UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

# PROGRAM OF GROUND-WATER INVESTIGATIONS

# FOR THE ANGLO-EGYPTIAN SUDAN

Prepared by United States Geological Survey
in Cooperation with
The Government of Anglo-Egyptian Sudan
and
The United States Operations Mission to Anglo-Egyptian Sudan

For Administrative Release

1955

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By

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# INTRODUCTION

As a result of requests by the Sudanese Government made through the Department of State to the United States Technical Assistance Administration, the United States Geological Survey was requested by the Foreign Operations Administration to detail a ground-water specialist to the Anglo-Egyptian Sudan for the purpose of making a preliminary reconnaissance and from that to make recommendations for an investigational program in that country. The basic request by the Sudanese Government was stimulated by suggestions contained in a report entitled "Memorandum on possible assistance in ground-water surveys in the Sudan" prepared by Dr. John B. Auden, Acting Director, Geological Survey Department, Ministry of Mineral Resources, Sudan Government. The memorandum was prepared for the perusal of the Council of Ministers as a consequence of a discussion that was held on April 4th between the Minister of Public Works and Messrs. G. Andrew, Director, and J. B. Auden, Geological Survey Department. The suggestion was made that the United States Government be approached formally for the loan of a ground-water geologist from the Ground Water Branch of the U. S. Geological Survey to assist the Sudan Geological Survey in investigations on hydrological problems in the Sudan.

The author, a geologist of the United States Geological Survey, was assigned to the project. The short-term detail involved reconnaissance of areas presumably favorable for development that would warrant investigation, and included areas for which early development is being considered. The reconnaissance in the Sudan spanned the period February 20 to April 26, 1955. This reconnaissance, together with an evaluation of personnel and equipment requirements for a definite ground-water investigational program, form the basis for the recommendations contained in this report. A field party was organized by March 1 that included the following personnel: George Yanni Karkanis, Geologist and Well Superintendent, Drilling Division, Public Works Department, Ministry of Public Works, Sudan Government; Philip Moon, Geologist, Geological Survey Department, Sudan Government; and the author. This party traveled 6,670 miles, and of this total, 3,410 miles were covered by motor transport, 1,530 miles were traveled by Sudan Railway, and 1,730 miles were traveled by Sudan Airways. (See Map attached. The long-dashed line represents the airplane trips and the short-dashed line the surface transport trips.) Data were collected on a great many representative wells and springs, and a number of hafirs, fulas, and other types of surface storage reservoirs were visited. The field work also included a reconnaissance of the geology of the areas visited. Four principal field treks were made (1) trip to western Kordofan and Darfur Provinces, March 3-22 inclusive; (2) trip to Equatoria Province, southern Sudan, including trips both east and west of Juba, April 1-8 inclusive; (3) trip to Nuba Mountains vicinity, April 10-14 inclusive; and (4) trip to Red Sea

Hills and coastal plain in vicinities of Suakin, Port Sudan and north, April 15-22 inclusive. Field work was completed on April 22, and the initial draft of the report was prepared in April and May 1955.

The author has drawn freely upon U. S. Geological Survey administrative reports such as the ones prepared by T. E. Eakin for Jamaica as a part of the Survey's activities of technical assistance program and by P. E. LaMoreaux on behalf of the United States Operations Mission for Thailand.

## ACKNOWLEDGMENTS

The author's work in the Sudan was greatly facilitated and expedited by the excellent cooperation received from all officials of the Sudanese Government contacted, including: His Excellency Sayed Ibrahim Hassan El Mahallawi, Minister of Mineral Resources; His Excellency Sayed Mohammed Nur El Din, Minister of Public Works; Mr. H. W. Luce, Advisor on Constitutional and External Affairs, Governor General's Palace; Sayed Ogeil Ahmed Ogeil, Interim Deputy Under Secretary of State for Foreign Affairs, Sudan Government, Council of Ministers; Mr. G. H. Leston, Drilling Engineer, and Kamil Abuseiph, Assistant Drilling Engineer, Government Drilling Section, Ministry of Public Works; Dr. John B. Auden, Acting Director of the Geological Survey Department, Ministry of Mineral Resources, Sudan Government, Mahmoud Ahmed Abdullah, Geologist, Geological Survey Department, and Arthur Beach, United States Liaison Officer, Khartoum. The author is especially indebted to Dr. Auden for his helpful advice and assistance during the entire assignment. Special acknowledgment is given to George Yanni Karkanis and Philip Moon, geologists, both of whom accompanied the author on all of the field treks. They deserve much of the credit for the successful planning and execution of the field treks. They also were responsible jointly for the selection of localities to be visited and of the best routes to be followed and for the maintaining of rigid schedules within the relatively brief time allotted to cover large areas. Mr. Karkanis joined the Sudan Geological Survey in 1919, and he has had broad field experience on problems related to geology and water supply in practically every part of the Sudan. His intimate acquaintance with many of the district and local officials with whom we frequently came in contact and his knowledge of routes and road conditions were invaluable in the successful planning and execution of the field work. He also acted as interpreter for the field party. The prosecution of the entire program was greatly enhanced as a result of Mr. Karkanis' assignment to the field party.

L. Z. Makowiecki, Geophysicist in charge of all geophysical surveys, and D. J. Gear, Geophysicist, both members of the Geological Survey Department, conferred with the author and supplied information relating to areas in which they had been working, especially in the Red Sea coastal plain.

## GENERAL STATEMENT

During the reconnaissance the author gave consideration to centralizing the collection of pertinent data, outlining the organizational needs, aiding in preparation of a basic budget, and defining several types of investigations that would be of immediate value as well as forming the basis for later systematic investigations. The proposed program, in part, could be initiated advantageously prior to an additional authorization of funds if personnel could be diverted temporarily from other work in the Sudan Geological Survey Department.

There is considerable merit in the idea of having the basic investigation of ground-water resources conducted by a single organization. This may not be practical, however. In the Sudan, the Ministry of Public Works through their Drilling Division is best equipped to conduct the program of drilling of bore holes, and the Geological Survey Department of the Ministry of Mineral Resources is best suited to carry on the ground-water investigations. This latter arrangement is recommended in view of the fact that these organizations plan to work in very close cooperation so that the resultant investigations of ground-water resources in the Sudan will meet the needs for development of the country.

No attempt has been made in this report to include a narrative summary of observations that were made by the field party at a great many localities during the course of the field investigation. Such a summary would not satisfactorily answer the specific questions that have been raised concerning the obtaining of adequate water supplies in a number of localities in the Sudan. The field party conferred with local officials and other interested parties in each of the localities visited and a great many detailed observations on local geology and on wells and hafir sites were made. Contacts were made with governors of provinces, deputy governors, district commissioners and other district officials, district councils, village councils, police officials, sheikhs, nazirs, and other local tribal leaders, as well as with many local individuals. The information gained from these contacts was of great value in obtaining first-hand knowledge of specific ground-water problems with which many of the communities in the Sudan are confronted. It was not feasible, however, to spend

sufficient time at any one place to arrive at a satisfactory on-the-spot solution for individual problems. In many instances it was necessary to acquire as much information as possible from conversation with various individuals interested in the local water-supply problem but generally not experienced on ground-water conditions, and based on that information together with information obtained from a brief field reconnaissance locally, it was then necessary to make tentative recommendations as to the best methods of developing a satisfactory water supply. This was the best that could be done under the circumstances, but much more effective assistance could have been rendered if general geologic and hydrologic investigations had already been carried out in the region. It is rather difficult to pass judgment on a local ground-water problem when such judgment is based on a relatively brief field visit. A more complete understanding of regional relationships as they apply to a specific locality is necessary before satisfactory solutions to individual problems can be obtained.

Many of the localities that were visited by the field party in connection with the present assignment had been visited previously (some of them several times) by geologists and geophysicists of the Geological Survey Department and by representatives of other government departments, and a number of reports covering these field inspections, both published and unpublished, are available in the files of the Geological Survey Department. In reviewing these reports, it appears that most of the recommendations and conclusions were sound, in view of the fact that the individuals responsible for their preparation were also handicapped by a general lack of regional basic data on ground-water resources.

It is expected that the program of ground-water investigations that is being recommended in this report will eventually provide much of the regional basic data that are now lacking.

## PROPOSED PROGRAM OF GROUND-WATER INVESTIGATIONS

The movement of water as it relates to the earth is called the "hydrologic cycle." This movement may be described simply as the movement of water from ocean to air, to land, and thence back to the ocean. Because of the great complexity of the hydrologic cycle, the actual movement of water is complex. Ground water is one of the major elements in the hydrologic cycle. A full understanding of ground water also requires a knowledge of its relation to the other phases of the movement of water in the hydrologic cycle. In passing through the

hydrologic cycle part of the water passes beneath the surface of the earth and remains in storage there for various periods of time. Thus, ground-water investigations include not only studies to define the extent and distribution of ground-water reservoirs but also the chemical quality, the manner of movement, and the conditions of recharge to and discharge from these ground-water bodies. Investigations of the conditions of recharge and discharge include consideration of recharge from precipitation and surface runoff, and discharge of ground water by means of springs, artificial withdrawals, evaporation from ground-water ponds or through a soil zone, and transpiration through plants which obtain part or all of their water supplies from ground-water sources.

As can be inferred from the above, the investigation of ground water utilizes techniques adapted from several fields of science. These constitute the "tools" with which an evaluation of ground-water resources is made.

Previous Work

The Sudan Geological Survey has accumulated a large amount of data regarding distribution of ground water in the different geological formations. It has also been responsible for choosing the site of the great majority of bore holes put down for obtaining water supplies by the Drilling Division of the Public Works Department. Due to shortage of staff it has not been in a position to undertake regional surveys of ground water, and much of its work, both geological and geophysical, has of necessity been on an ad hoc basis.

The following history of research in the Sudan has been condensed from Chapter VI of a handbook of agriculture as practiced in the Anglo-Egyptian Sudan and entitled "Agriculture in the Sudan", by numerous authors, edited by J. T. Tothill. Chapter VI, entitled "Geology of the Sudan" was written by Gerald Andrew, Government Geologist, later Director of the Geological Survey. The earliest account of the geology of the Sudan was by Russeger, who made extensive excursions in search of mineral wealth early in the nineteenth century. Schweinfurth also traveled through the Sudan, but appears to have collected less geological information than he did in Egypt.

The Geological Survey began in 1905 by the appointment of T. Barron. After his early death in 1906 the survey was carried on by G. W. Grabham (1907-39), G. V. Colchester (1922-32), and J. M. Edmonds (1934-39); G. Y. Karkanis joined the staff in 1918.

During the period numerous reports were written on a wide range of subjects: pottery, brick, and tile materials; limestone, building sites; soils; water supply. The geological side of the work of the Egyptian Irrigation Department and for the Sennar and Jebel Auliya dams was done by the Geological Survey. Publications issued included

bulletins on water supply and mineral resources, a handbook for non-geologists on how to collect specimens and information, and a number of contributions to the publications sponsored by the International Geological Congress (on coal, iron ore, gold) ..... Seven geologists from abroad have visited the country south of Halfa and have published geological accounts in the twentieth century; Johannes Walther, W. H. Hobbs, K. S. Sandford, and E. J. Wayland, and three prospectors, A. Llewellyn, G. Linck, and W. H. Taylor, published geological reports of the areas visited.

