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GROUND WATER IN AFRICA

UNITED NATIONS

UNITED NATIONS

SECRETARIAT

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GROUND WATER IN AFRICA

Corrigendum

Page 4, fourth paragraph, line 1

For clearing read cleaning

Page 9, fifth paragraph, lines 2 and 3

For production; unirrigated crops tend to be only read production, considering the fact that many crops which are produced at little or no cost for irrigation water are only

Page 45, ninth paragraph, lines 2 and 3

For in the (continental) sandstones of the Albian (Algeria) and Nubia (Egypt) read in the continental Albian sandstones (Algeria) and Nubian sandstones (Egypt)

Page 46, fifth paragraph, line 3

For basins and read basins are

Page 67

Seventh line from top

For file read records system

Seventh line from bottom

For sources read resources

Page 76, line 6

For drilled read dug

Page 84, line 22

For trial borings have shown read exploratory drilling has shown

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July 1973 - 3,500
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English only

Page 94, penultimate line

For contains few impurities read has a low content in dissolved solids

Page 106, line 10

For (acolian) read (aeolian)

Page 116, final line

For Mauritius read Mauritius, an independent State and member of the Commonwealth

Page 117, thirteenth line from bottom

For sensulato read lato sensu

Page 121, line 17

For contamination by brine read sea-water intrusion into the aquifer

Page 124, last paragraph, line 1

For trial bores have been made read exploration bore-holes have been drilled

Page 127

First paragraph, line 4

For water read hydrographic

Seventh paragraph, line 1

For The entire country read Most of the country

Page 134, second heading

For Surface aquifer covering whole of country read Shallow aquifer covering the whole of the country

Page 135, second paragraph, line 4

For pressurized by read confined under

Page 139, fourth line from bottom

For (dry wells) read (nearly dry wells)

/...

Page 145, fourth paragraph

For assemblages read units

Page 146, final line

For results obtained, if any, are read water obtained, if any, is

Page 149, table, first line

For 0.9 to 48 read 0.9 to 4

Page 150, line 8

For tried read drilled

Page 152

Fifth paragraph, line 11

For made read are

Seventh line from bottom

For Water Borings Service read water-drilling service

Page 155

Third paragraph, line 1

For are confined to the Mediterranean coast read are present only in the vicinity of the Mediterranean shores

Fourth line from bottom

For salts read solids

Page 158, fifth line from bottom

For sources read points

Page 160, seventh paragraph, line 1

For basement collapse trough read rift valley

9484

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Department of Economic and Social Affairs

GROUND WATER IN AFRICA

UNITED NATIONS
New York, 1973

NOTE

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country or territory or of its authorities, or concerning the delimitation of its frontiers.

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PART III. CONCLUSIONS AND RECOMMENDATIONS

Map

FOREWORD

The Economic and Social Council, by its resolution 675 (XXV) of 2 May 1958, requested the Secretary-General to take appropriate measures for the establishment, within the Secretariat, of a centre to promote co-ordinated efforts for the development of water resources. It also singled out ground-water problems as one of the priority subjects in the development of a programme of studies.

Large-Scale Ground-Water Development, published in 1960,[1/] was the first study prepared in this field by the Water Resources Development Centre. During the First United Nations Development Decade many projects assisted by the United Nations Development Programme (UNDP) and other United Nations technical co-operation programmes were entirely or partially devoted to ground-water prospection, assessment or pilot development. In Africa alone, 30 such projects have been or are being executed.

The utilization of ground water other than spring water has, in fact, begun only recently in many African countries, especially in humid areas, since in the tropical zones, where most of Africa's population lives, surface waters are abundant and widespread. However, the chemical peculiarities and degree of pollution of these surface waters, which sometimes contain large quantities of pathogenic agents, make them in many cases unfit for human consumption - and in some cases even unfit for animal consumption - according to the generally accepted sanitary standards for drinking water. For this reason, ground water is more and more often being used to supply towns and villages, since its quality is usually good enough to render unnecessary the costly treatment facilities required by urban centres that rely on surface water.

Moreover, many African cities (including recently established or recently developed capitals) and their industrial areas are situated on or near the seacoast, and they draw their fresh water from underground sources. In the deserts, ground water constitutes the only available source - and then only at certain select locations. Lastly, ground water, whether from springs, drains, traditional wells, modern wells - i.e. wells with motor-driven pumps - or artesian bore-holes, is being more and more frequently used for the irrigation of food or industrial crops, chiefly in the arid and semi-arid zones.

Thus, the exploitation of ground water in Africa is an essential factor in the development of the continent: it affects every country and every economic sector.

In the following pages the reader will find, firstly, a general view of Africa's ground-water resources and their utilization. Methods of ground-water exploration and exploitation are discussed and a brief account is given of the present state of knowledge, including a description of Africa's major ground-water reservoirs, the yields of which are indicated and illustrated in the schematic map

1/ United Nations publication, Sales No.: 1960.II.B.3.

of African ground water annexed to this report. Next, there are brief country monographs incorporating the information submitted by the specialized technical services of many African countries in response to a United Nations questionnaire. The study ends with a set of conclusions concerning the potential resources, the needs and the development prospects of each region and with some recommendations for the future.

Preliminary general reports of the same kind are planned for Latin America, for Asia and the Far East, for the Middle East and for Mediterranean Europe.

INTRODUCTION

A. Historical outline

In Africa, as in the rest of the Old World, the existence of populous ancient civilizations, with an advanced social organization and a sophisticated way of life, is linked to the presence of large rivers. These rivers provide a plentiful supply of water, rich soil, fish and game in the valleys and deltas, ease of transport and relative safety.

Two of the greatest African civilizations were those of Egypt, which Herodotus called "the gift of the Nile", and Benin on the lower Niger, which may have been founded by peoples migrating from the upper Nile valley. The Chad civilization arose in a sort of African Mesopotamia between the Chari and the Logone. Another centre developed between the upper Senegal and the upper Niger, in the Mali and Songhai empires. The Ashanti country, near the Volta, is famous for its artistic productions. Mention should also be made of the civilization that arose between the Zambezi and the Limpopo (Monomatapa, Zimbabwe), which was noted for its advanced metal-working; here, however, the river relationship is less clear.

Away from the great rivers, Africa does not have a great many surface-water sources, especially during the dry season. In tropical Africa they consist of ponds, which did not in general promote the development of social structures, since settlement near them was dispersed.

In northern Africa the earlier inhabitants, the Berbers, generally lived in the mountainous areas, near perennial streams and springs. It was the Arabs, occupying the plains and the oases of the Sahara, who developed ground water by sinking wells and building drainage galleries, employing techniques brought from central Asia and the Near East. Various mechanical means for water extraction were also brought from those regions.

Until recently, however, except for the Arabized parts of Africa, ground water was taken only from relatively shallow holes dug in alluvial beds where the surface water disappears during the dry season. Such dug wells are widely found on the periphery of the Sahara. They are seldom more than 1 metre in depth and serve as temporary watering points still often used by nomads; they are usually short-lived, since any appreciable flooding will destroy them.

B. Traditional wells and drains

Traditional wells and drains (underground galleries connecting a series of wells) have been used chiefly in the arid countries of northern Africa under Arab or Turkish influence, including the oases of the Sahara, Libya and Nubia and some of the southern fringes of these desert areas.

The wells were sunk with simple digging tools, in soil which was fairly soft but with good bearing strength. In some cases the gallery walls or roofs were locally reinforced with timber or with masonry, dry-stone or lime-mortar shoring. Some of the wells, particularly near the arid mountain piedmonts, reach considerable depths, to 100 m or more in exceptional cases.

