the results indicated that the water table is slightly above sea level and that properly constructed wells would produce moderate amounts of usable water.

Al Fuwayhāt waterworks consisted of a series of shallow collecting galleries, shallow wells, and five deeper wells ranging in depth from 39.6 to 100.1 meters. During World War II, sections of the galleries were blocked and the pumping station and elevated storage tank destroyed.

Al Manāstīr waterworks consisted of two shallow infiltration galleries located in a sand dune area along the coast. The galleries yielded approximately 340 cubic meters a day of water containing an average of 1,100 ppm chloride.

After World War II, some sections of the collecting galleries at Al Fuwayhāt were cleared, and two new wells were drilled in the galleries to a depth of approximately 88.3 meters. Later, four additional wells ranging in depth from 85.4 to 100.4 meters were drilled in the vicinity of the galleries by the British Military Administration. The water-collecting system now (1959) yields 4,200 cubic meters a day of water averaging 549 ppm chloride. The water from all sources is pumped into a ground-storage reservoir of 4,545 cubic meters capacity. In addition, an elevated concrete water storage tank has been constructed and put into service.

In the years following World War II, exploration for additional ground-water supplies was undertaken in the Banīnah area by the Public Works Department, which had begun exploration and had completed a test well approximately 3 kilometers north of the Banīnah railway station. The firm of A. P. I. Cotterell and Son was contracted by the British Military Administration to do the actual exploration. Cotterell continued the test-drilling operations and carried out a geophysical survey of the area. Twenty-three test wells were drilled along a north-south trending line near the 100-meter contour. The locations of 21 of the wells are shown in figure 2. The wells range in depth from 79.2 meters in well 32 to 112.5 meters in well 34. Water levels range from 1.03 meters above sea level in well 31 to 4.87 meters above sea level in well 34. The range in water levels suggests that the water is moving northwestward.

Three of the wells had yields of 25.1 liters per second, the capacity of the test pump; 11 had yields ranging from a few tenths to nearly 12.5 liters per second; and 9, the southernmost wells, had such low yields that they were considered dry. The three wells with the highest yields, Nos. 30, 32 and 33, were finished and equipped, and the water is now pumped into a reservoir that was constructed at Banīnah. A 12-inch water main connects the reservoir with the Bengási system. Water for the Bengási supply is now (1959) being obtained entirely from the Banīnah wells and Al Fuwayhāt waterworks. Al Manāstīr galleries are no longer used.

Four test wells located between wells 15 and 21 were drilled by Cotterell, 13 kilometers southeast of Bengási, within a few hundred meters of each other. The wells ranged from 88.1 to 106.8 meters in depth and produced yields of 5.0 to 6.9 liters per second. The chloride content of the water was 490 ppm. The yields were not considered sufficient to justify construction of a pipeline to either Al Fuwayhāt or Banīnah, and the wells were plugged and abandoned.

Detailed information on the exploration program is given in the report by A. P. I. Cotterell,[3] which also contains recommendations for water supply development in Al Jabal al Akhḍar area. The explora-

[3] See footnote p. B8.

tion program demonstrated that substantial water supplies of good quality could be developed from wells in the Banīnah area.

OTHER WATER SUPPLIES

South of Bengási are scattered small oases in which water for limited irrigation is obtained from shallow wells. The oases are generally found within 8 kilometers of the coast. Typical of the oases is the Al Qawārishah area, located about 10 kilometers south of Bengási. Here many shallow wells ranging in depth from about 6 to 12 meters were used to irrigate small garden areas. About 80 of the wells in the area, apparently the shallower wells, are reported to have gone dry since World War II. This evidence indicates that a general lowering of the water table has taken place. An open collecting trench south of well 18, in the same area was also used during the war to supply water to the former Italian airfields of Al Birkah II and Al Birkah III. The trench yielded 1,020 cubic meters of water a day, containing about 490 ppm chloride.