The Geological Survey of Egypt carried out work in the Sudan; W. F. Hume made a traverse up the Nile from Halfa to Uganda, T. Barron visited Chelga in Abyssinia, and J. Ball studied the Nile as far as Semna. In 1927, J. Ball described conditions of ground-water occurrence and presented a contour map showing the direction of ground-water movement through the Nubian sandstone in parts of Egypt and including the northwestern part of the Sudan. His conclusions were published in a series of 3 papers in the Geographical Journal, Vol. 70, July - December 1927. The most important recent work on the region has been carried out by K. S. Sandford and W. J. Arkell on the Nile Valley as far as Semna, and by K. S. Sandford in the northwestern desert area.

H. Lynes and W. C. Smith described a part of Kordofan and Darfur; The Times African Flight discovered an unknown volcanic field in the Bayuda desert (Gregory, 1920; Grabham, 1920). In 1942 Edmonds described the distribution of the Kordofan qoz sand of the Anglo-Egyptian Sudan in an article appearing in the Geological Magazine, Vol. 79. A considerable amount of information is available, collected by the Geological Survey and sent in by prospectors, travelers, and Government officials.

Some of the information obtained has been published or set forth in manuscript form, and these reports are listed in the bibliography included in Bulletin No. 3, by Gerald Andrew, and entitled "Sources of information on the geology of the Anglo-Egyptian Sudan", published by the Sudan Government Geological Survey, Khartoum. Some of the information that has been obtained in regard to water supply has been published in Bulletin No. 2, Sudan Government Geological Survey, "Water supply of the Anglo-Egyptian Sudan", by G. W. Grabham, and in a report of the Geological Survey of the Anglo-Egyptian Sudan for the period 1950-1952, by Gerald Andrew, Director, Geological Survey. The latest published information regarding the sites drilled for water has appeared in Appendices A, B, and C, respectively, of the last-mentioned report. These appendices give depth, salinity, yield figures, etc., for the majority of the sites drilled up to 1952. To date, however, work in the investigation of ground water has been

done largely with respect to spot problems or has been incidental to more general geologic studies. During 1954 J. B. Auden, Acting Director, Sudan Geological Survey, prepared four typescript memorandum reports which related wholly or in part to the geology and ground-water resources of the Sudan: (1) Memorandum on possible assistance in ground-water surveys in the Sudan (April 1954), (2) Geological observations on ground-water conditions in parts of northern Kordofan (July 1954), (3) Memorandum on the Sudan Geological Survey (October 1954), and (4) Memorandum on oil potentialities in the Sudan (November 1954). The subject matter of these four memoranda has been drawn upon liberally by the author, and several pertinent statements have been incorporated in this report either in abstract form or as almost direct quotations.

The obtaining of satisfactory water supplies is recognized as one of the most important factors in the development of the Sudan, and it would appear prudent to undertake a program of systematic evaluation of ground-water resources. Such an evaluation could be undertaken in a priority sequence related to areal water needs. In time, an over-all appraisal of the ground-water resources of the Sudan would be available.

There are several general types of ground-water investigations. In a large and variable area such as the Anglo-Egyptian Sudan, nearly all the techniques of the different types of investigation are needed to obtain a better, more definite, and more useful understanding of ground water and the possibilities for its development.

## A. OCCURRENCE OF GROUND WATER

Parts of the following discussion have been abstracted liberally from Sudan Geological Survey Bulletin No. 2 entitled "Water supplies in the Anglo-Egyptian Sudan" by G. W. Grabham. On the basis of work previously done, supported by observations made during the present water-resources reconnaissance, the Sudan may be divided into three fairly distinct physiographic regions, each with characteristic land forms, geology, and occurrence of ground water. These are: (1) the northern area, mainly desert, with rock at or near the surface, covered by thin poor soils. This lies to the north of zones 2 and 3 below, (2) the western "qoz", an area of undulating sand, which merges on the north into the desert zone (1). The southern boundary is a fairly sharp but irregular line separating the qoz from the clay plain, and (3) the clay plain.

The Sudan is, in form, an immense plain or plateau, isolated on the north side by a desert, through which the Nile has provided a means of communication, and on the east side by the elevated tract bounding the Red Sea in the form of an escarpment facing east-northeast.

The northwestern area is mainly occupied by the Nubian Series of interbedded sandstones and mudstones, which forms flat-topped low hills intersected by fairly deep and steep-sided gullies. Where these rocks have been worn to a plain the surface is flat, monotonous, and gravelly or sandy, with occasional dunes.

In the central area the plain is diversified by many small isolated steep-sided hills (inselbergs) or by small groups of hills with the same characteristic "beehive" outline, among which the largest form the Nuba Mountains. (See Map 1 for location of these and other physical features, and places names). The volcanic pile of the Jebel Marra range rising to nearly 2,200 m. above the plains (3,000 m. above M.S.L.) is nearly 200 km. long and 35 to 50 km. wide, and forms the Nile-Chad watershed and the western boundary of the plain (here mainly a qoz plain). Local small plateaus, such as Gedaref, Jebel Meidob, Boma, are formed by outliers of the Tertiary lavas.

The clay plain occupies a wedge-shaped area widening eastwards, between the qoz country of southern Darfur Province and the "ironstone" country of western Equatoria Province, flanks the Nuba Mountains, and extends across the southern and central Sudan lapping against the foothills of the southern and eastern boundaries. West of the White Nile its edge skims the northern edge of the Nuba Mountains to near Kosti, but extends to just north of Khartoum in the basin of the Blue and White Niles, crossing the Butana and Atbara valley further north than Khartoum, as far as the plains around Kassala.

The center of the clay plain adjacent to the Nile is occupied by swamps (the Sudd).

The southern Sudan consists of two contrasting parts. West of the Bahr el Jebel there is a plateau, on which two peneplains can be distinguished. Both are inclined northwards and disappear at about 400 m. under the clay plain in the basin of the Bahr el Arab. This plateau rises to the east to over 1,000 m. ending in an abrupt scarp flanking the Bahr el Jebel between Nimule and Juba. The plateau is diversified with inselbergs.

The eastern part consists of massive mountain ranges with peaks rising to over 3,000 m. (Kinyeti) having the steep sides of the inselberg type, between which the plain at about 800 m. extends into Uganda. East of 34° east Longitude, lava plateaus extend toward the western boundary scarp of Lake Rudolph, continuing the Boma plateau.

The Sudan is essentially a plain of aggradation. A land surface, developed by erosion to a mature stage by the middle of Tertiary times, was later disturbed by movements, of which the most important was the rising of the eastern part now forming the Red Sea Hills and extending

into Eritrea and Ethiopia. In addition the central area, south of Khartoum, became depressed, forming an immense basin. This basin was filled in by sediments (the Umm Ruwaba Series,) to the present level (of approximately 400 m. in the White Nile drainage basin). The hills represent the unburied remains of the older topography. Locally the surface was further modified by the accumulations of lava (Jebel Marra, Meidob, Gedaref, Boma, etc.).

The present drainage of this plain is entirely through the Nile. The Blue Nile and its tributaries, and the Atbara, are probably the oldest drainage lines and original sources of the main Nile, together with streams which now do not discharge into the Nile (Wadi Hawar, Wadi el Milk, Wadi Muqaddam, all west of the main Nile; and the Wadi el Arab east of Atbara and perhaps the Gash river). The Sobat and Umbelasha, and the main drainage lines in Darfur and Equatoria are also probably ancient. The White Nile from Lake No to Khartoum, now the main stream of the southern Nile, occupies the filled-in depression and is probably of comparatively recent origin, with a present fall of only 16.5 m. in 956 km. (difference of mean maximum of river levels, Lake No to Khartoum) or less than 1.73 cm. per km. mean slope.

The northern Sudan lies in an arid region. In fact, throughout 43 percent of the Sudan the average annual rainfall is less than 200 mm (about 8 inches). The rainfall diminishes northwards toward Egypt, so that near Wadi Halfa the average precipitation, so far as an average has any meaning in the desert, is only 0.1 mm (0.004 inch). Inasmuch as rain is the source of practically all the water in the Anglo-Egyptian Sudan, water supplies are directly dependent on the amount and distribution of the rainfall.

The principal geological formations hitherto recognized in the Anglo-Egyptian Sudan are as follows:

- Alluvium
- Dune sands (Qoz)
- Wind-deposited clay (Loess)
- Umm Ruwaba Series of fluviatile and lacustrine deposits of Plio-Pleistocene age
- Volcanic formations
- Nubian sandstone Series
- Nawa Series arkosic grits and mudstones
- Crystalline rocks including gneiss, schists, granites and diorites (Basement Complex)

The different formations each present essential features in regard to water supplies and it is necessary to understand the geological conditions that affect the various formations.

Approximately 53 percent of the Sudan is occupied by peneplaned rocks of the Basement Complex, together with relatively unimportant Tertiary volcanics, whereas the Nubian formation covers about 23 percent of the area. A greater proportion of the Nubian is found in the north of the Sudan, where the rainfall is least. Valley-fill deposits are virtually absent in the areas occupied by Basement Complex and Nubian.

Notwithstanding the low rainfall of the Sahara region stretching right across Northern Africa, some geological formations in parts of this area hold relatively large quantities of water, as for example, the sandstones of formations equivalent to the Nubian. Other geological formations yield only small quantities of water.

Basement Complex.- Although most of the crystalline rocks of the Basement Complex are hard, impermeable, and unfavorable for water supplies in their fresh conditions, perfectly fresh rock is rare near the surface and, in decomposed and weathered conditions, some types of these rocks form important reservoirs for ground water and yield valuable supplies. Even in the freshest condition in which they are found at the surface of the ground, crystalline rocks are never completely free from joints, and fairly deep wells may yield some water though the amount may be small and the quality sometimes poor. Yields of water to wells in the rocks of the Basement Complex are generally of the order of 300-1,000 gallons per hour (23 to 76 litres per minute), and the ground water is believed not to occur in the form of a continuous zone of saturation.

Nawa Series.- The Nawa Series of Upper Paleozoic age comprise gently-dipping, non-metamorphic, purple or olive-green, arkosic grits and mudstones, resembling flagstones, with a noteworthy proportion of detrital white mica. The Nawa beds are only found in wells and bores in the Kashgeil and Abu Habl basin in the central Sudan and are covered by superficial deposits. The state of compaction of the sediments is greater than that of the Nubian Series. This succession occurs between 12°12' and 12°50' N., 30°00' and 34°50' E., in three apparently disconnected areas separated by rocks of the basement complex. The Nawa beds were proved in bores at Semeih Station, to a depth of 447 feet in an abrupt and steep contact, probably faulted, with a granite. During our field trek to the western Kordofan we visited 2 wells at the En Nabak School for boys at En Nabak and both of these wells penetrated the Nawa Series, as evidenced by slabs of fresh flagstone on the spoil pile before bottoming in Basement Complex.