Drained wells are ancient enough to have been described in the Bible, and many of them are to be found in Iran, where they are known as qanats. The drained-well system is widespread in northern Africa, with galleries whose aggregate length runs to several thousand kilometres. In Egypt and the Sahara they are known as foggaras, while in Morocco they are called rhettaras. By this system it is possible to extract ground water from the soil without using mechanical devices. The galleries, which are tunnels cut into the sides of hills, penetrate the water-bearing strata for a certain distance and drain the water from them. The gallery has a gentle slope, less steep than that of the piezometric surface of the intersected strata and also less steep than the natural slope of the ground. As a result, the farther the tunnel goes into the hillside, the greater the depth of the wells sunk from above. Thus the length of galleries is limited by the greatest possible depth of the (uppermost) "mother well" as conditioned by the techniques used and the nature of the terrain.

Such drains can be constructed only in ground which is easy to excavate but has adequate supporting strength: lacustrine formations, soft sandstones, tuffs, consolidated alluvia, etc. The water-bearing strata must be relatively shallow and the ground surface must slope enough for the galleries to have an open-air outlet but not so much as to make the mother well unreasonably deep. Foggaras are found in the beds of some wadis and the areas near them - in the intermediate or adjacent beds (the beds inundated during periods of moderate flooding), on the flanks of gently sloping valleys and at the base of alluvial fans in the piedmonts. Some drains traverse rock formations to reach reservoirs which are blocked in their downstream course by these natural obstacles.

The construction, clearing and maintenance of these drains is difficult and dangerous work, which in the past was frequently done by slaves under the direction of master well-diggers. Such work is very expensive to do today, and lack of maintenance is causing many drains to deteriorate and collapse. Owners and users have found that it is almost always more economical to install small motor-driven pumps at certain producing wells in a drain system. This arrangement also makes it possible to economize on water by withdrawing only as much water as is needed; the drain itself, taking water from aquifers which are sometimes small and irregularly recharged, may cause permanent (and often needless) depletion which quickly leads to a complete drying up of the source.

The traditional methods of withdrawing water from wells vary with the region, the materials, the depth of the well and the use to which the water is put. Norias - scoop-type water wheels driven by animal power - are widely used with shallow irrigation wells. For deeper wells, a simpler method is often used: an animal (cow, camel) moves along an inclined plane and hauls up a goatskin of water by means of a rope-and-pulley system. Such an arrangement seldom brings up more than 10 to 20 m^3 of water per day.

Water from the deepest wells is brought up by hand, since such wells are used only to obtain drinking water for humans and animals. Wells with sweeps, originating in central Asia, have been widely used in the countries of the former Ottoman Empire. In the Nile valley, as in the Hungarian puszta, such wells are a traditional part of the landscape; they are common in the Sudan and have been introduced into Chad. They are also found in other African countries, extending as far west as Mauritania.

C. Drilled and dug wells of modern construction

In the deserts, oil exploration makes it necessary to find ground water by deep drilling. General geological surveys and geophysical studies for prospecting purposes have revealed the presence of confined water, which has subsequently been exploited by means of artesian wells. Where the quality of the water is satisfactory, it has been used for preparing drilling mud and for the water supply of work sites.

Before the African countries formerly under United Kingdom administration attained their independence, progress had been made in the exploitation of ground-water resources as a result of two factors arising during the second quarter of the twentieth century: the experience acquired in oil exploration in the Middle East and the expansion of the drilling-equipment industry in the United Kingdom and Sweden. In French-speaking Africa there was also a great expansion in water-drilling operations, especially with the start of active oil exploration in the Sahara, i.e. the 1950s.

Exploitation of ground water began first in the arid regions of northern Africa: the Maghreb, Egypt, the Sahara and northern Nigeria, where there are vast reservoirs of ground water. These sometimes have natural outlets in topographically depressed areas, such as chotts, in which the ground water is subject to direct evaporation; in other cases, these depressions provide a favourable area for artesian wells. As early as the late nineteenth century, artesian wells were sunk in the Tunisian chotts by means of large augers with radial arms pushed round by teams of workmen. Mention should also be made of the many artesian wells drilled during the 1940s and 1950s in the New Valley, i.e. the Kharga and Dakhla depressions of the Western Desert of Egypt.

In all the countries of the semi-arid or arid zone, many small wells were drilled in order to obtain water from shallow deposits to supply urban and rural administrative or economic centres, as well as modern farms. Such work was first carried on in the northern and southern parts of Africa, later extending to the more humid regions, and even to the equator, since humid countries, contrary to a widely held misconception, also need ground water to supply towns and villages.

There is relatively little water-drilling machinery in Africa today. Although no exact statistics are available, the total number of drilling rigs in 1970 may be estimated at about 1,000. 2/ Some of this machinery is owned by private companies,

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2/ This number does not include South Africa, where ground-water use has reached an exceptionally high level: 600,000 water wells have been drilled and 300,000 are productive at present.

either local or foreign, more specifically British, French, Swedish and Yugoslav; other machines, in increasing numbers, are owned by Government agencies: water development departments, directions de l'hydraulique and directions de l'equipement rural. In many cases, these governmental technical services were established and equipped with the help of bilateral or international technical co-operation organizations.

The drilled wells are not always equipped with mechanical pumping devices. Many different hand-operated or animal-driven pumps have been tested for use in rural areas. Some of these are particularly simple and sturdy, such as the model used in Uganda.

In addition to drilling, manual methods have been extensively used by Government services to sink wells in areas where holes could not be dug by the traditional means available to the local inhabitants (shovels, picks, small amounts of explosives). In areas with hard rocks, such as Palaeozoic sandstones and shales, the wells are sunk by means of compressed-air tools and explosive devices. Such excavations are very expensive, costing as much as $US 1,500-2,000 per metre.

In many African countries within the humid tropical zone, the surface terrain is the product of the decomposition of a crystalline substratum which frequently consists of granite gneiss; the ground usually includes strata of very loose clays which also preclude the digging of wells by hand, since the walls crumble even before the well-diggers have reached the aquifer levels that lie below the clays. In such terrain, a suitable casing must be inserted as the well is dug; this operation is always delicate and sometimes inordinately expensive or difficult, making it necessary to resort to drilled wells.

Well-digging is also very difficult in areas with sand-and-clay sediments, where a prefabricated reinforced-concrete casing must always be used.

The installation of mechanical pumping equipment is justifiable only where water needs are large and where due consideration has been given to the economic and social factors, to the chemical quality of the water and to the pumping head. Furthermore, the communities or authorities concerned must have the necessary technical and financial means to maintain or repair the equipment.

D. Ground water and the water supply of large cities

A great many African cities grew out of the trading posts established along the coasts, which seldom had abundant near-by sources of surface water. A glance at a map of Africa shows that in most coastal States and territories (about 35, not including small islands) the capitals and major cities (those with more than 100,000 inhabitants), comprising some 60 cities in all, are on or very near the seacoast. Exceptions to this rule include Fez, Marrakech, Constantine, Cairo, Khartoum, Addis Ababa, Nairobi, Tananarive, Pretoria, Johannesburg, Windhoek, Yaoundé, Ibadan, Brazzaville and Kinshasa. However, while more than half of these 15 cities are old population centres built along very large or important rivers, the others are recently created and not situated near such rivers; the same is true of most of the 45 capitals and large cities that lie on the coast.

In the land-locked States and territories (14 if the Democratic Republic of the Congo is included), the capitals and large cities are situated on rivers or on the shores of large lakes; however, Lubumbashi, Kigali, Lusaka, Salisbury and Mbabane, all recently established cities, are exceptions to this rule.