A number of scattered wells are in the coastal plain southeast of the Bengási-Al Qawārishah area. The wells (Nos. 12–29) are shown in figure 2 and are described in table 1. The deepest of the wells, No. 26, is approximately 23 kilometers southeast of Bengási and is 65.3 meters deep. Four of the wells (Nos. 17, 22, 24, and 26) are reported to have been dug by the Romans. The total dissolved-solids content of water from the wells ranges from approximately 250 ppm in well 27 to approximately 2,250 ppm in wells 17, 18, and 24. All the wells are reported to have low yields, and several are reported to go dry in the summer.

A test hole (No. 35, table 1) was drilled by the Hydraulique Afrique Co. to a depth of 350 meters at the former site of the U.S. Aircraft Control and Warning station (Al Birkah II), 6 kilometers south of Bengási. Water from the well contained 11,200 ppm dissolved solids and 5,170 ppm chloride; for this reason it was abandoned.

Approximately 6 kilometers east of Bengási on the north side of the Bengási-Banīnah road are the Lete grottoes, consisting of a chain of underground caverns in limestone. Ground water collects in and moves through the interconnected caverns. A pumping test made in the cavern near the King's Palace obtained a sustained yield of 3,490 cubic meters of water a day containing a chloride content of 1,040 ppm.

Much of the basic water supply in the area for domestic and stock use is obtained from cisterns, many of which were constructed in the limestone during Roman times. These cisterns are in or near watercourses and collect water from rainfall runoff.

TEST DRILLING

During the period September 1957 to June 1958, the writers participated in a test-drilling program carried out in the coastal plain southeast of Bengási (fig. 2). This program was undertaken because (1) little information was available on the occurrence or quality of the water in the area, (2) the U.S. Army Corps of Engineers was interested in the area as the possible site of a military establishment and financed the program, (3) the Cyrenaican Public Works Department, which could not guarantee an adequate water supply from the Bengási city system for a military installation, requested that no ground-water development be undertaken within 16 kilometers of the Banīnah well field, making it necessary to seek new sources.

Test-drilling was begun at Qabr 'Abd Allāh near well 26, which yields water of good quality. Wells, 1, 2, 3, 10, and 11 were drilled with a percussion drilling machine belonging to the Libyan-American Joint Service. Wells 4, 5, 6, 7, 8, and 9 were put down with a percussion drilling machine belonging to the Cyrenaican Drilling Co.

All the test wells, except 3, 7, 9, and 11, were tested with a deep-well turbine pump. These four wells gave small yields in a bailing test, and no further tests were made. Water levels were not measured in any pumping wells because of the lack of proper equipment, but the discharge of the test pump was regulated so that a sustained yield could be maintained. The specific electrical conductance of the water from the test wells was measured with a Solubridge water tester, and the approximate amount of dissolved solids in the water was computed from the conductance.

Wells 1 and 10 yielded the largest quantities of water of any of the test wells. Well 1 was tested at 11.3 liters per second and well 10 at 12.6 liters per second, the capacity of the pump. In both wells, however, the mineral content of the water increased shortly after pumping was started.

Water was found at a depth of 73.3 meters in well 1 and rose to 61.5 meters below land surface. Drilling was continued to 155.5 meters, but no additional water was found, and the hole was plugged back to 106.8 meters below the surface. Water taken from the well prior to pumping contained about 500 ppm of dissolved solids. After the well had been pumped 1½ hours at 11.3 liters per second, the amount of dissolved solids had increased to about 3,500 ppm, where it remained for the duration of the test.

Water was found in well 10 at 10.7 meters and at 91.5 meters. The maximum sustained yield from the shallow zone was 0.31 liters per second, and the water contained a total of about 1,600 ppm dissolved solids. The quality of the water from the deeper zone stabilized at about 6,000 ppm dissolved solids shortly after the test pump was started. The well was plugged back to 56.4 meters below the surface and completed in the shallow zone. The present water supply for the village of Jardīnah is obtained from the shallow zone.

Water was found in well 2 at 85.4 meters and rose in the hole to a depth of 70.1 meters below the surface. The well was completed at a depth of 119 meters. A yield of 2.5 liters per second was obtained, and the water contained about 3,200 ppm of dissolved solids after 4 hours of pumping.