Nubian Series.- The Nubian sandstone series, although mainly composed of porous sandstones, also includes mudstones, clays, ironstones, and some very small limestone beds. It is the most important

water-bearing formation in the Sudan and the quality of the water is usually good. Locally, especially near the surface, the sandstone may be cemented with either iron or silica forming hard, non-porous rocks: ironstone and silcrete (sandstone). Borings have penetrated the Nubian to depths of nearly 800 feet without reaching the base. It is estimated that it probably attains a maximum thickness of more than 1,000 feet in the Sudan. There is evidence that different parts of the Nubian are not of the same geological age and probably when these can be distinguished it may be desirable to identify them as different formations, perhaps ranging in age from Paleozoic to Cretaceous.

Yields in certain localities in the Nubian, and rocks similar to the Nubian, are known to be of the order of 12,000 gallons per hour or 900 litres per minute, but such comparatively large supplies depend on suitable intake areas and a favorable geological structure, and are uncommon. The average yield from the Nubian sandstones in the Sudan, so far determined, is 1,650 gallons per hour or 125 litres per minute. In some dune sand areas where there is a sufficient depth of such sands, and, presumably, some suitable floor of compact or impermeable material, satisfactory supplies of water may be obtained by means of shallow wells.

Umm Ruwaba Series.- Approximately 23 percent of the Sudan is occupied by rocks of the Umm Ruwaba Series. Although no marine fossils are known, the ground water in some of these sediments, particularly near Kosti, is very saline, with a concentration as high as 17,000 ppm (17 grams per litre). Dr. Auden considers that this salinity is not necessarily due to the former existence of marine conditions in the Umm Ruwaba Series, because the nature of the salts present is not that which is typically developed from the evaporation of sea water. At El Ga'a, north of El Obeid, brine is extracted from open wells in a shallow basin for the manufacture of common salt. The brine has much sodium sulphate, but is strikingly deficient in magnesium and calcium salts. There was evidently a shallow playa at El Ga'a in which a fresh-water lake was subjected throughout a period of years to evaporation and increasing salinity, until it became a true saline lake. Subsequently the lake must have been filled in by wind-blown and alluvial material, and all the original salt accumulations are preserved at or below the original lake level, now 140 feet below ground surface. The brine as now extracted has a concentration of 192,000 ppm total solids, which is 5½ times the concentration of sea water.

Alluvium.- The sands and gravels of the alluvium are capable of holding and transmitting water freely and under favorable circumstances, such alluvial deposits yield very important supplies of water. In the Sudan, the alluvial deposits flanking the Blue Nile and the Main Nile north of Khartoum are saturated with water from the river. Besides the Nile alluvium, the delta of the Gash and

deltaic formations in Kordofan yield important water supplies. The deposits of valley fill forming the floors of the more important valleys in the Red Sea Hills absorb some proportion of the scanty rainfall and supply many good wells.

On the basis of the ground water development seen during this reconnaissance most ground water in the Sudan occurs under unconfined conditions.

The chemical quality of the water contained in several different types of aquifers in the Sudan is variable and ranges from good to poor. If the quantity of salts in solution is less than 1,000 ppm, such water in the Sudan is considered as good. Where the concentration rises to more than 2,000 ppm, the water is not desirable in ordinary circumstances. At Tokar, however, water having a total concentration of 4,000 ppm of dissolved solids is regularly drawn from wells for human consumption. Usually these salts comprise mainly chlorides, sulphates, and carbonates of sodium, magnesium, and calcium.

In the lower parts of the coastal plains and associated deltas bordering the Red Sea, ground water may be saline and locally unsuitable for use.

## B. METHODS OF INVESTIGATION

The several phases of the ground-water investigations are based on the systematic collection, recording, and analysis of the data collected. Accordingly, it is desirable to establish, at an early date, a mechanism for the orderly handling of data collected before and during the several phases of the investigation.

### Collection and Recording of Data

Currently, most available data on bore holes and springs are in the files of the Drilling Division of the Public Works Department and of the Sudan Government Geological Survey of the Mineral Resources Department. However, additional information can be obtained from other government agencies, well drillers, private companies, and individuals.

It would be highly desirable that all such pertinent data be filed with one government agency so that full use of the data could be made. For ease of handling and for facilitating interpretation, data should be placed on standard forms, insofar as possible. A sample set of forms, as given in Appendix A, may be used as a guide.

Well schedules.- These forms are used to provide data on location of a well, name of the owner, and information about the well, such as depth, date drilled, depth to water, location of water-bearing zones,

length and diameter of casing, temperature of water, type of pumping and driving power, and rate of discharge. Data on the development or capacity test also may be given. This is something of a summary form, and additional forms commonly are used for more detailed information. This form (9-185) should be filled out as completely as possible; an attempt should be made to get all available information on the first visit to each well.

Well logs - These forms are used to record a written or graphic description of the successive kinds of material and the depths at which they were penetrated during drilling. Water-bearing zones and other information noted during drilling are included. A record of the construction of the well is commonly given in these forms - that is, diameters and length of casing, perforations or screen intervals, and other data pertaining to construction that may be of assistance in interpreting the geology and water-bearing characteristics of the materials penetrated.

Water-level measurements - Periodic measurements of water level in a given well ordinarily are listed on a separate form (9-195). Over a period of time several sheets might be used for a given well.

Pumpage forms - Where it is necessary to obtain data to permit computation of monthly or annual discharge, a standard form may be devised. These forms are adapted to fit best the type of data collected for the computations.

Chemical analysis forms - In geochemical investigations where periodic samples are obtained to detect changes in chemical components, a form may be used that will allow recording of several analyses for ready comparison. These forms are adapted to fit special study requirements. However, it is desirable to have a general form to record relatively complete analyses.

Spring schedules - This form serves the same purpose for a spring as the well schedule does for a well.

The above forms are designed to permit recording of all useful data of a well or spring. When preparing summaries of such data for use in reports, additional forms are used. These include tables of well and spring records, logs, chemical analyses, and changes in depths to water.

Because there are a great many native wells dug by hand in the Sudan, data on representative dug wells also should be collected. Although it may not always be possible to obtain a complete set of data, the information is often quite useful in furthering the knowledge of the occurrence and movement of ground water in the area under investigation.

## Continuing Observations

Unlike other minerals, ground water is a renewable resource, and, as such, reacts in dynamic response to changes of recharge and discharge. To define and interpret such changes, a program of periodic observation at selected points is required. Observations include water-level measurements in wells, measurement of discharge of springs and wells, measurement of precipitation, chemical analysis of samples of water from selected points, and other information as necessary. Periodic observations for all such data may not be entirely practical at times. The difficulties involved in transport from one place to another in many parts of the Sudan are well recognized. However, it is believed that a minimum program could be established in the Sudan which could be expanded in accordance with future requirements.

To be of real value in the evaluation of the ground-water potential, the data should be analyzed and interpreted periodically.

## Areal Geologic and Hydrologic Studies

A primary function of the Sudan Government Geological Survey is the systematic study of the geology of the Sudan. Three geologic maps have been published thus far: (1) Geological map of the Anglo-Egyptian Sudan, Scale 1:4,000,000 (2) Geological map of Sheet 55 Khartoum, Scale 1:1,000,000 and (3) Geological map of Eastern Khartoum Province, Scale 1:250,000. It is understood that the results of geologic studies now pending publication as well as the results of geologic studies in the future will be released in the form of written reports and accompanying maps on a scale of 1:250,000. Presumably this information will be released successively by sheet units of the 1:250,000 base map for the Sudan. Investigations of ground water could be integrated with much of the work of the general survey of the geology of the Sudan, although the issuance of reports based on hydrologic units rather than by sheets may be warranted.

Base maps covering the Sudan are available in two other scales, including AMS series 1391, World 1:1,000,000, and AMS series Y 401 (GSGS4355) East Africa 1:500,000.

It should be pointed out that the 1:250,000 sheets of the base map for the Sudan lack altitudes and topographic contours. Not only are heights unknown for the most part, but positions must often be regarded as uncertain, except for a few very accurately fixed triangulation stations close to the 30th meridian. This points up the need for an expansion in regard to topographical surveys, for without accurate topographic maps no other work dependent on location in space can be fully satisfactory. This is particularly relevant to ground-water and normal geological studies in which water-table and structural data are referred to mean sea level. It also applies to investigations of surface-storage projects, such as dam sites and the capacity of reservoir basins.

The U. S. Trimetrogen Photographs cover part of the area, but there is no adequate overlap between obliques. Dr. Auden has pointed out that in connection with the initial geological survey of the Sudan, it is important at an early date to study all of the American Trimetrogon air photographs, as well as those taken more recently by the Sudan Airways, so that there can be a collation of regional structure. Although there has been sporadic study of the photographs, it is desirable systematically to place the data on the 1:1,000,000 maps.

The areal ground-water investigations require a sound knowledge of the geology of the area, especially of its stratigraphy and structure. Details of the nature, disposition, and structure of the different rock formations are essential in any investigation of the distribution and disposition of ground water in the Sudan. From this basic geologic study it should then be possible to delineate the major ground-water provinces.

Data needed for a given hydrologic unit would be obtained by a detailed study of the water-level fluctuations in wells and withdrawals of water from wells, details of occurrence of water-bearing zones penetrated by wells, details of the occurrence and character of springs and the fluctuation of their discharge, areas of recharge and discharge within the unit, distribution and amount of precipitation within the area, character and distribution of stream flow, and geochemistry of ground and surface water in the area.

Integration of the geologic and hydrologic phases leads to a better knowledge of the potentialities and limitations of the development of water in the areas studied. Ordinarily, for efficiency and economy of operations these studies preferably are approached with a view of evaluating the ground-water resources for the development of water supplies for domestic, municipal, irrigation, or industrial use, rather than making studies for only single-purpose development. It is recognized that there are many individual well-site problems in the Sudan, particularly in western Kordofan and Darfur. It must be emphasized, however, that to investigate these small-scale problems individually would greatly hinder progress on the all-important, long-range, ground-water program. If it is later decided to investigate these small-scale individual problems, it is essential that an additional mechanism be set up for this purpose.

In addition to the systematic areal investigations or in conjunction with them, there will likely be the need for certain special studies. At least three types of special studies appear to be needed, although the need may be for certain local areas only. Other types of studies may become apparent in the course of systematic areal investigations.

## Hydraulic Studies

Such studies involve quantitative determinations of the capacity of water-bearing beds to store and transmit water. The tests generally involve the artificial withdrawal of ground water, ordinarily through wells, with suitable observations of the rate of discharge, time, and fluctuations of water level with time in the pumped well and nearby observation wells. Such studies probably would have considerable value in evaluating potential ground-water sources in Kordofan and Darfur provinces, in parts of the Northern Province where the Nubian sandstone series comprises an important water-bearing unit, in the Nile Valley where irrigation wells have been drilled, and in other areas of comparable interest in the Sudan. A detailed discussion of procedures is not within the scope of this report. Actual procedures can be adapted for specific use from certain publications of the United States Geological Survey and others that are available.