In short, most of Africa's capitals and modern cities are wholly or partly dependent on ground water. This explains why the earliest ground-water explorations were concerned primarily with coastal areas including the major cities and capitals, and sometimes with some very specific inland areas. For a long time, no hydrogeological surveys were conducted outside the coastal areas. This is still true in some countries, such as Gabon. At Dakar there has been considerable development in ground-water exploration and studies, and the hinterland as a whole has also been investigated. Hydrogeological prospecting now covers almost all of Senegal.

In some cases it may happen that the ground-water sources locally available are considered inadequate for the water supply of cities. It then becomes necessary to resort to surface waters, and since these are not in the immediate vicinity of the cities, their development requires expensive installations: dams, aqueducts (sometimes covering great distances) and sophisticated purification facilities. This is the case at Monrovia. A last resort is the construction of plants to desalinate sea water (or brackish water), as in the case of Nouakchott. Obviously, such extreme solutions should be envisaged only when hydrogeological surveys have shown that no ground-water reserves of adequate quantity and quality are available within a reasonable distance. The necessary investment is very high, and the operation and maintenance of the installations is very expensive; the total cost often represents a heavy financial burden for certain countries.

E. Ground water and economic and social development

Ground water has a growing role to play in the economic and social development of Africa, for it is a basic ingredient of that development in every field, and in particular in the field of mining. On-site ore concentration is carried out in most cases by washing. This operation usually determines the profitability of the mining venture; thus, as in the case of oil, it is always desirable to combine mining exploration and ground-water exploration. A typical example is described below.

A considerable portion of Africa's mineral wealth is situated stratigraphically in Terminal Pre-Cambrian (Infra-Cambrian or Lower Cambrian) formations. This geological period saw in many parts of Africa the deposition of marine sediments, sometimes of great thickness, including horizons of carbonate rock which are sometimes the only substantial aquifers in the entire geological complex. These horizons are particularly well-developed in Morocco's Anti-Atlas mountains, in South Africa and in Katanga; they also occur in western Africa. Thus, in the Upper Volta, a manganese ore exploration project conducted by the United Nations under the United Nations Development Programme (UNDP) included prospecting for ground water in Infra-Cambrian limestones.

Ground water also serves to meet the need for industrial water supplies, particularly for the suburban and industrial areas of large cities that have no surface-water resources, such as Dakar, for some public works (road and airport construction) and for tourism, particularly in arid and semi-arid regions and in coastal areas.

Where the requirements of public health, sanitation and welfare are to be met economically, ground water has to be used in most cases. In many population centres of tropical Africa and the periphery of the Sahara, the water taken from ponds, which are often fouled with animal excreta, provides an environment conducive to the development of pathogenic agents of such water-borne diseases as bilharziasis and various types of amoebiasis. It has been recognized that in some areas, reservoirs created behind dams may lead to the development of onchocercosis. For this reason, many agencies engaged in bilateral and international technical co-operation have supported the substantial efforts being made by African Governments to provide all population centres with wells to supply potable water. Moreover, in many cases the provision of an adequate water supply also helps to improve the social situation. To cite two particularly striking examples, the establishment of watering points enables nomads to settle at centres where their children may attend school, and the improvement of the water supply in some areas makes it possible to stem the exodus from countryside to city.

It is often impossible to water livestock, particularly during the dry season, unless ground water is used. In large regions of Africa, particularly in the belt of dry savannas extending south of the Sahara and spreading out towards the east in the Dakar-Khartoum-Cape Guardafui-Nairobi quadrilateral (excluding the Ethiopian mountain massif), stock-raising is the only resource of the semi-nomad or nomad populations. In some areas the establishment of watering points is indispensable for this activity, particularly during movement to new pastures. However, the establishment of new watering points is not desirable everywhere, since it may lead to overgrazing and to depletion of reserves that could help to restore pasture vegetation through the mechanism of seed dispersal by wind.

The development of irrigated agriculture through the use of ground water is possible in areas where the underground reservoirs are extensive enough and have adequate replenishment. The yield obtainable from each well must also be large enough, and therefore the ground water must circulate freely enough in the ground when pumping is applied. These conditions are present in the North African plains and valleys of alluvial or lacustrine origin, the lower Nile valley and the Nile delta, and the Sahara and its periphery, where the vast continuous aquifer strata in the Nubian Sandstones, the "Continental intercalaire" and the "Continental terminal" can be reached by artesian and non-artesian wells.

Irrigation involving the pumping of ground water requires between one-tenth and one-fifth as much investment per unit of irrigated surface as irrigation using impounding dams. Furthermore, the former method enables the water and land resources to be developed immediately and progressively. It is not surprising, therefore, that ground-water irrigation may be regarded as the key to the rapid industrial development of certain areas. However, the tempting prospects offered by this type of irrigation are not without their limitations and shortcomings.

The limitations are due to natural and economic factors. For large-scale long-term irrigation the underground reservoirs must be extensive and must be rechargeable by infiltrating rain and run-off. Many coastal areas, where the ground-water reservoirs are poorly recharged and over-exploited and have been contaminated by incursions of sea water or brackish water (Casablanca area) or are threatened with such contamination (Lomé area), do not meet these requirements.

Similarly, the requirements are not met by the reservoirs in the deserts of northern Africa. The yields of artesian wells in these areas tend to fall off, and the recharging of the reservoirs, often described as "fossil reservoirs", is uncertain. Moreover, the locations most favourable for tapping the reservoirs are not always well placed for agricultural use.

Conditions are even more unfavourable in all those areas which have a crystalline or metamorphic basement and have their Palaeozoic fringes covered with fine-grained schists and sandstones. In these very extensive areas, which are predominant in tropical Africa, the ground-water resources are limited and must be reserved primarily for human use and in some cases for livestock watering.

In some coastal areas, short-sighted development of irrigated agriculture may even dry up the ground-water resources available for the towns, making it necessary to resort to desalination of sea water for urban water supplies. Since desalination plants are very expensive and must furthermore be bought with foreign currency, it is unlikely that the increase in agricultural production would suffice to cover their cost.

Limitations of an economic nature arise from the cost of the ground water, whose development often requires the importation of piping, strainers, pumps, motors and even fuel. The cost of ground water is affected by three kinds of factors: the cost of locally available energy (fuel, electricity); the pumping lift, i.e. at least the depth below ground level of the pumped water, plus several metres; and, lastly, the distance from the well-head to the point of utilization; if this distance is big, it becomes necessary either to construct expensive conduits or to use earth-walled ditches and accept a considerable loss through infiltration or evaporation as the water moves towards its destination.

Generally speaking, the cost of irrigation water represents only a small fraction of the cost price of agricultural production; unirrigated crops tend to be only marginally profitable. A cost price of two to three cents (U.S.) per cubic metre for water may be considered very high. In Israel, where agriculture is heavily subsidized by the State for reasons of general policy and where the lack of water resources poses very severe problems, it is recognized that farmers cannot pay more than 6 cents per cubic metre for irrigation water, even though its cost is sometimes actually higher. It must be pointed out that in many African countries agriculture represents most, or almost all, of the gross national product, so that it cannot be subsidized, and hence the need to keep farm production profitable is even greater than in industrial countries. The market value of crops grown under irrigation, especially export crops (taking into account in some cases the price-support measures applied in certain markets), should, therefore, always be compared with the crop's cost price in any plan to develop irrigation with pumped ground water.

In many cases it appears that ground-water irrigation can be used as a stopgap measure during dry spells, especially in semi-arid areas, in order to maintain perennial crops. In desert areas, where evapo-transpiration is very high throughout the year, irrigation is almost impossible except in very unusual cases, as when gardens are planted near remote work sites or administrative posts in order to avoid the expense of bringing in fruit and vegetables by air.