Well 4 was drilled to a depth of 90.8 meters, and water was found at 79.3 meters. The water rose in the well to 55.2 meters below the ground surface. The well yielded 1.9 liters per second of water containing 900 ppm dissolved solids.

Water was found in well 5 at 97.0 meters and rose to within 81.5 meters of the surface. Drilling was continued to a depth of 110 meters. The well yielded 1.3 liters per second of water containing approximately 2,600 ppm dissolved solids.

Well 6 was drilled to a depth of 57.9 meters. Water was found at 47.9 meters and rose in the well to a level 36.0 meters below land surface. The well yielded 1.0 liter per second of water containing approximately 900 ppm of dissolved solids. This well apparently penetrated a zone of perched water.

Water was found in test well 8 at 47.9 and at 76.2 meters, and the well was completed at a depth of 88.1 meters. Water rose in the hole to within 39.6 meters of the land surface. The well yielded 3.8 liters per second with 10.7 meters of drawdown, and the mineral content of the water increased from about 650 ppm of dissolved solids to 900 ppm after 4 hours of pumping.

Test wells 3, 7, 9, and 11 yielded 0.31 liters per second or less in a bailing test and were not tested further with a pump. Well 3 was drilled to a depth of 188.5 meters and water was found at 151 meters. The water, containing about 3,000 ppm dissolved solids, rose in the hole to a depth of 137.7 meters. Well 7 was drilled to a depth of 189.1 meters. Water containing about 1,100 ppm dissolved solids was found at 178.2 meters and came up in the hole to within 172.1 meters of the surface. Well 9 was drilled to a depth of 186.0 meters and reached water at a depth of 172.1 meters. Water rose to within 170.0 meters of the surface and contained about 900 ppm of dissolved solids. Well 11 was drilled to a depth of 251 meters. Water containing about 3,000 ppm dissolved solids was found at 118.0 meters and rose to a depth of 93.0 meters. A second water-bearing zone was penetrated at 249.5 meters and yielded water containing about 4,000 ppm dissolved solids. The water level remained at 249.5 meters.

The results of the test-drilling program show that water is generally present under slight artesian head in solution cavities and other openings in limestone throughout the explored area. The yield of each well was found to be dependent on the size and number of openings penetrated in drilling. Only wells 1 and 10 penetrated sizeable openings, and their yields were larger than those of any of the other test wells. When most of the test wells were pumped, the dissolved-solids content in the water increased abruptly. This fact suggests that only a thin skim of comparatively fresh water overlies more highly mineralized water.

Small bodies of perched water are present in the explored area, as shown by wells 6 and 10. These bodies are probably sustained by local recharge and are isolated hydrologically from the principal ground-water reservoir. The quality of the perched water probably would not change as a result of pumping, but the bodies are probably small and substantial development would deplete them rapidly.

The behavior of wells 3, 7, and 11 indicates that some type of physical discontinuity is present between them and the test wells to the west. Further investigation would be necessary to determine whether this behavior is due to a fault, a facies change, or some other geologic or hydrologic discontinuity.

CONCLUSIONS

A zone of saturation underlies the coastal plain of the Bengási area, where the water occurs in solution cavities and other openings in limestone. The ground-water reservoir is recharged by infiltration from rainfall on the area, and from ephemeral streams (wadis) while in flood. Some recharge also takes place by lateral inflow of water from the Miocene and older rocks in Al Jabal al Akhḍar.

The results of the test drilling and other earlier exploratory work show that the quantity of water necessary for irrigation or for public supply can be obtained readily. However, in the part of the area that is not reserved for the Bengási public supply, the water is too highly mineralized for public-supply use without expensive treatment. The water located by test drilling could be used for irrigation, provided application of the water to the soil and drainage conditions are closely controlled.

Ground water in the area southeast of Bengási could also be used for moderately large municipal requirements, provided one of the water demineralization processes that are now in pilot-development stage becomes economically feasible. When such demineralization becomes feasible, it will be necessary to obtain more quantitative data regarding the extent of the ground-water reservoir and the amount of recharge to it. Additional exploratory drilling in the area is not justified until such time as the data are needed.