## Geochemical Studies

These studies involve periodic sampling of water at representative wells and springs in an area, analysis of the water samples by competent chemists, and interpretation of the results in conjunction with the geological and environmental factors that control the chemical quality of ground water. These studies are needed in some areas in the Sudan occupied by rocks of the Umm Ruwaba Series. These rocks occur in one main basin, with two arms extending from Malakal to Muglad and to Kosti. The ground water in some of these sediments, particularly near Kosti, is very saline, with a concentration as high as 17,000 ppm. (17 grams per litre). Samples of well water should be obtained and analyzed, and this information, when added to the analytical data already available from the boring operations undertaken by the Drilling Division, would aid in delineating the areas of saline-water occurrence. When sufficient chemical quality information has been obtained, maps showing contours of salinity could be prepared. This information will be essential in selecting sites for successful boreholes in the future. Similar studies appear to be needed in certain of the coastal plain areas of the Sudan bordering the Red Sea. Saline ground water locally unsuitable for use has been known to exist in these areas, as near Suakin, Tokar, Port Sudan, and other places, and if the rate of artificial withdrawal of ground water is not carefully controlled, there may be an inland movement of the fresh - salt-water contact. In certain areas fresh and saline springs occur close together, and geochemical studies are needed because of possible problems of contamination of the fresh-water springs.

## Geophysical Studies

These studies require the use of specialized geophysical instruments to conduct resistivity, gravimetric, magnetometer, and seismic

surveys. Geophysical surveys have been carried on in the Sudan by the Geological Survey Department since about 1940. Resistivity probes were started in 1940 to give guidance in the selection of favorable sites for bore holes put down by the Drilling Division. More recently the geophysical surveys have been expanded to include resistivity and gravity surveys for exploring ground-water possibilities in a number of localities in the Sudan. These surveys were designed to supply pertinent information on the character and thickness of unconsolidated sediments, the approximate thickness of water-saturated material, the depth to underlying bedrock, and the configuration of the bedrock floor.

A general program of ascertaining the extents and limits of several basins in Kordofan and Darfur Provinces using geophysical methods was carried on during 1952-1953. Dr. Auden has pointed out that geophysical resistivity investigations in some parts of northern Kordofan have not proved to be very reliable, mainly because of the thick cover of dry qoz sands. He believes that seismic traverses should be very useful in indicating the thickness of qoz in different places, but will indicate nothing about the nature of the zone of saturation. Both methods are valuable tools in ground-water investigation, but neither alone can be a substitute for geological interpretation. Dr. Auden hopes to continue with resistivity work in Kordofan Province, in suitable places, and to undertake seismic sounding, particularly in connection with a study of the Kheirans.

In other parts of the Sudan similar geophysical surveys have been undertaken to obtain all possible subsurface information to aid in the selection of the very best sites for bore holes. The coastal plain along the Red Sea has recently been the site of geophysical investigations by geophysicists of the Sudan Geological Survey. They have used the gravimetric, magnetometer, and seismic methods, and their results are still in process of interpretation.

When properly interpreted and qualified, geophysical studies can supplement ground-water studies very effectively, and in some investigations geophysical investigations have contributed substantially to the successful solution of ground-water reservoir problems. It should be pointed out, however, that geophysical observations do not automatically indicate where there is utilizable ground water, and in many terranes the results are of necessity ambiguous. It is highly important that geophysical studies be closely integrated with related geological and hydrological work. In the past there has been a tendency to send geophysicists into an area without carrying out any related geological investigations, and that is not always a wise procedure.

Sometimes it has been necessary to predict success and/or to condemn proposed sites for boreholes generally without the benefit of prior investigational work in the area concerned. In some instances

predictions have been based on records of boreholes in the vicinity of a later proposed one, but many times there has been very little information available upon which reliable forecasts could be based. The several types of studies outlined above would go a long way toward eliminating some of the guesswork involved in evaluating ground-water supplies in the future.

## C. EQUIPMENT

Equipment needed for ground-water investigations differs widely with the type and intensity of the investigation. It is believed desirable to start with a minimum amount of equipment in the early stages of the program. As the program develops, however, due consideration should be given to the fact that additional equipment will be needed to obtain the required data.

Most equipment needed for geologic studies and field studies, together with necessary precision instruments for carrying out geophysical studies, is already in use by the Geological Survey Department, Sudan Government.

Base maps and aerial photographs, such as the currently available 1:1,000,000, 1:500,000, and 1:250,000 base maps and the aerial photographs including both the U. S. Trimetrogon photographs as well as those taken more recently by the Sudan Airways that cover a part of the area, are of great assistance to the ground-water investigations.

Sanction should definitely be granted for personnel of the Sudan Geological Survey Department to make frequent reconnaissance flights for the purpose of inspecting the geologic and physiographic features of various regions and to supplement the existing knowledge of the geology of many parts of the Sudan.

Equipment for measuring water levels and depths of wells, measuring discharge of wells and springs, and collecting and chemically analyzing water samples will also be needed in early phases of the program.

In time, when the stage of investigations warrants, it may be necessary to have drilling equipment for putting down exploratory and observation wells. At the present time the Drilling Division of the Public Works Department, Ministry of Public Works, is responsible for carrying on drilling activities for the Sudan Government. This Division now has 25 drilling rigs at its disposal, and of this total, 21 are of the percussion or cable-tool type and 4 are diamond core drills. The drilling equipment is used: (1) to put down bore holes for rural water supplies; (2) to obtain water supplies for towns, industry, and for irrigation; (3) for miscellaneous investigation work, dam foundations, etc.; (4) for drilling for the Gezira Board in the Gezira Irrigation Scheme in the clay plain between the White and Blue Niles; and (5) for maintenance and repair work on already completed bore holes and wells.

Any proposals for test drilling in connection with ground-water studies will want to be closely coordinated with the work program of the Drilling Division. G. H. Leston, Drilling Engineer, in charge of this Division, should be in a position to render additional valuable assistance on ground-water investigations in the future.

Other equipment, such as electric-logging equipment, deep-well current meters, deep-well water samplers, and similar specialized equipment may also be needed as the investigational work progresses. However, much can be done in the first year of the program without highly specialized equipment.

## D. REPORTS

The results of the various ground-water investigations normally should be presented in formal reports with appropriate maps and illustrations and reproduced in sufficient copies to meet probable demands. For those reports of limited interest, probably reproduction in mimeographed form would be acceptable. However, reports of systematic areal investigations warrant formal reproduction.

All such reports should contain information that is pertinent to give the proper understanding of the purpose and use for which it is intended. The areal investigations might appropriately include geographical and other general information in an introduction followed by parts on climate and precipitation, physiography and drainage, geology (including stratigraphy and structure) and water-bearing character of the rocks, ground water (including sections on the occurrence, movement, recharge, discharge, and chemical quality), present development, and potentialities for development.

Tables might include information on stratigraphic relations, precipitation records within the area, streamflow records, records of wells, logs of wells, discharge of wells and springs, and chemical analyses. These can be included within the body of the report or as appendices.

Illustrations may be of many types, such as photographs of geologic and hydrologic interest, diagrams of precipitation relationship and distribution, etc. However, they should include wherever possible, geologic maps, maps showing by contours the altitude of the piezometric surface of the ground water, and perhaps isopachous maps showing the thickness of the saturated water-bearing material, maps showing the depth to and thickness of important aquifers (perhaps this information can be combined with the information shown on the isopachous map), maps showing the depth to water below land surface, maps showing location of wells and springs and other pertinent hydrologic features and cross sections showing geologic and hydrologic relationships. Appendices C and D list topics for consideration in comprehensive and reconnaissance areal reports respectively.

## E. IMPLEMENTATION OF PROGRAM

The discussion of ground-water investigations in the previous sections outlines the kind and direction of the proposed investigations. Obviously not all the investigations can be made immediately or at the same time. It is hoped, therefore, that the following suggestions will lead to the development of a unit that can undertake certain projects which will form the basis for the systematic evaluation of the ground-water resources of the Sudan. The proposed projects were selected to obtain information currently needed and to afford a means of applying methods and techniques of investigation that can be applied in other areas subsequently to be investigated.

### Organization

It is believed that under existing conditions, the Geological Survey Department, Sudan Government, would be the most suitable organization to assume the responsibility for systematic ground-water investigations. This belief is based on three principal points: (1) The Department is an investigative rather than a construction or "action" agency: such an agency ordinarily is in a better position than an "action" agency to evaluate impartially the needs for information and to facilitate ground-water development, whether the developments are to be made by the government or by private interests; (2) the Department currently is responsible for a basic geological survey of the entire Sudan. As the geologic information is a prime requisite in the ground-water investigations, the work could be combined for better continuity and greater efficiency; (3) conducting the ground-water investigations as a component of the Geological Survey Department would be more economical than handling it through a new organizational unit.

Personnel - The current work load of the Geological Survey Department is too great to permit the continuity of effort needed to properly conduct the systematic investigations of ground water in addition to the present studies of the general geology and the numerous local investigations of mineral occurrences. This is particularly true in view of the recent reduction in staff of the Geological Survey Department. Therefore assuming some assistance from the present staff, it is proposed that two additional field geologists be added to the staff at the earliest possible time to work essentially full time on ground-water investigations or to replace current personnel who may be assigned full time to ground-water investigations.

Certain equipment will be needed for the personnel to conduct the investigations. An estimated budget for the proposed unit is given in the Appendix B and includes equipment items.

It is not expected that the personnel would be available to conduct the investigations without additional training, but such training could be given on the ground by the assignment of a ground-water specialist from the United States Geological Survey. During the course of the investigation perhaps additional personnel from the Sudan Geological Survey could receive training in methods of ground-water investigation. This aspect will be discussed subsequently.

Proposed Projects

It is recognized that it may take some time to establish the positions of the two field geologists and to recruit competent men. Both should be obtained as soon as possible, however.

Because of the interest in developing the program at the earliest practicable time, it appears desirable to take some initial steps with existing personnel of the Geological Survey Department, although it must be recognized that this would involve a diversion of personnel from other investigational work that must be done.

The following three proposed projects encompass basic principles of investigation that apply to most investigations.

Project-A - Compilation of Records - The collection of records of wells and springs is a necessary, though time-consuming, part of the investigation of ground water. In the Sudan, efforts should be made to collect such previous records as are available from various sources and then continue the collection of such information as new wells are constructed or additional springs are located. Samples of forms that may be useful in tabulating these data are given in Appendix A.

Information is available for many bore holes in the files of the Drilling Division of the Public Works Department, Ministry of Public Works; additional information apparently is available from drilling contractors and private owners. It is important that there should be coordination with the Geological Survey Department as a central depository for all data from drilling, test pumping, and well construction. The information collected should include also, as available, description and location of wells, description of the geologic units penetrated, details of well construction, measurements of water level, temperature of water, chemical analyses of the water, pumping equipment, rate of discharge, and development and production tests. In fact it should include any information that may be useful in assisting an interpretation of the ground water in the area in which the well is located.