F. Conclusion

The rapid progress being made in the use of ground water in Africa parallels the continent's rapid entry into the modern world. While affecting all sectors of the economy, it first involved the towns, the mining centres and certain favourably located agricultural areas. The present trend is towards ground-water development at small centres in the most isolated tropical and desert areas. Considerable work is being done in this direction both by Governments and by international and bilateral technical co-operation agencies. The reason for the rapid advance in ground-water use is that it is almost always a basic prerequisite of economic and social development, representing the essential factor in the life, or the survival, of many existing population centres and the prime requisite for the establishment of new ones.

It would therefore be a matter of great significance for the continent's development to assemble the following statistical information:

Ground-water resources available for the water supply of towns and industrial areas that have no access to large surface-water resources. The ground-water resources, both potential and exploitable, should be compared with the estimated requirements;

Inventory of water requirements and available water resources in villages. Such an inventory is already well advanced in many countries, particularly in western Africa. In some cases precise maps have been prepared, as was done in Togo as a part of the United Nations ground-water exploration project;

Location of areas where wells should be drilled to obtain water for livestock, with account taken both of requirements and of the need to protect certain pasture-land; and

Inventory of areas in which irrigation using ground water is feasible and economically efficient.

In addition, a study of the cost of African ground water for irrigation and its impact on the profitability of agricultural crops for internal consumption and for export should be undertaken without delay on the basis of data now available on agricultural production.

PART I

OVERVIEW OF AFRICA'S GROUND-WATER RESOURCES

I. PROSPECTING FOR GROUND WATER IN AFRICA

A. Historical outline

As in other continents, ground-water exploration in Africa, particularly in the arid northern regions, was very often conducted on a hit-or-miss basis. It still happens today that wells are dug in places where there is virtually no chance of finding a water-bearing layer at a normally accessible depth. Over the course of time, knowledge of the favourable areas is transmitted by tradition, while unproductive wells are filled in; this is why some areas have a very high density of wells, whereas others have no wells at all. The difficulty of finding adequate supplies of ground water has lent considerable prestige to the art of the water-dowser. The frequently irrational nature of traditional exploration methods should not obscure the well-diggers' understanding of local conditions, nor their perseverance and skill, which has helped them to achieve some astonishing results, such as hand-dug wells reaching down to a depth of 100 m in the arid zones of northern Africa.

Except for these regions, most of the continent consists of flat and humid land, with bodies of surface water scattered about, particularly in the form of ponds during the dry season. The peoples of these areas have always felt that their water problems would be solved by the coming of the rains. For this reason, invocations for rainfall have an important place in many African civilizations.

Since water is regarded as a gift from heaven - and a relatively generous one - it is not surprising that little effort has been made to search for water under ground, except in the alluvium of stream beds when the streams dry up during the dry season.

At the beginning of the colonial period, modern wells were sunk by military engineers and by the administrative authorities and especially their public works agencies. Frequently, for political, strategic, logistic or climatic reasons, military and administrative posts were established some distance away from populated areas, and hence from areas with readily accessible water.

As these posts subsequently turned into markets, rural centres, urban centres or large cities, water problems became progressively more acute. Public works engineers and geologists were called in to solve ground-water problems. In English-speaking Africa, water supply engineers, with a remarkable sense of the terrain, sank a large number of wells, many of which proved to be productive.

Before the Second World War, water-drilling on a regional scale was almost non-existent in Africa except for the southern part of the continent. Elsewhere water-drilling was of importance primarily to a number of towns and mining installations. In many places, however, engineers and geologists gradually began to specialize in the study of ground water, conducting hydrogeological explorations, surveys of underground reservoirs and chemical analyses of the water.

Interest increased greatly after the Second World War as a result of the refinement of existing techniques and the development of completely new ones. Systematic use of aerial photography made possible the rapid preparation of topographical and geological maps and the photographic localization of areas favourable for exploration, and furnished some geomorphological interpretations which were helpful in building up knowledge of ground waters.

Europe's demand for hydrocarbons at the end of the War set off a great surge of oil exploration in Africa, both in the sedimentary basins of the north and in the coastal basins. In the arid regions the search for ground water was a prerequisite for the drilling of oil wells, often involving very deep drilling, as, for example, in the Sahara. Great advances were made in this way towards an understanding of ground water in the desert areas. In some cases, spectacular artesian wells were drilled, and the water was, in a sense, a by-product of oil. In French-speaking countries, oil exploration brought an increase in drilling ventures, which extended their activities to water drilling, a field that had been very limited in the 1930s.

Similarly, geophysical prospecting methods made great advances both in technical improvements and in geographical coverage; their application in local or regional ground-water investigations became the general rule in the 1950s.

Modern quantitative methods of underground hydrology came into use in Africa only at a relatively recent date. Large-yield pumping tests were interpreted by the Theis and Jacob methods for the first time in Morocco in 1954. The study of artesian reservoirs by quantitative methods, as in the New Valley in the United Arab Republic, began at about the same time. These methods made it possible to determine both the capacity of underground reservoirs and their short-term and long-term yields.

The improvement of water-analysis methods, including flame spectrophotometry and atomic absorption, did not have any great impact in Africa because the equipment needed is expensive and requires highly skilled handling and maintenance; such equipment is found only in a few large cities, whereas specimens are taken hundreds or thousands of kilometres away and often require prompt on-site analysis. Some advances in the use of radio-active isotopes in underground hydrology were made during the 1960s, in the United Arab Republic and in the Niger, and progress is still continuing. The use of analogue and mathematical models is only just beginning, as in the United Arab Republic; in this connexion we may mention the UNDP (Special Fund) Projects in Algeria, in Morocco and Tunisia, in Senegal and in the Chad basin.

The various methods used in Africa for ground-water prospecting will be described very briefly below and illustrated with a few examples. The chapter ends with some considerations on the technical and economic efficiency of these methods with special reference to the African continent.

B. Hydrogeological reconnaissance

The geological map forms the basis for any hydrogeological reconnaissance. Many geological maps have been prepared for Africa, but in some cases the scale or the accuracy is not adequate for local or regional surveys. For this reason, hydrogeologists have often had to prepare geological maps before any operations were undertaken. In particular, this was the case in many local studies on urban water supplies which required large-scale mappings, as, for example, at Dakar and Lusaka.

When a geological map and basic geological surveys are available for a country, the hydrogeologist's geological reconnaissance work consists of identifying the horizons, areas or structures favourable for the storage of ample supplies of good-quality ground water, including in particular those capable of collecting infiltration waters from rain or run-off and especially those suitable for tapping by productive wells or other means. The last-mentioned task is very important and very difficult, since the nature of the problem varies widely from case to case. For example, in a crystalline-basement area the search for tapping areas is guided by the presence of fracture zones, dikes, sills and inclusions in a geomorphologically favourable setting; aerial photography has been widely used for this purpose in both western and eastern Africa. In sedimentary areas, where the clay and sand cover is thick and has a complex structure, reconnaissance consists chiefly in the identification of reservoirs in sand beds or lenses by means of hand-operated augers; this is the case in the Chad basin. In karst areas the morphology is an essential factor.

Apart from strictly geological observations, some related observations may prove very useful and in fact must be made by hydrogeologists in almost every case. These relate, in particular, to vegetation, soil and geomorphology. The nature, condition and distribution of the vegetation, clearly visible in aerial photographs, sometimes give a vivid indication of the depth, abundance and quality (salinity) of ground water. Thus, in the depressed and arid regions of northern Africa the presence of salsolaceous plants is associated with the occurrence of a shallow reservoir of salt water, while patches of fruze and reeds indicate that there is fresh water near the surface. A greater density of vegetation may indicate the existence of a fossil bed containing significant amounts of ground water. In tropical areas with a crystalline basement overlain by a weathered zone, the distribution of trees is often directly related to the thickness of this zone and to the thickness of the permeable horizons in it.