The Miocene limestone probably contains a continuous ground-water reservoir throughout the coastal plain of the Bengási area.

Considerable amounts of water of better quality than that found in the area explored by the test drilling program can be obtained from wells in the Banīnah area because of the presence of larger and more continuous openings in the limestone, as indicated by surface evidence and possibly because of a higher rate of recharge. The water flowing from 'Ayn Zayyanah and the other springs east and northeast of Bengâsi represents discharge from the ground-water reservoir, probably from the Banīnah area.

The water-bearing limestone extends westward under the Mediterranean Sea, where it contains salt water. Increased withdrawals in the Banīnah area or large-scale withdrawls elsewhere in the Bengâsi area could result in the movement of salty water toward the area of heavy withdrawals, ultimately resulting in salt-water contamination. Additional investigation and exploration should be carried out to determine the long-term potential yield from the ground-water reservoir in the Banīnah area; that is, the amount of water that could be withdrawn without either depleting the reservoir or causing the encroachment of salty water.

No perennial surface-water supplies are available in the Bengâsi area, although water flows in the wadis for short periods after heavy rains. The only other surface-water supplies are those that collect annually in cisterns excavated in the limestone.

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TABLE 1.—*Records of selected wells in the Bengási area*

Type of well: Dr, drilled; Dg, dug. Use of water: D, domestic; Ir, irrigation; N, none; P, public supply; S, stock

Well	Year completed	Depth of well (meters)	Diameter of well (inches)	Water level: Below land surface datum (meters)	Water level: Date of measurement	Type of well	Use of water	Specific conductance (micromhos at 25° C)	Approximate total dissolved solids (ppm)	Remarks
1. Corps of Engineers 1	1957	155.5	12	61.5	Oct. 1957	Dr	N	5,400	3,500	Test well. Water at 73.3 meters. 750 micromhos. Plugged back to 106.8 meters. When pumped at 11.3 liters per second for 1½ hr. conductance increased to 5,400 micromhos.
2. Corps of Engineers 2	do	119	10	70.2	do	Dr	N	5,100	3,500	Test well. Water at 85.4 meters. Yield 2.5 liters per second. After pumping 4 hr. water quality stabilized at 5,100 micromhos.
3. Corps of Engineers 4	do	188.5	10	[1] 137.7	Dec. 1957	Dr	N	4,500	3,000	Test well. Water at 151 meters. Yield 0.31 liters per second on bailer test. Well obstructed by rocks.
4. Corps of Engineers 5	do	90.8	12	55.4	Oct. 1958	Dr	N	1,390	900	Test well. Water at 79.3 meters. Yield 1.9 liters per second.
5. Corps of Engineers 6	do	110	12	81.6	do	Dr	N	4,000	2,600	Test well. Water at 97.0 meters. Yield 1.3 liters per second.
6. Corps of Engineers 7	do	57.9	12	36.0	Oct. 1957	Dr	N	1,380	900	Test well. Water at 47.9 meters. Yield 1.0 liter per second. Well obstructed by rocks.
7. Corps of Engineers 8		189.1	12	172.1	do	Dr	N	1,750	1,100	Test well. Water at 178.2 meters. Yield 0.31 liters per second on bailer test. Well obstructed by rocks.
8. Corps of Engineers 9	1958	88.1	12	[1] 39.7	Feb. 1958	Dr	N	1,400	900	Test well. Water at 47.9 meters and 76.2 meters. Yield 3.8 liters per second with 10.7 meters of drawdown. Conductance increased from 1,000 micromhos to 1,400 micromhos. (Total solids of shallow water about 650 ppm).
9. Corps of Engineers 10	do	186.0	12	[1] 170.0	Jan. 1958	Dr	N	1,400	900	Test well. Water at 172.1 meters. Well bailed dry in 1 hour. Well obstructed by rocks.

[1] Water level reported by owner or driller.