As in the case of wells, data on springs should be collected and compiled systematically. The information would include a description of the geologic environment and the conditions under which the spring issues at that location, measurements of discharge, temperature of water, chemical analyses of water, and any documented information relating to the source of water issuing at the spring.

Project B - Continuing Observations - It is desirable to establish a project of periodic observations at selected localities to determine the fluctuations of water levels in wells, and the characteristics of discharge and chemical quality for representative springs.

The prime purpose of a continuing ground-water observation program is to provide data for analysis of long-term conditions. This is especially valuable in areas in which relatively large-scale development is in progress or is being planned.

The area of the Sudan is about 967,000 square miles. It would be virtually impossible and highly impracticable to include immediately all of the principal areas of the Sudan in an observation-well program. The distances involved in periodically visiting far-distant wells in remote areas would be prohibitive, and the costs of transportation over difficult and many times waterless terrane would constitute a definite limiting factor in planning any observation-well program.

It would seem desirable to select a small representative group of observation wells in one of the principal regions of interest. Such a region has already been suggested by Dr. Auden as being a logical place to begin a ground-water survey. As part of the recommendations included in his report of April 20, 1954 to the Council of Ministers, Sudan Government, entitled "Memorandum on possible assistance in ground-water surveys in the Sudan" Dr. Auden stated that the particular region in which the Sudan Geological Survey is interested is located in Kordofan Province, between Nahud and El Obeid, Dilling and Sodiri. It occupies an area of 46,000 square miles (120,000 square kilometers) between north latitudes $12^{\circ}$ and $14\frac{1}{2}^{\circ}$, and east longitudes $27^{\circ}$ and $31^{\circ}$.

He pointed out further that the area was selected for two main reasons (1) the rainfall is varied, ranging from 20 inches in the south to 8 inches in the north, and (2) the area includes a considerable variety of geological formations, which should display a corresponding diversity of ground-water occurrences and problems.

For the purposes of starting a project of periodic observations at selected localities to determine the fluctuations of water levels in wells, it is recommended that the original area proposed by Dr. Auden be expanded to include a few observation wells in the Darfur Province, extending westward as far as the vicinity of El Fasher, and to include also a representative group of observation

wells in the general vicinity of the Nuba Mountains. It is proposed that at least one well be selected for periodic measurement in the vicinities of the following localities: Umm Ruwaba, Rashad, Dilling, Abu Zabad, Er Rahad, El Obeid, Bara, El Gaa, Sodiri, Mazrub, En Nahud, El Muglad, Abu Matariq, Ed Da'ein, Nyala, El Fasher, Khureit, Umm Keddada, El Hilla, and Wad Banda.

It should be emphasized that the localities cited above have been selected arbitrarily with a view to obtaining representative coverage of a relatively large region. In setting up the observation-well program, it will first be necessary to spend a considerable amount of time in the field searching for suitable wells that can be used for periodic observation. The persons responsible for making the selections in the field will need to exercise a good deal of personal judgement in choosing existing wells that will qualify for inclusion in the proposed water-level observation program. The above-suggested localities are to be considered only as a guide for selection purposes. During the field canvass, suitable observation wells may be found in localities not included in the above list, and it may be desirable to deviate somewhat from the pattern of coverage herein suggested. The number of wells selected and their exact locations will be dependent necessarily on the availability of suitable existing wells in the region. After the network of observation wells has been established, the program should be kept flexible enough that from time to time new observation wells can be added as the need arises, and unsatisfactory wells can be discontinued.

The frequency of visits to individual wells for the purpose of measuring water levels will be governed by a great many factors, including general accessibility, transportation limitations, season of the year, availability of personnel and funds, and perhaps other imponderable circumstances. The problem of motor transport is one of the most important factors of all, because much of the travel to these localities will be over poorly defined routes. In many instances it will be necessary to traverse faint tracks in loose qoz sand. Visits to the wells can only be accomplished in conjunction with well-planned, time-consuming, field treks, during which it will be necessary for a field party to remain in the field for extended periods away from any base of operations. Weather must also be reckoned with in establishing the frequency of visits to the observation wells. Starting about the first of July and lasting from 2 to 3 months, the rainy season in this part of the Sudan can often interfere seriously with all types of overland transportation.

In countries where transportation problems are not as significant as they are in many parts of the Sudan, monthly or perhaps bimonthly visits to observation wells are often recommended. Sometimes the observation-well programs are designed for visits on an approximate

quarterly, semi-annual, or perhaps even annual basis. The frequency of the visits is generally determined by the type of program being conducted and by the purpose for which the water-level information is being obtained.

It is recommended that an observation-well program be established along the lines suggested, and that the matter of frequency of visits be held in temporary abeyance until more experience has been gained following the implementation of the program. At first, it may only be practicable to visit the wells once a year. When conditions warrant, it would be desirable to visit the wells semi-annually, or perhaps even quarterly.

An attempt should be made to select observation wells that will be representative of the several different types of aquifers that supply wells in the region. Accordingly, it would be desirable to include one or more wells that penetrate any of the following aquifers: (1) dune sand (2) alluvium (3) Umm Ruwaba Series of fluviatile and lacustrine deposits (4) Nubian Sandstone Series (5) Nawa Series of grits and mudstones and (6) Basement Complex of crystalline rocks.

It is fully recognized that it may not always be a simple task to find existing wells for observation that are only seldom used. Practically every existing well in the region in question is subject to heavy withdrawals at rather regular intervals. It is doubtful that many completely unused wells will be found. Caution will need to be exercised in avoiding the selection of heavily used wells, particularly in areas where the yields are small and where the wells are readily exhausted. If a well is subjected to practically continuous withdrawals, and if the rate of recovery of the water level in the well is relatively slow, it is obvious that such a well would be unsatisfactory for periodic observation.

The success of the entire observation-well program is largely dependent on the caliber of the wells that are selected for observation. It may well be that satisfactory existing wells cannot be found in some localities where water-level information is sorely needed to complete the distribution desired. In such instances it is suggested that consideration be given to drilling a small-diameter well to be used for observation purposes exclusively. It will doubtless be feasible to enlist the aid of the Drilling Division of the Public Works Department to accomplish this purpose. Similarly, if some previously selected existing well fails to live up to expectations as a representative observation well, it may be practicable to replace it eventually with a new drilled observation well in the same locality. This would again require assistance from the Drilling Division.

Although it is probably out of the question for present considerations, an enviable goal to strive for would be establish a network of small-diameter observation wells put down by the Sudan Government, and drilled exclusively for observation purposes.

Eventually it may become desirable to expand the suggested regional program of water-level observation to include the measurement of representative observation wells in other parts of the Sudan. As conditions warrant, the program could be expanded to include other areas of interest. In the future, this coverage might extend to each of the nine provinces. Such an expansion would have to be geared to future requirements.

Project C - Investigation of parts of western Kordofan and Darfur Provinces: Although there is interest in the ground-water conditions of nearly every part of the Sudan, it is believed desirable to select one area for investigation where necessary data can be obtained to permit the demonstration of a variety of techniques used in ground-water investigations. The area selected is approximately equivalent to the area referred to earlier in the discussion of establishing an observation-well program. As pointed out earlier by Dr. Auden, the area includes a considerable variety of geological formations and this should result in a corresponding diversity of ground-water occurrences and problems. Such an investigation not only would increase the existing knowledge of the ground-water potentialities of the western part of the Sudan but also would reveal basic geologic and hydrologic relationships that would materially assist in the investigations of other similar bordering areas. In addition, the techniques utilized have application either directly or with adaptation to other parts of the Sudan. There has been a heavier demand for assistance on developing water supplies in western Kordofan and Darfur Provinces than elsewhere in the Sudan. All of the government agencies that deal with problems of water supply have been besieged with requests for assisting the towns, villages, and rural districts in obtaining satisfactory water supplies both for human and animal populations. The problem of providing water supplies sufficient for sustaining life during each successive dry season is a serious one. High evaporation loss causes surface water to disappear at some stage of the dry season with only a few exceptions. Underground water supplies are necessary for a great part of the area, and where these are naturally scarce it is necessary to provide means for conserving surface water as far into the dry season as possible. The Drilling Division of the Public Works Department is called upon to drill a great many boreholes in this area in a continuous effort to find and develop adequate ground-water supplies in the towns and rural communities. It is believed that information already available on bore holes and dug wells in western Kordofan and Darfur Provinces and information obtained in the proposed study would permit a better selection of exploratory drilling sites in other parts of the Sudan.

It should be noted that the investigation of this area need not exclude ground-water investigations elsewhere, and the methods used for this study can be utilized elsewhere as personnel become familiar with the methods of investigations.

Some surficial geologic work has already been done in parts of western Kordofan and Darfur Provinces. The information should be reviewed to clear up questionable points and additional field work should be carried out where needed. The field party would carry out as far as possible a detailed geological survey of the area and relate the distribution of the ground water to the different geological formations that had been demarcated. Sub-surface geologic investigations could be largely done by the study of available logs of boreholes and dug wells. The Geological Survey Department is already carrying on sub-surface studies in connection with the inspection and classification of samples of rock cuttings from bore holes and wells drilled in the Sudan. These studies should be continued and expanded in order to establish the relationship of lithologic units. Faunal identification of stratigraphic units should be made where possible. The investigation requires extensive information on stratigraphy, structure, and physiographic history to establish the framework that controls the recharge, movement, storage, and discharge of ground water in the western Kordofan and Darfur Provinces area. The 1:250,000 sheets of the base map for the Sudan could be used for compiling the geologic map in the field. The field data could then be transferred to a base map of the scale 1:1,000,000. The U. S. Trimetrogon photographs cover part of the area and all available aerial photographs on which geologic information could be plotted should be made available for field use. Dr. Auden has pointed out that the Sudan aerial photographs are invaluable for undertaking geological surveys. Exposures of rock formations tend to be good in all the hilly tracts of the Sudan and to show up well from the air. The country is fortunate in having been covered to a considerable extent by air photography, partly undertaken by the U. S. Army Air Force during the last war, partly more recently by the Sudan Airways on behalf of the Survey Department. The preliminary outline in Appendix C indicates the various aspects to be considered.

The hydrologic aspects of the investigation would include a study of the precipitation records within the area, of any available streamflow records and of miscellaneous measurements of streamflow during the course of the investigation, and compilation of well records. Water-level measurements should be made semi-annually and preferably quarterly at 20-25 wells located in various parts of the area. An inventory of pumpage from wells in use should be made to obtain data required for the computation of the amount of water pumped each season and year. It is realized that this type of information will be difficult to obtain, particularly in the rural districts where in many communities water is obtained from a number of shallow

dug wells located on the floors of wadis. Withdrawals are generally made by hand using ropes attached to leather skin buckets, and in such instances the amount of water used will need to be estimated. Measurement of the discharge of any springs in the area to determine the characteristics of seasonal fluctuations and approximate annual discharge, and chemical analyses of samples of water from representative wells and springs will also be needed. In some parts of the northern Kordofan the ground water is charged with various saline constituents, and in other parts of Kordofan Province the thick accumulations of unconsolidated sands, gravels, and clays in the Umm Ruwaba and Muglad depressions carry water, but parts of these depressions, notably east of Tendelti, contain water too saline for consumption. It will be necessary to acquire considerable analytical data in order to delineate the areas of saline water occurrence in the area. As more is learned of the general characteristics of the wells, a few can be selected to make suitable tests for the determination of the capacity of water-bearing formations to transmit water, in order that potential maximum yields can be estimated.