The permeability of soils depends on certain of the soil's characteristics, chiefly the texture and structure.

The type and characteristics of relief forms may reveal much about the occurrence of underground water, particularly in crystalline-basement areas; the shape of crystalline outcrops gives an idea of the thickness, structure and lithology of the weathered zone, and hence an idea of its aquifer potential. More generally, it gives an indication of the composition of the alluvial zones which play so big a part in the filling and recharge of aquifers. Lastly, a study of surface gradients also gives information on the infiltration potential, which is practically negligible in arid regions if the slope is steeper than 5 to 10 degrees, or in any climate if the slope is steeper than 20 degrees.

In the course of a reconnaissance operation an initial partial inventory is made of the most important water points: springs, permanent or seasonal ponds, water courses and, where appropriate, water wells, drains and bore-holes. Some types of data, such as the depth of the piezometric level in relation to ground level, the yield of springs and the chemical composition of the water, as well as the fluctuations in some of these values, provide essential information on ground-water resources and on aquifer discharge and recharge. Resistivity measurements and field analyses of the chemical composition of the terrain, particularly the silver nitrate test for chloride content, which are in general use in the semi-arid and arid regions of north-western Africa, are a very useful part of these preliminary operations. The measurement of water resistivity by means of portable resistimeters is an easy, cheap and rapid means of obtaining information on the permeability of the aquifers (saline water signifying very slow circulation), on the origin of the water, on the extent of the salt-water reservoirs and on the identification of the origin of mineralized waters. However, the interpretation of the data is difficult and may give rise to controversy.

All of the information thus gathered is sometimes entered on hydrogeological maps known as "reconnaissance maps" or "guidance maps for future ground-water exploration": the aquifers are shown in outline and marked by hachures or colours which indicate the nature and magnitude of the porosity. The maps may show major springs and existing bore-holes, as well as isopiestic lines in cases where the depth of the water in the wells has been measured and the ground elevation is known with sufficient accuracy from maps or by barometric levelling. Some hydrochemical data may be entered, and proposals for future operations may be indicated.

The following table gives a list of small-scale hydrogeological reconnaissance maps of African regions:

Year of publication	Country	Region	Scale
1950 and 1957	Madagascar	South-west	1:500,000
1961	Ghana		1:1,000,000
1962	Senegal	Northern part of the Ferlo desert	1:500,000
1962	Mauritania	South-west	1:500,000
1964	Libya		1:1,000,000
1964	Niger	South-west	1:1,000,000
1964	Ivory Coast		1:1,000,000
1964-1968	Chad		1:500,000
1965	Senegal		1:500,000
1965	Niger	South-west	1:1,000,000

The maps listed above were published by the technical services of the countries concerned. A map of the metamorphic and crystalline formations of western Africa on a scale of 1:2,000,000 was published in 1967 by the Inter-African Committee for Hydraulic Studies. Other maps (unpublished) are kept in the files of the technical services of various African countries.

C. Inventory of water resources

The inventorying of water resources, a never-ending operation, first became widespread in the Maghreb and the countries of French-speaking Africa and was subsequently introduced into other African countries. It consists of recording all known water points on index-cards and maps. Each water point is indicated by a number and an index symbol, the latter corresponding to a sheet of the map coverage at 1:500,000, 1:200,000, 1:100,000 or 1:50,000. In the case of the 1:200,000 map of western Africa, each sheet corresponds to one square degree of the international geographical co-ordinates.

The water points recorded may be springs, ponds and marigots, watercourses, temporary pools, lakes, wells, piezometric bore-holes, test or exploitation bore-holes, drains, seeps or reservoirs created by dams. A sketch on the index-card shows the position of the water point, together with its designation, name and co-ordinates; also indicated are the depth of the well and of the water, the yield, the chemical and physical characteristics (temperature and resistivity) of the water, the nature and characteristics of the aquifers, the results of pumping tests or flow tests, a description of the existing or planned water installations and the quantity of water extracted. In addition, bore-hole index-cards include a sketch and a geological log of the formations.

Certain special types of index-cards have been designed for population centres. Cards for towns include a brief description of the installations and data on water consumption. Cards for villages indicate the number of water points serving the village, the quantities of water extracted and the village's present and future needs, and give data on the potability of the water.

A large number of water points have been inventoried in this way in northern and western Africa. Thus, in the Niger, 7,000 out of an estimated total of 20,000 water points had been registered by 1964. By 1966, 3,000 water points had been registered in Mauritania, 25,000 in Morocco and 2,500 in northern Cameroon. In the Upper Volta, index-cards had been prepared for 1,500 villages out of a total of 5,000 by 1969.

The large amount of data assembled in this manner makes it possible to deal with certain problems by means of computers. In many cases the index-cards are made of transparent paper or film for ease of correction and reproduction.

Ground-water projects carried out by the United Nations in Africa have among their objectives the organization, reorganization or continuation of such inventories. In a project in Togo, for example, 1,700 villages and 2,262 water points have been inventoried, including 1,447 water points in the coastal sedimentary basin. Similarly, the project carried out in Mali has as one of its objectives the reorganization and completion of the inventory of existing water points, particularly for areas near the frontier between Mauritania and the Upper Volta, which would make it possible to conduct investigations on an international basis.

In English-speaking African countries the inventory of drilled wells is often done on a chronological basis, in the form of drilling registers. In some cases there is a lack of geological information, and it is sometimes difficult to locate previously drilled holes in the field; that was the case when attempts were made to trace some 300 pre-existing bore-holes in the Karamoja district (Uganda) during the initial phase of the ground-water project carried out by the United Nations in 1966.

D. Geophysical prospecting

Geophysical prospecting for ground water in Africa is carried on by several different methods and techniques, which are outlined, with examples, below.

Electrical resistivity sounding

This is the most widely used method. A four-electrode system (two electrodes connected to a direct-current source and two potential electrodes) is used for measuring resistivity, a physical characteristic closely related to the geological facies of a formation. The quantity measures is the "apparent" resistivity, which often includes several horizons of different resistivities.

The spacing of the electrodes can be varied depending on the depth that is to be reached. The arrangement of the electrodes varies with the method, the Schlumberger method being used in French-speaking Africa and the Wenner method in English-speaking Africa. Interpretation of the curves can identify as many as three horizons, one above the other, each having a different resistivity. Contrast is much more readily detected if the measurements are confined to shallow layers. The depth may be as great as several thousand metres, but better results are obtained at lesser depths (from 100 to 200 m). Whenever possible, the results should be compared with control data obtained by mechanical drilling of the tested layers; it is also important to measure the true resistivities of the layers by testing outcrops. Some examples are the following:

Algeria: Study of the Chéliff valley, the Mitidja plain and the High Plateaux.

Morocco: Structural study of the substratum of the Atlantic plains (Gharb, Saïs, Doukkala, Sous).

Mauritania and Senegal: Structural study of the sedimentary basin. The map of apparent resistivities gives an idea of the depth of the impermeable substratum (Infra-Maestrichtian clays overlying the basement).

Mali: Study of the subsidence troughs of the Nigerian basin and the "Sudanese Strait".

Chad: Studies in the sedimentary basin: identification of sandy layers with a view to drilling for urban and stock-watering supplies.

Senegal: Detailed structural studies in the Cap Vert area, e.g. Sébikotane-Pout, with a view to determining ground-water resources to supply Dakar.

United Arab Republic: Upper Nile - study of the aquifer potential of the Nubian Sandstones and the contact between the recent surface formations and the Pliocene clays.

Northern Cameroon: Study of "dry wedges", narrow bands of sedimentary rocks containing no ground water, bordering an area of basement-formation outcrops. By electrical resistivity sounding it can be determined whether or not the formations are saturated with water.