TABLE 1.—*Records of selected wells in the Bengási area*—Continued

Type of well: Dr, drilled; Dg, dug. Use of water: D, domestic; Ir, irrigation; N, none; P, public supply; S, stock

Well	Year completed	Depth of well (meters)	Diameter of well (inches)	Water level		Type of well	Use of water	Specific conductance (micromhos at 25° C)	Approximate total dissolved solids (ppm)	Remarks
				Below land surface datum (meters)	Date of measurement					
10. Corps of Engineers 11	1958	137.0	8	7.56	Apr. 1958	Dr	N	2,500	1,600	Test well. Water at 10.7 meters and 91.5 meters. Yielded 12.6 liters per second, capacity of pump. Conductance increased from 2,500 micromhos to 8,500 micromhos after pumping 15 minutes. Well plugged back to 62.3 meters and cased to 56.4 meters. (Total solids of deeper water about 6,000 ppm).
11. Libyan-American Joint Services 1.	do	251	12	[1] 93.0	Jan. 1958	Dr	N	6,500	3,000	Test well. First water at 118.0 meters, 4,500 micromhos. (Total solids about 3,000 ppm). Bailed dry. Next water at 249.5 meters. Yield small. Well obstructed by rock.
12. Abdul Rahim Cherif	Old	5.8	60	5.1	Feb. 1957	Dg	Ir			Irrigates garden patch. Water reported salty, yield low. Saniyat.
13. Hassan Mohelel	do	19.8	72	16.4	do	Dg	Ir			Do.
14. Gardoweer	1947	34.4	96	32.6	do	Dg	Ir			Reported to be a good supply. Saniyat.
15. Berriwin	Old	36.5	36	33.8	Aug. 1957	Dg	Ir	850	480	Saniyat.
16.		7.3	60	no water	Dec. 1957	Dg	Ir			Reported to have gone dry since World War II. Saniyat.
17. Feitury	Old	5.5	48	4.6	July 1957	Dg	Ir	3,500	2,250	Irrigates small garden. Reported to go dry in summer. Saniyat. Said to be Roman well.
18.	do	11.3		10.8	Dec. 1957	Dg	N	3,500	2,250	
19. Sayed Bulgassem	do	26.6		24.4	Aug. 1957	Dg	D, S	900	580	
20. Abdullati	1955	27.2	36	26.6	July 1957	Dg	D, S	2,500	1,600	Used by four families. Reported to go dry in summer.
21. Ali Ben Zheligh		39.6		36.1	Aug. 1957	Dg	S	450	300	
22. Abdulah Fellah	Old	1.5	48	1.2	July 1957	Dg	D	2,000	1,300	Reported to go dry in late summer. Probably perched water. Said to be Roman well.
23. Abdullah Kalil	do	29.2	24	28.1	do	Dg	D	2,500	1,600	Reported to go dry in summer.
24. Suliman	do	7.6	48	7.3	do	Dg	D	3,500	2,300	Reported to go dry in summer. Said to be Roman well.
25. Haj Kalil	do	61.4	36	60.0	do	Dg	D	2,500	1,600	Reported to go dry in summer.
26. Chamro	do	65.3	36	64.0	do	Dg	N	525	360	Reported to go dry in summer. Said to be Roman well.
27. Ahmed Aghila	do	51.5	48	49.6	do	Dg	D, S	400	250	Reported to go dry in summer.
28.	do	61.0	24	51.2	do	Dg	D, S	2,500	1,600	Do.

29.	Old	45.1	50	43.5	Feb. 1958	Dg	N			Formerly pumped with windmill.
30. A.P. Cotterell G-1						Dr	P			Municipal well. Chloride content 488 ppm. Yield greater than 25.1 liters per second.
31. A.P. Cotterell G-2						Dr	N			Test well. Chloride content 153 ppm.
32. A.P. Cotterell 3		79.2				Dr	P			Municipal well. Chloride content 604 ppm. Yield greater than 25.1 liters per second.
33. A.P. Cotterell G-8						Dr	P			Municipal well. Chloride content 564 ppm. Yield greater than 25.1 liters per second.
34. A.P. Cotterell G-16		112.5				Dr	N			Test well. Very low yield.
35. Hydraulique Afrique Co.		350				Dr	N		11,200	Test well. Chloride content 5,170 ppm.

[1] Water level reported by owner or driller.

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