Available precipitation records can be statistically analyzed in order to develop the characteristic variations in precipitation in the several parts of the area and to give an approximation of the total water coming into the area. It may also be desirable to establish some temporary precipitation gages to supplement available records. It is necessary to direct attention to a statistical analysis of rainfall observations, because, as has already been pointed out, rain is the source of practically all the water in the Sudan. In fact it is probable that the country does not contain any supplies from terrestrial sources that cannot eventually be traced to rain.

In defining the shape and position of the water level in parts of western Kordofan and Darfur Provinces, it will be necessary to determine the altitude of the measuring point at each well used for control. Such levelling as will be necessary probably can be done to acceptable accuracy with a plane table and telescopic alidade. Dr. Auden has suggested that this work could be accomplished by the assignment to the project of levellers from the Survey Department.

This comprehensive ground-water survey would make use of all existing information in the records of the Geological Survey Department, and would be an extension of more scattered and individual site problem studies which have been already undertaken.

Assistance from United States

Shortly before the termination of the recent short-term assignment to the Sudan, the Minister of Mineral Resources, Sayed El Mahallawi,

asked the author to make informal inquiry upon his return to Washington as to the possibility of the United States Geological Survey furnishing a ground-water specialist for a longer-term assignment to the Sudan. In reply to this request, Sayed El Mahallawi was informed that there was some uncertainty about the availability of a ground-water geologist for immediate assignment to the Sudan, but assurance was given that the U. S. Geological Survey will give consideration to any forthcoming request for assistance, if personnel subsequently become available. Accordingly, the question of whether or not the United States Geological Survey will be in a position to furnish a specialist must remain unanswered for the time being, pending receipt of a formal request from the Sudan Government for technical assistance. However, as the need for current information is a continuing one, it seems essential for the Sudan Government to have appropriate personnel available to become familiar with both the field and office aspects of systematic ground-water investigations. Thus, although the work of the ground-water specialist will have a temporary value in specific work undertaken, his greatest value will be to provide training in investigational methods so that personnel of the Sudan Government can continue to conduct investigations effectively after his departure. Therefore it is most desirable that the Government provide funds for the two additional field geologists in the Geological Survey Department. Funds also should be included for the equipment necessary to conduct the investigations.

After the two field geologists are assigned to the Geological Survey Department, it would be desirable to have a ground-water specialist work primarily in the western Kordofan and Darfur Provinces project with them for a period of about a year. During this time, methods and techniques used in ground-water investigations could be demonstrated by field operations. Subsequently the work could be continued by the two Sudan Geological Survey geologists until the data necessary for the western Kordofan and Darfur Provinces project investigations had been obtained. When the data are obtained (sometime in the second year from the start of operations) a ground-water specialist might work with them for a period of about four months in interpreting the data and preparing the report for publication. Ground-water investigations are, in fact, required in every province in the Sudan and, in addition to the intensive investigation in Kordofan and Darfur Provinces, other surveys and special studies will be needed throughout the country. During the time that the ground-water specialist is in the Sudan it would also be possible for him to assist in programming additional work in other types of ground-water problems in the Sudan and he could demonstrate methods and techniques that might be applicable for specific aspects of investigations of a type other than that of the western Kordofan and Darfur Provinces project.

As the Sudan Government desires to press the ground-water investigations (Sayed El Mahallawi, Minister of Mineral Resources, has expressed the hope that a ground-water specialist can be assigned immediately for at least a 2-year term), some immediate assistance can be given in several features in the collection of data (Project A) that might well be done with the available staff, recognizing that, if this is done, work on other necessary projects necessarily would be delayed. Assistance in details of this work can be given by direct correspondence together with reference to specific publications. As specific questions may arise, an exchange of correspondence may serve to answer the problem. If a substantial start can be made prior to the arrival of the ground-water specialist, his work will be much more effective. During one of the several conferences that were held in the Geological Survey Department offices in Khartoum at the time of the author's assignment to the Sudan, Dr. Auden suggested to Sayed El Mahallawi that it would be highly desirable to create an opportunity for George Y. Karkanis, Geologist and Well Supervisor, Drilling Division, Public Works Department, to collect and compile all of the geologic and water-supply information that he has acquired during his long and active career in the field in the Sudan. This would constitute a most valuable start on the task of compiling and assembling all available data that would be of assistance in initiating a ground-water investigation in the Sudan.

The purpose of concentrating investigational effort in Kordofan and Darfur Provinces is to obtain information sufficiently comprehensive that ground-water developments can be planned to meet the needs of the people in this region, which currently has more critical water-supply problems than any other part of the Sudan. These investigations and the scientific conclusions based on them require time - perhaps several man years of effort - but the benefits of the project cannot be realized until the project is completed. It is important therefore that qualified personnel be assigned full time to the project until it is completed, and not be diverted to other work.

In every region that is embarking upon comprehensive programs of ground-water investigation, there are also urgent needs for information to assist in current drilling programs. This has been true at the beginning of many regional projects in the United States, where immediate needs could not be met by the over-all program.

Undoubtedly, during the time that ground-water studies are in progress in western Kordofan and Darfur Provinces many requests for assistance on local ground-water problems will be received from other localities in the Sudan. It is recommended that provision be made separately for assigning specialists to investigate and give professional advice on these individual site problems as they arise. It is not intended to minimize the importance of giving assistance to

towns and rural districts on water-supply problems, but this type of grass-roots service should be handled by a team of specialists for that purpose. Important as the latter type of program is, it is equally important that the ground-water investigations proceed with a minimum of deviation from previously recognized objectives.

Summary

1. Systematic ground-water investigations should be considered as a continuing program in the Sudan.

2. Under present conditions ground-water investigations probably can best be conducted by the Geological Survey Department, which is responsible also for systematic geological work in the Sudan.

3. To handle the responsibilities for ground-water investigations, the Geological Survey Department additionally should have at least two professional field geologists and later a draftsman assigned to the present staff. The possibility of organizing a special Ground Water Section should be considered to include the above personnel. Certain equipment also will be needed.

4. United States technical assistance can best be directed toward training selected personnel in the Sudan in the methods and techniques of ground-water investigations by means of on-the-ground studies.

5. As the acquisition of additional personnel and the assigning of the United States ground-water specialist may take several months, certain assistance can be given at an early date, through correspondence, if part of the present Survey staff can be assigned to the collection and compilation of available information.

## APPENDIX A

### List of Sample Forms (U. S. Geological Survey) for Recording Data Obtained in Ground-Water Investigations

| Form | Number |
|---|---|
| Water Sample | 9-016 |
| Public Water Supply Schedule | 9-184 |
| Well Schedule | 9-185 |
| Record of Wells | 9-185a |
| Spring Schedule | 9-187 |
| Spring Table | 9-187a |
| Notebook | 9-189 |
| Water Level Measurements | 9-195 |
| Precipitation in Inches | 9-241 |
| Water Level Measurement Card | 9-256 |
| Partial Analysis Notes | 9-261 |
| Analytical Notes | 9-262 |
| Discharge Measurement Notes | 9-275f |
| Hydrograph | 9-279h |
| Analytical Statement (Chemical) | -- |

APPENDIX B

ESTIMATED BUDGET FOR A GROUND-WATER INVESTIGATIONAL UNIT PROPOSED TO BE ESTABLISHED IN THE GEOLOGICAL SURVEY DEPARTMENT, SUDAN GOVERNMENT

First Year

| | | | Estimate in Pounds |
|---|---|---|---|
| I. | Expenditure for local expenses of U. S. Ground-water specialist for full year* | | |
| | Living expenses at about L 3.5 per day | 1,280 | |
| | Travel and subsistence | 820 | |
| | Sub-Total | | 2,100 |
| II. | Expenditure for Geological Survey Department Staff | | |
| | Geologist, Salary and cost of living allowance | 1,650 | |
| | Trek allowance (based on an estimate of 200 days per year) | 120 | |
| | Geologist, Salary and cost of living allowance | 1,250 | |
| | Trek allowance (based on an estimate of 200 days per year) | 120 | |
| | Transport expenditures | | |
| | Fuel | 1,000 | |
| | Driver's and assistant driver's salaries | 1,500 | |
| | Maintenance | 200 | |
| | Field expenses, casual laborers, gage readers | 500 | |
| | Office furniture, equipment, reference publications, and expenses | 500 | |
| | Sub-Total | | 6,740 |
| III. | Equipment | | |
| | Field trucks, Jeep type, (3), Austin Champion, 4-wheel drive @ L 1,400 | 4,200 | |
| | Trucks, 2-3 ton (6) British Commer or equivalent @ L 1,200 | 7,200 | |
| | Normal Field Trekking kit (2) | | |
| | Tents 600 | | |
| | Jerry cans, etc. 50 | | |
| | Other 50 | 700 | |
| | Additional equipment for ground-water investigations (Lump-sum estimate includes such items as follows:) | 1,500 | |
| | Sub-Total | | 13,600 |

* See foot note at the end of Appendix B

Estimate in Pounds

Surveying altimeter (?) Short & Mason or equivalent, 10,000 foot range
Alidade, telescopic (1), with Beaman arc attachment
Plane table (1)
Stadia rods (2)
Level rods (2), Philadelphia type
Water-stage recorders, weekly Stevens type F or equivalent
Pressure gage (1), range 0-50 feet (direct reading in feet)
Current meter (1), pygmy type

Accessories for current meter (including 5 one-foot units of wading rod, 2 base plates, extra bushings and pivots, and headphone)

Steel tapes, 500-foot (?) and reels (graduated in tenths and hundredths of a foot)
Steel tapes, 200-foot (4) and reels (graduated in tenths and hundredths of a foot)
Steel tape, 200-foot and reel, square type (2) (graduated in tenths and hundredths of a foot)
Steel tapes, 50-foot (2), (graduated in tenths and hundredths of a foot)
Tape, 200-foot (1) electric-contact type
Wire-weight well-depth sounder, 1,000 foot
Rule, 6-foot, roller type (inches and fractions on one side, tenths and hundredths of a foot on other side)
Carpenters' level, 3-foot (1)
Field analysis kit (1), Betz or equivalent (Hardness, sulphate, and chloride determinations)
Conductivity bridge and cell (1), Beckman type or equivalent
Conductivity cells (?) - spares
Water Sampler, 1-litre capacity (Foerst type) with 500-foot cable and reel
Thermometers, with metal case for field use (12) graduated 30-250 (or 300) degrees F
Bottles (12-oz. citrate), 200 units for collecting water samples
Bottles, (4 liter), 20 units for collecting water samples
Boxes (5) for carrying 12 12-oz. bottles
Boxes (5) for carrying 1 4-litre bottles