Togo, Senegal and Ivory Coast: Study of sea-water invasion of aquifers in the coastal sedimentary basins.

Niger and Uganda: Studies of alluvial aquifers.

Mauritania, Upper Volta, Ghana, Ivory Coast, Togo, Dahomey, Chad, Kenya, Uganda, Malawi and South Africa: Studies on the thickness and aquifer potential of the weathered zone overlying the granite-gneissic crystalline basement and on sill and dike zones (quartz, pegmatites, differential zones).

Mauritania: Delimitation of the Bennichab fresh-water lens, surrounded by saline or gypseous terrain.

Zambia, Botswana and Nigeria: Local studies (pastoral watering points).

Electrical logging

Electrical logging consists of moving one or more electrodes vertically within a bore-hole to record spontaneous potentials (SP) and resistivities. These two types of diagrams are interpreted simultaneously, making it possible to delineate boundaries of each lithologic unit. Good permeability is often manifested in high values of SP; fresh water is indicated by high resistivity values. Electrical logging is used chiefly in alluvium and sedimentary formations. In igneous and metamorphic formations, investigators use natural gamma radiation logging and neutron logging, the two often being combined in a single probe.

Electrical logging has been widely used in regional and local investigations in most African countries, particularly in English-speaking Africa. Among the most recent projects, mention should be made of the Northern Cameroon study of Chad basin sediments involving electrical logging in bore-holes of an average depth of 500 m (1967-1968). The method is particularly suitable for studying a large number of bore-holes grouped in the same area.

Other electrical methods

Two electrical methods used much less often than those described above are:

(a) Measurement of the difference of surface potentials. This involves the phenomenon of electrofiltration, used in particular for the granitic sands of the Ivory Coast;

(b) Electromagnetism. This method, using low-frequency alternating current, is often employed by Scandinavian firms. The procedure consists of setting up an alternating primary magnetic field and measuring the effects of the induced secondary magnetic field; it is used for identifying fault planes and doleritic dikes in South Africa. The electromagnetic method has sometimes been used in airborne prospecting in the Sahara region, e.g. in Mauritania.

Seismic methods

Seismic methods involve observing the propagation of elastic waves caused by a seism produced at a given point by means of percussion or explosion.

There are two types of seismic prospecting, using either reflection or refraction of the shock waves. The refraction method is far more often used in hydrology for studying shallow and relatively undifferentiated aquifers, such as limestones and saturated alluvia, whose resistivity values are close to each other and cannot be differentiated by electrical prospecting techniques.

The seismic and electrical methods are often combined, particularly in areas with a crystalline basement overlain by a relatively thick weathered zone. In such circumstances the seismic method often yields better results than the electrical method. The seismic method is also used for detecting hard-rock structures under fill formations. Some examples of combined electrical and seismic prospecting are the following:

Mauritania: The water supply of Nouadhibou.

United Republic of Tanzania: Establishment of rural water points.

Northern Cameroon: Estimation of the depth of the crystalline basement in the "flats" region.

Ivory Coast, Mauritania and Chad (Ouddaï): Creation of water points in crystalline-basement areas.

Dahomey: Studies aimed at finding correlations between wave-propagation velocity and permeability, with a view to identifying deep structures.

Guinea: Study of aquifers for the water supply of Conakry.

Among the United Nations ground-water projects using these methods, we may mention the Togo, Upper Volta, Uganda and Dahomey projects in crystalline areas, and the Madagascar (west coast) project in a sedimentary area. Future operations will be conducted in Mauritania and Mali.

Combined operations in the Upper Volta and in Uganda have shown that seismic prospecting yields the best results in assessing the total thickness of weathered zones overlying the crystalline basement. However, the largest water yields are not always obtained from the thickest zones.

Electrical prospecting requires a team of two technicians, one engineer and one operator, working at a rate of 75 stations per month; if it is combined with the seismic method, an additional operator is needed.

Other geophysical methods

The gravimetric method consists of measuring the variation of density with depth, which is manifested in the "Bouguer anomaly" - the difference between the true (measured) value and the theoretical value of gravitational acceleration at a given point. This method has been used for general surveys of Africa's great sedimentary basins, sometimes by airborne prospecting; it provides only very small-scale data of a very general nature. The magnetic method, which involves measuring the magnetism induced in certain bodies by the earth's magnetic field, and hence measuring the anomalies of the earth's field, is seldom used in prospecting for ground water. Nevertheless, it sometimes serves to determine the morphology of a crystalline substratum overlain by a sedimentary basin, and sometimes to determine its major tectonic features.

The magnetic and gravimetric methods have been used in Africa a number of times, sometimes in combination. Some examples are the following:

Mali: Study of the "Sudanese Strait" trough.

South Africa: Study of the Ecca dolerites.

Saharan regions: Study of the Crystalline basement complex and the thickness of its sedimentary cover.

Chad basin: Gravimetric map on a scale of 1:1,000,000.

Kenya (Rift Valley): Magnetic study of the faults at Thomson's Falls.

United Arab Republic (New Valley region, Western Desert): Study of the Nubian Sandstones.

E. Drilling

Mechanical drilling is the most direct method of investigation. Three types of bore-holes are generally considered: reconnaissance, test and exploitation bore-holes.

Geological reconnaissance bore-holes are, as a rule, of small diameter and designed to investigate certain specific horizons. They are generally drilled with the aid of drilling mud; electrical logging is used to identify the permeable horizons. Some of these bore-holes may reach great depths, as much as 500 or even 1,000 m. If the bore-hole penetrates an aquifer, it can be used as a piezometer for measuring the depth below ground of the piezometric level, for various purposes such as studying the natural fluctuations in the level of an aquifer, fluctuations due to pumping and fluctuations of pressure in an artesian reservoir, etc.

Most piezometric bore-holes are fitted with a two-inch pipe 3/ slotted at the level of the aquifer layers. Some of them are equipped with recording limnigraphs. The water level is often measured by means of an electrical probe; when the probe comes into contact with water, a battery sets up a current between two electrodes, which is measured by a galvanometer.

In test bore-holes the pipe diameter is large enough (4 to 10 inches) to allow the installation of a mechanical or electrical pump for pumping tests at flow rates of as much as 20 to 30 litres per second.

The exploitation bore-hole is actually a mechanically drilled well whose diameter may reach 24 to 40 inches. It is drilled down to (and not beyond) an optimum depth determined by a technico-economic study.

3/ The diameters of casings, and sometimes those of the bore-holes, are given in inches, in accordance with the practice followed by drilling crews and enterprises in most countries. The inch (equal to 25.4 mm), the standard unit of length in English-speaking countries, is commonly used in drilling work even in countries which normally use the metric system.

As a general rule, test bore-holes (or pre-exploitation bore-holes) with a diameter of 6 to 8 inches are the kind most frequently used in Africa, both in the past and today.

There are two principal methods of drilling: 4/ cable tool (percussion) drilling and rotary drilling, using either mud or clear water.