Total estimate for First year 22,440

Second Year

I. Expenditure for local expenses of U. S. ground-water specialist for full year

| | Estimate in Pounds | |
|---|---|---|
| Living expenses at about £ 3.5 per day | 1,280 | |
| Travel and subsistence | 820 | |
| Sub-total | | 2,100 |

II. Expenditure for Geological Survey Department Staff

| | | |
|---|---|---|
| Geologist, Salary and cost of living allowance | 1,650 | |
| Trek allowance (based on an estimate of 200 days per year) | 120 | |
| Geologist, Salary and cost of living allowance | 1,250 | |
| Trek allowance (based on an estimate of 200 days per year) | 120 | |
| Survey draftsman, Salary and cost of living allowance | 300 | |
| Transport expenditures | | |
| Fuel | 1,000 | |
| Driver's and assistant driver's salaries | 1,500 | |
| Maintenance | 200 | |
| Field expenses, casual laborers, gage readers | 200 | |
| Office furniture, equipment, reference publications, and expenses | 400 | |
| Sub-total | | 6,740 |

III. Equipment

| | | |
|---|---|---|
| Additional equipment for ground-water investigations | 500 | |
| Sub-total | | 500 |
| Total estimate for Second year | | 9,340 |

Third Year

I. None

II. Expenditure for Geological Survey Dpartment Staff

| | |
|---|---|
| Geologist, Salary and cost of living allowance | 1,650 |
| Trek allowance (based on an estimate of 200 days per year) | 120 |

| | Estimate in Pounds | |
|---|---|---|
| Brt. Fwd. | 1,770 | |
| Geologist, Salary and cost of living allowance | 1,250 | |
| Trek allowance (based on an estimate of 200 days per year) | 120 | |
| Survey draftsman, Salary and cost-of-living allowance | 300 | |
| Transport expenditures | | |
| Fuel | 1,000 | |
| Driver's and assistant driver's salaries | 1,500 | |
| Maintenance | 200 | |
| Field expenses, casual laborers, page readers | 200 | |
| Office furniture, equipment, reference publications, and expenses | 400 | |
| Sub-total | | 6,740 |
| **III. Equipment** | | |
| Additional equipment for ground-water investigations | 500 | |
| Sub-total | | 500 |
| Total estimate for Third year | | 7,240 |

Note: Subsequent years at about 7,500 pounds unless expansion of program is contemplated, then it would be necessary to have additional experienced personnel or if a test-drilling program is added to the current program. Either or both of these changes would require additional funds.

* This estimate is only an approximation. The actual cost would depend, in part, on the general terms of agreement and the manner of distribution of the total cost for supplying the American specialist.

## APPENDIX C

Topics to be considered for a comprehensive areal report

- Abstract
- Introduction
  - Purpose and scope of investigation
  - Location of area
  - Previous investigations
  - Acknowledgments
- Geography
  - Surface features
    - Land forms
    - Physiographic history
  - Drainage
  - Climate
    - Precipitation
    - Temperature
    - Humidity
    - Evaporation
    - Growing season
  - Development
    - Agriculture
    - Industries
    - Transportation
    - Minerals
    - Water
      - Municipal and domestic
      - Irrigation
      - Industrial
- Geology
  - Stratigraphy
    - Pre-Cambrian
    - Paleozoic
    - Mesozoic
    - Cenozoic

Geology (continued)

- Igneous activity
  - Intrusive rocks of _____ age
  - Extrusive rocks of _____ age
- Structure
  - Folding
  - Faulting
- Summary of geologic history

Water resources

- Hydrologic cycle
  - Evaporation
  - Precipitation
  - Surface water
    - Streams
    - Lakes and ponds
  - Ground water
  - Transpiration
  - Surface water
    - Principal streams
      - Inflow
      - Outflow
      - Use in the area
        - Municipal and domestic
        - Irrigation
        - Industrial
        - Nonconsumptive
    - Minor streams
      - Inflow
      - Outflow
      - Use in the area
        - Municipal and domestic
        - Irrigation
        - Industrial
        - Nonconsumptive

Water resources (continued)
- Hydrologic cycle (continued)
  - Ground water
    - Source
    - Occurrence
      - Unconfined (non-artesian or water-table) conditions
      - Confined (artesian conditions
      - In consolidated rocks
        - Igneous rock
        - Limestone
        - Chert
        - Shale
        - Sandstone
        - Conglomerate
      - In semi-consolidated and unconsolidated rocks
        - Limestone (marl)
        - Clay
        - Silt
        - Sand
        - Gravel
      - Aquifer properties
        - Porosity
          - Effective porosity
        - Specific yield
        - Specific retention
        - Permeability
          - Primary
          - Secondary
          - Laboratory determination
            - Problems of sampling
            - Problems of testing
            - Selection and description of test method
            - Causes of variations
            - Reliability
          - Field determination
            - Infiltration tests

Water resources (continued)
- Hydrologic cycle (continued)
  - Ground water (continued)
    - Occurrence (continued)
      - Aquifer properties (continued)
        - Permeability (continued)
          - Transmissibility tests
            - Pumping methods
              - Controlling conditions
              - Problems of testing
              - Causes of variations
              - Reliability
            - Drainage methods
              - Controlling conditions
              - Problems of testing
              - Causes of variations
              - Reliability
            - Analysis of water-level fluctuations
              - Controlling conditions
              - Problems of testing
              - Causes of variations
              - Reliability
          - Relation to geologic structure
          - Relation to land forms
    - Recharge
      - In areas of aquifer outcrop
      - Interformational leakage
        - Vertical transmissibility
        - Lateral transmissibility
        - Along fault zones
        - Through faulty wells
    - Discharge
      - Natural
        - Springs
          - Gravity
          - Artesian

Water resources (continued)
- Hydrologic cycle (continued)
  - Ground water (continued)
    - Discharge (continued)
      - Natural (continued)
        - Springs (continued)
          - Fault line
          - Conduit
        - Interformational leakage
        - Evapotranspiration
      - Artificial
        - Wells
        - Infiltration
        - Drainage systems
    - Development
      - Springs
      - Wells
        - Drilling techniques
        - Construction
        - Development
        - Pumping equipment
      - Infiltration systems
    - Chemical quality
      - Constituents
      - Methods of expressing analyses
      - Geochemical relations
        - Solution of soluble minerals
        - Salt-water encroachment
        - Industrial wastes
        - Organic wastes
      - Effect on specific gravity
      - Relation to use
    - Temperature
      - Methods of measurement
        - Reliability

Water resources (continued)
- Hydrologic cycle (continued)
  - Ground water (continued)
    - Temperature (continued)
      - Interpretation
        - Relation to geology
        - Relation to depth
        - Relation to transmissibility
        - Relation to hydrostatic head
        - Relation to use

Water-bearing formations

- Paleozoic rocks
  - Ordovician system
    - Hermitage formation
      - Location and extent
      - Character
      - Transmissibility
      - Storage capacity
      - Recharge to the formation
        - Natural
          - In area of outcrop
          - Other sources
        - Artificial
          - Spreading grounds
          - Wells
        - Summary
      - Movement of water in the formation
      - Discharge from the formation
        - Natural
          - Underflow
          - Leakage
          - Springs

Water-bearing formations (continued)
- Paleozoic rocks (continued)
  - Ordovician system (continued)
    - Discharge from the formation (continued)
      - Artificial
        - Wells
        - Infiltration system
      - Potential development
      - Summary
    - Chemical quality of the water
      - Constituents
      - Variations
      - Relation to use
    - Temperature of the water
      - Variations
      - Interpretation

Ground-water resources by counties (areas)
- History of water development
  - Pumpage by units
- Fluctuations of water level
  - Resulting from natural causes
    - Daily
    - Seasonal
    - Annual
    - Long-term
  - Resulting from artificial causes
    - Daily
    - Seasonal
    - Annual
    - Long-term
  - Potential development

Glossary of ground-water terms

Bibliography

Tables

- Record of wells
- Well logs
  - Drillers' logs
  - Sample logs
  - Geophysical logs
- Chemical analyses

Illustrations

- Plates
  - Cultural map
  - Physiographic and topographic map
  - General geologic map
  - General hydrologic map
  - Water-level contour map
  - Others for specific illustration
- Figures
  - Index map showing relative location of the area in the State
  - Geologic profiles
  - Hydrologic profiles
  - Others for specific points

## APPENDIX D

### Topics for consideration in a reconnaissance report

Abstract

Introduction

- Purpose and scope of the investigation (may include methods of investigation)
- Location and extent of the area
- Natural resources and cultural features
- Previous investigations
- Acknowledgements

Land forms and drainage

- Uplands
- Lowlands
- Streams and/or lakes

Climate

General geology

- Summary of geologic history
- Water-bearing character of the formations

Ground water

- Source
- Occurrence
- Movement
- Recharge
- Discharge
  - Natural
  - Artificial
- Utilization
  - Present
  - Potential
- Chemical quality

Summary

References

Plates

Map showing general geologic and hydrologic features of the area

Figures

Index map showing location of area in the State

Tables

Climatological data
Records of wells
Well logs
Records of pumpage
Chemical analyses

Note: This list is intended as a guide only. It may suggest other items for study in planning the project as well as in writing the report, and it should be useful as a checklist in evaluating the various phases of the investigation.

## APPENDIX E

### Selected Reading List

A collection of general references in the broad field of hydrology with additional references in the specific field of ground water.


General hydrology

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_____ 1928, Compressibility and elasticity of artesian aquifers: Econ. Geology, vol. 23, no. 3, pp. 263-291.

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_____ 1934, The history and development of ground-water hydrology: Washington Acad. Sci. Jour., vol. 24, no. 1, pp. 6-32.

_____ 1936, Movements of ground water: Amer. Assoc. Petroleum Geologists Bull., vol. 20, no. 6, pp. 704-725, 9 figs.

_____ 1939, Ground water in the United States: a summary of ground-water conditions and resources, utilization of water from wells and springs, methods of scientific investigation, and literature relating to the subject: U. S. Geol. Survey Water-Supply Paper 836-D, pp. 157-232, 1 pl., 31 figs.

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Washington, D. C.
February 1952

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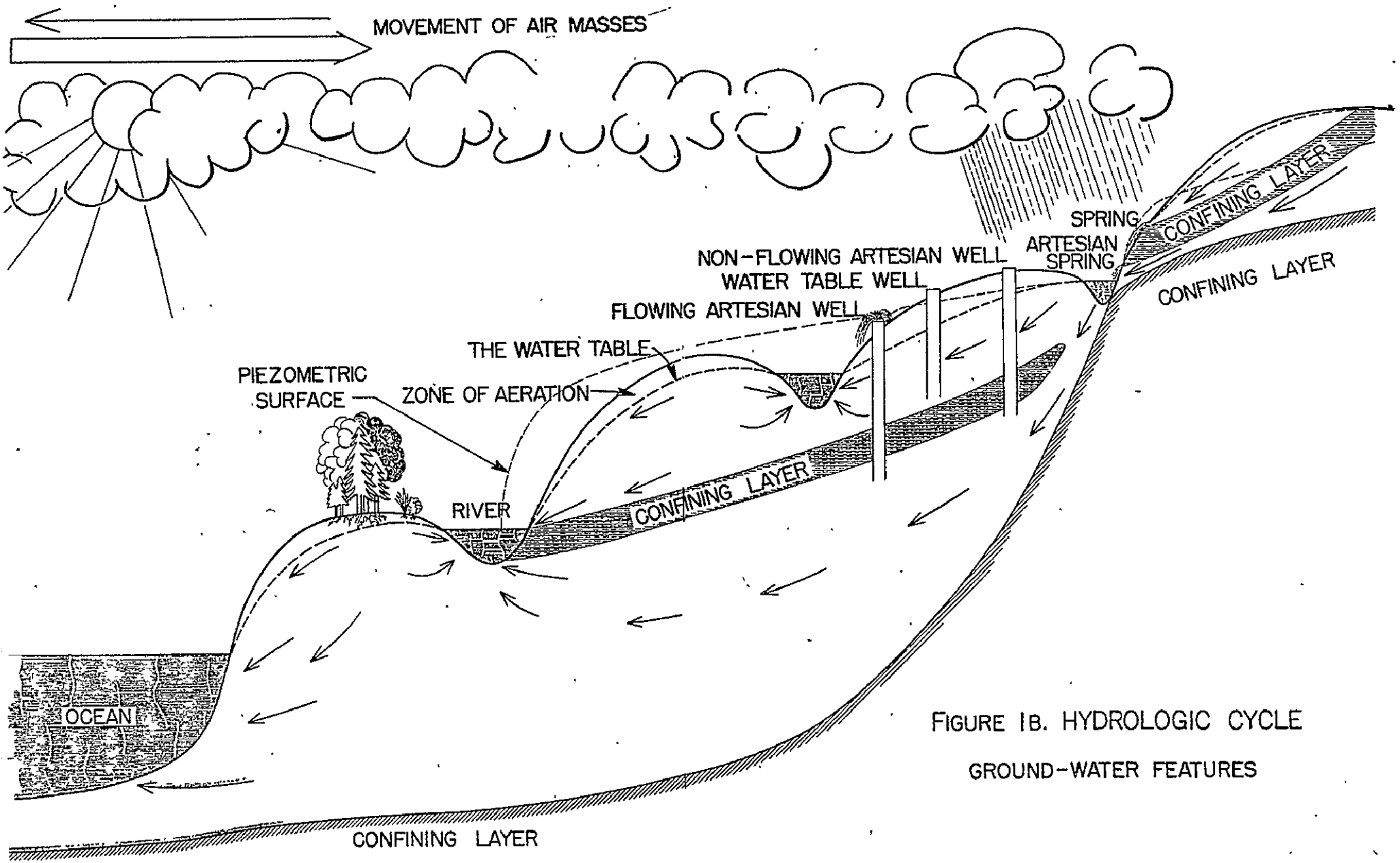



FIGURE 1B. HYDROLOGIC CYCLE

GROUND-WATER FEATURES

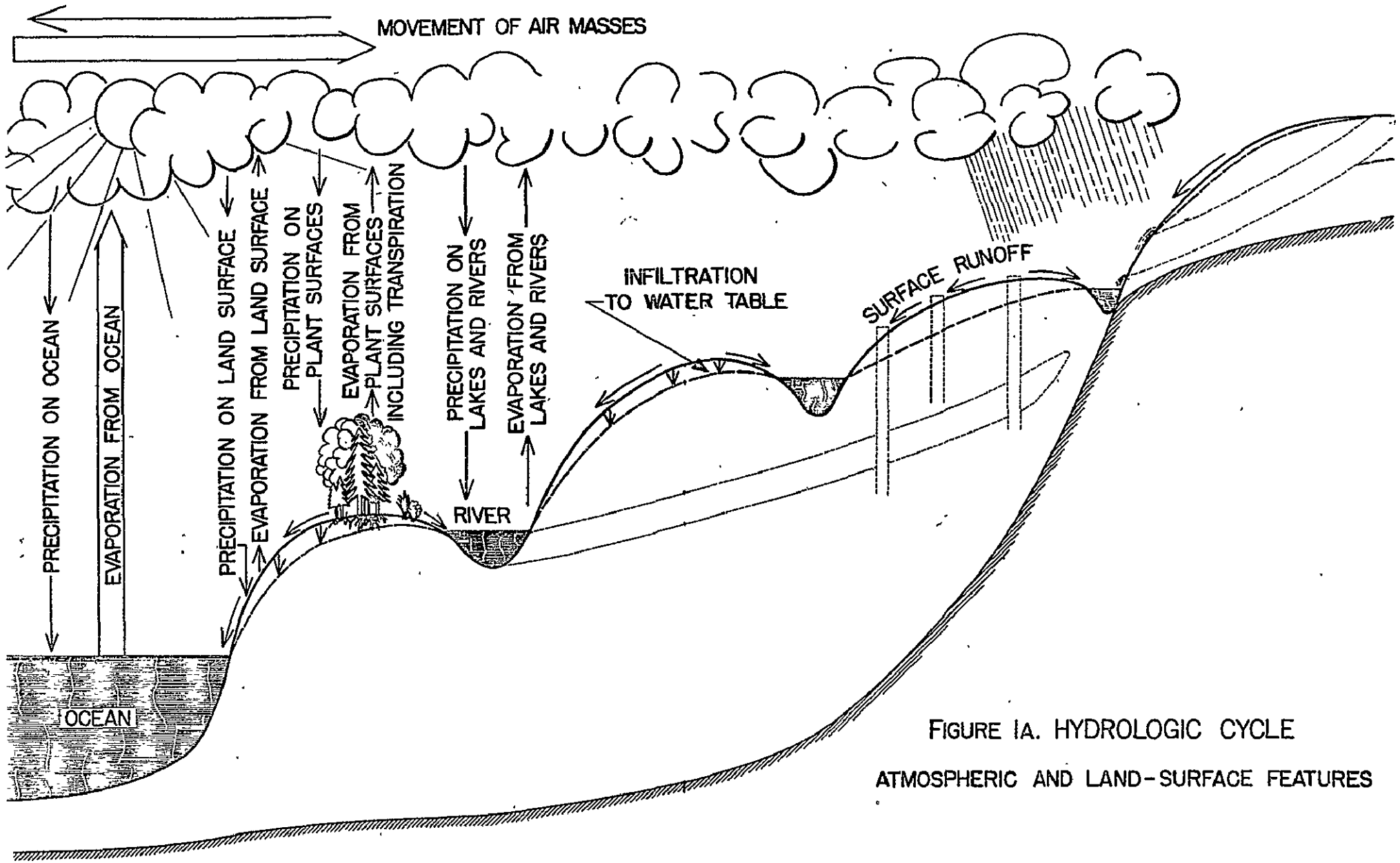
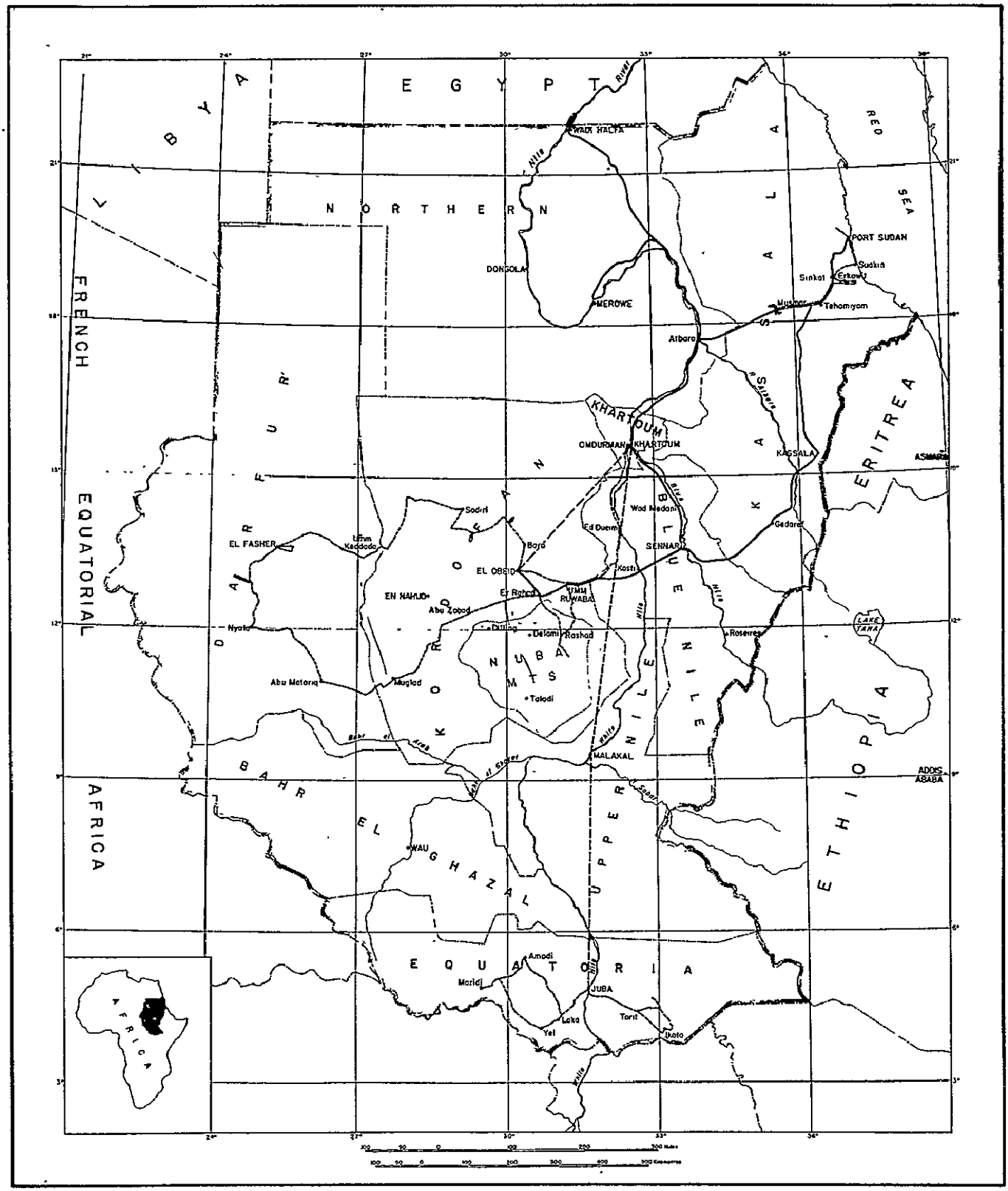



FIGURE 1A. HYDROLOGIC CYCLE

ATMOSPHERIC AND LAND-SURFACE FEATURES




MAP OF THE ANGLO-EGYPTIAN SUDAN