Each of these two methods has its advantages and disadvantages, which make one preferable to the other in specific cases. Combination rigs can use the two methods together, but they are not common in Africa, as they are expensive and require skilled operation and maintenance. The characteristics of these two methods are given below:

Cable tool (percussion) drilling	Rotary drilling
Water needs are minimal.	May require large quantities of water, especially if clear water is used.
Slow drilling because the bit moves slowly and often casing must be driven to prevent caving, and the rock chips must be bailed out of the hole.	Fast drilling, but with risk of wedging the bit and the rods, and risk of clogging the aquifers with drilling mud.
Easy to test the aquifers separately.	Difficult to isolate the aquifers for separate tests.
Can be used for large-diameter drilling (more than 20 inches). Not practical for small-diameter drilling.	Cannot be used for large-diameter drilling.
Cannot, in general, be used for reaching depths of more than 100 m.	Can be used for reaching great depths.
Can operate in any type of terrain. Particularly suitable for hard rocks: shales, flints, limestones, dolomites, hard sandstones (especially in outcrop formations) and fractured, karstic and permeable rocks.	Can be used in any kind of terrain, but the best results are obtained in fine-grained sedimentary formations (sandstones, marls, clays). Drilling is easy in metamorphic and volcanic rocks; however, flint nodules wear out the bit. Blocks and hard boulders are difficult to drill, with violent shocks that may damage the rods and even the rig itself. Drilling of fractured and karstic formations is unsatisfactory because the formations can absorb great quantities of drilling mud (or water). The start of a bore-hole in hard terrain is difficult.

4/ There are other methods, such as compressed-air or turbine rotary drilling and compressed-air down-the-hole hammer-percussion drilling, but these are much less frequently used.

Sturdy and unsophisticated equipment.	Operation and maintenance of the equipment requires highly skilled and specialized personnel.
Sturdy bits; worn cutting edges can be retipped.	Expensive bits, wearing out fast.

In general, the rotary method has been used in Africa mainly in sedimentary basins for investigating deep confined aquifers.

The cable-tool method is very often used in alluvial terrain, in areas with hard and fractured limestones, and in Pre-Cambrian basement regions, particularly in eastern Africa. Most of the rigs used in Africa (a total of 600 to 800 drilling rigs outside of South Africa) are manufactured in the United States, Canada, the United Kingdom, Sweden, the Union of Soviet Socialist Republics and the Federal Republic of Germany.

No water-drilling machinery is manufactured in Africa.

F. Pumping tests

The purpose of pumping tests is to determine the hydrological characteristics of aquifers, and hence the available short-term and long-term yields. If a test is to be usable in hydraulic calculations, the water level must be stabilized after a certain time, with the pumping yield being kept constant.

Pumping tests are made at progressively increasing yield values, each successive value being tried after about 12 to 36 hours of "development", i.e. preliminary pumping designed to force the fine particles out of the gravel-pack and the near-by formations. A pumping test should be conducted only after the bore-hole has begun to yield clear water. The duration of a pumping test is usually 24 to 72 hours, at an average cost of $20 per hour. In some cases, particularly when large yields are needed for urban water supplies or for irrigation, "long-term" pumping tests are undertaken. In 1954 a three-month pumping test, with a discharge of 500 litres per second, was carried out at the Haffaya, in southern Morocco, and in 1956 a pumping test lasting several months was run in Chott ech Chergui, Algeria.

In the case of artesian aquifers, soil pressure measurements serve as an equivalent of pumping-test data. Non-flowing artesian or low-yield artesian aquifers are tested by pumping, as in the New Valley, United Arab Republic.

The pumping yield depends on the type and size of pump used, as their capacity for example in the case of cylinder pumps, is limited by the inside diameter of the well casing and the dimensions of the pump cylinder. These implements fall into three categories. In reconnaissance bore-holes, pumps in the range of several inches are used; a 2-inch or 3-inch vertical pump can draw 1 litre per second, or even more, for a pumping head of about 50 m. Pumps used in test bore-holes average 8 inches and deliver 20 to 30 litres per second for the same head. Lastly, exploitation wells with very large diameters use a battery of pumps which may deliver as much as 500 litres per second or more.

In karst areas, and even more so in crystalline regions, pumping tests are unlikely to produce conclusive results concerning the hydrological parameters of the formations, and hence concerning the estimated magnitude and duration of the flow. It is not surprising, therefore, that regular pumping tests have been made chiefly in the sedimentary basins, essentially in the north of the continent, where the aquifers are porous, homogeneous and extensive (Saharan "Continental intercalaire", Nubian Sandstones).

Subsurface water calculations, which only a few years ago were the exclusive province of a small group of specialized hydraulic engineers, are now being carried out more and more often by hydrogeologists, who use the Theis and Jacob methods with simplified formulae, in such places as the coastal sedimentary basins and the alluvial valleys of the Maghreb, Libya, the United Arab Republic, western Africa and eastern Africa.

The most widely used method is one for calculating the transmissivity coefficient (T), based on the time it takes the water to return to its previous level after the pumps are stopped, since determination of the storage coefficient (S) would require drilling one or more satellite piezometer bore-holes, which are sometimes expensive and whose value has often been questioned. Pumping is always accompanied by monitoring of the piezometric levels and by tests of the quality (chiefly the salinity) of the water.

In rare instances, injection tests are substituted for pumping tests, with a view to determining the hydrological characteristics of the terrain under the least favourable conditions, particularly in experiments for the artificial recharge of aquifers.

G. Water analyses, tracers, nuclear techniques

Hydrochemical analyses serve not only to determine whether the water is suitable for use as drinking water for humans or animals or fit for agricultural or industrial use; they also provide information on the nature of the terrain and the rate of circulation and origin of the ground water (recharge zones and horizons). It is useful to supplement such analyses with resistivity and temperature measurements.

A great many "complete" water analyses have been conducted in Africa, especially in the Maghreb and in western Africa (10,000 analyses). A "complete" analysis includes a measurement of the total dissolved solids and of the ion content (Na, Ca, Mg, Cl, SO_4, CO_3). There are relatively few laboratories and it is difficult to transport water samples to them over long distances; for this reason, the composition of African waters is not yet comprehensively known.

Hydrochemical maps have been prepared for certain regions that have been studied in detail, such as the Maghreb, Libya, the United Arab Republic and western Africa.

Thermal and thermomineral springs are abundant in Africa, but information about them is still very fragmentary.

The use of tracers to ascertain the path and velocity of ground water has not advanced far in Africa. Some experiments using fluorescein or dissolved salts have been conducted in northern Africa, particularly in karstic limestone massifs and in alluvial zones.

Recent advances have demonstrated that isotopic and nuclear techniques can have many applications in the study of ground water. For example, soil moisture can be tested and measured by means of neutron or gamma-ray logs. The movement of water infiltrating into the zone of aeration can often be followed by using an isotopic tracer, such as tritium. The origin and distribution of water in the zone of saturation can be determined economically by studying stable isotopes such as deuterium (^{2}H) and oxygen 18 (^{18}O) or radio-active isotopes such as tritium (^{3}H) and carbon 14 (^{14}C). The characteristics of aquifers (porosity, transmissivity, dispersion of ground-water flow) and the direction and speed of underground flow in water bore-holes can be determined with the aid of radio-active tracers; water bore-holes may also be studied by means of stable isotopes.

Mention should also be made of the study of stratified aquifers by neutron and gamma-ray logging, the study of ground-water stratification in an aquifer as determined by isotope tests and dating studies using radio-active isotopes (tritium, carbon 14, silicon 32).

Lastly, studying the relationship between surface water and ground water by nuclear methods makes it possible to determine the modalities of the recharge of ground-water reservoirs, flow in fractured rocks and salt-water invasion of aquifers. Nuclear methods can also be used for determining water balances.

Artificial isotopes have been little used in Africa thus far; a few experimental studies have been carried out in the United Arab Republic.

Progress is being made, especially in arid regions, in the study of water by analysis of natural isotopes, both radio-active and non-radio-active, in order to determine their age and the recharge zones from the concentrations of various isotopes (deuterium, tritium, oxygen 18 and carbon 14). 5/ The Isotope Hydrology Section of the International Atomic Energy Agency is particularly active in this field: an initial study of this kind was carried out in 1966 in the eastern Niger, in the Zinder area (between the Aïr massif and Lake Chad); but it did not yield any fully conclusive answer to the question being investigated, namely, whether the aquifers were recharged to any substantial extent by current rainfall.

Other studies of this type are planned for Senegal, Morocco, Tunisia and Togo.

5/ Tritium and carbon 14 are radio-active, while deuterium and oxygen 18 are not.

H. Analogue models

The quantitative study of ground-water reservoirs by means of flow simulators and models has made considerable progress in recent years in the industrialized countries. Advances are also being made in Africa, chiefly with regard to the sedimentary basins of the arid and semi-arid zones of northern Africa.

The most widely used types of models are the following:

(a) Electrical models, in which water flow is represented by an electrical current in a conducting medium simulating the aquifer; water recharge and extraction areas are represented by electrodes. Regions studied since 1960 include the following:

Algeria:	Chott ech Chergui, Oued Biskra, Oued Marnia (alluvial aquifer), Albian aquifer in the northern Sahara.
United Arab Republic:	New Valley.
Tunisia:	Kairouan plain (control of Oued Nebhana).

(b) Mathematical models. The differential equation expressing the unsteady flow of water in a saturated porous medium is solved by approximate methods and applied to each unit of land, due regard being given to all the geological and hydrological data (recharge, discharge, fluctuations). The entire study is handled by computers the raw results are sometimes obtained in the form of a numerical array representing a map or a graph.

Among investigations using mathematical models, the following projects carried out by the United Nations Development Programme should be mentioned:

Algeria-Tunisia:	Study of deep aquifers in the Sahara.
Senegal:	Study of surface aquifers in the Dakar region.
Southern Tunisia:	Study conducted in 1964 on artesian aquifers (Médenine, Zarzis, Djerba).

I. Ground-water organizations

Ground-water prospecting in Africa is carried out most often by governmental agencies or by firms under contract to them. Much less often, surveys are conducted at the request of private firms, as in the exploration and exploitation of oil (Libya) or mineral deposits, in the provision of water supplies to certain towns by firms holding concessions (Abidjan) and in the pumping of water to irrigate modern farms. In most cases the operations relating to ground water require the importation of personnel, technology, equipment and capital from outside Africa. However, there is now a clear trend towards Africanization, and it is being encouraged by bilateral or international assistance agencies, which today are still predominant in African ground-water prospecting and exploitation.

Where ground-water prospecting is done on a systematic basis it is usually handled by a specialized governmental hydrology or ground-water service. Since ground-water problems come under both geology and water science, it is not surprising that this specialized service is attached to the geological service. Since ground-water problems come under both geology and water science, it is not surprising that this specialized service is attached to the geological survey in some cases and to the water resources department in others. The first type of service is likely to have a more scientific orientation, whereas the second tends to be more concerned with water management. The water resources department is, in turn, sometimes subordinate to the Ministry of Works, sometimes to the Ministry of Agriculture and sometimes to the Ministry of Economic Affairs and Planning, which may include a geology department.

In some countries, such as Madagascar and Ghana, the study of ground water is the responsibility of the government offices concerned with urban water supplies.

Regardless of the ministerial framework in which the ground-water service is placed, a number of conditions are essential for the proper functioning and effectiveness of the service. It should be individualized; in other words, everything relating to hydrogeology should be combined in a unit (subdivision, service, section, branch, division or centre) under the supervision of a hydrogeology expert. The service should have close ties with the Geological Survey so that it can readily obtain maps and basic data and draw on the experience of geologists; with the services responsible for the study of surface waters so as to have ready access to water and weather monitoring data; and with the services responsible for water drilling operations if such operations do not come directly under the ground-water service itself.

The personnel of a state ground-water service ideally includes hydrogeologists, hydrologists, hydraulic engineers and specialized technicians (specialists in inventories, pumping, etc.). The organization may have separate units for studies, inventory (maps and card-indexes), geophysics, a laboratory (hydrochemistry), a draughting and cartographic office and regional services. In some cases the service has its own drilling equipment, as in Tunisia and in eastern Africa. In other cases the service has a drilling operations unit which prepares and supervises work contracts let to outside firms. Besides African state services operating with their own facilities, many private firms (mostly European) are engaged in every kind of activity relating to ground-water prospecting and exploitation: general hydrogeological studies, analogue models, preparation of survey reports, geophysics, drilling and pumping.

These studies and operational projects are financed either directly by the Governments concerned or by bilateral or international assistance agencies through the use of grants or low-interest loans.

J. Bilateral and international assistance

Bilateral assistance

Bilateral assistance in the ground-water field has involved many countries under a variety of arrangements. The table below, which is necessarily incomplete, gives a general picture. The countries furnishing aid in the form of grants or loans are shown in alphabetical order; all of these countries normally offer fellowships to African university students and technicians.

Donor country	Recipient country	Type of assistance
Belgium	Democratic Republic of the Congo, Rwanda, Burundi	Experts; drilling equipment
Federal Republic of Germany	Niger	Hydrogeological cartography
Federal Republic of Germany	Sudan	Geophysics
France	Algeria, Tunisia, Morocco, Libya; the entire group of French-speaking African countries; Madagascar, Mauritius, Réunion, French Territory of the Afars and the Issas;	Experts, equipment, study contracts, hydrogeological and geophysical projects, drilling operations
Hungary	Guinea, Mali	Hydrogeological studies and supervision of drilling
Italy	Somalia	Experts
Portugal	African Territories under Portuguese administration a/	All operations relating to ground water
Spain	Spanish Sahara	Drilling operations
Sweden	Sudan	Drilling eqipment
Union of Soviet Socialist Republics	Algeria, Mali, Somalia, Ghana, Guinea, Sudan, United Republic of Tanzania, United Arab Republic	Water-drilling contracts, personnel, loan and/or sale of drilling equipment, studies
United Kingdom	Sierra Leone, Ghana, Nigeria, Libya, Sudan, Kenya, Uganda, United Republic of Tanzania, Zambia, Malawi, Lesotho, Botswana, Swaziland	Experts, equipment, study contracts
United States	Tunisia, Libya, United Arab Republic, Southern Rhodesia, Nigeria, Liberia, Sudan	Hydrogeological experts
United States	Ethiopia, Tunisia, Madagascar, Nigeria, Sudan	Drilling machinery

a/ Portugal constitutes a very special case, since the aid is not regarded as bilateral assistance either from the Portuguese or from the African point of view.

Moreover, as was mentioned above, private firms or state agencies of the donor countries are operating under contract in Africa in the fields of hydrogeology and geophysics are are engaged in drilling for water.

International assistance

International assistance is furnished through two main financing agencies:

(a) The European Development Fund (FED), which has provided financial support for work on hydrogeological and geophysical studies and the digging or drilling of wells, specifically in Burundi, Cameroon, the Central African Republic, Chad, Dahomey, Madagascar, Mali, Mauritania, the Niger, Rwanda, Senegal and the Upper Volta;

(b) The United Nations Development Programme (Special Fund), which has carried out pre-investment projects wholly or partly concerned with ground water, through various executing agencies (see the table below).

The total budget of these UNDP projects is of the order of $50 million, almost half of it furnished by the Special Fund, while the rest represents the contributions made in local currency or facilities by the African countries concerned. 6/

It should be pointed out that there exists in Africa an Inter-African Committee for Hydraulic Studies, which includes most of Africa's French-speaking and some of its English-speaking countries, either as participating members or as observers. The Committee meets once a year in Africa in order to exchange information on studies and projects relating to water, particularly ground water. Data collection, research and the dissemination of results are handled by a technical office at Ougadougou.

6/ In addition to pre-investment projects, UNDP has provided the services of experts for technical co-operation activities, but on a smaller scale.

Ground-water Projects in Africa sponsored by UNDP

Country and project number	Project	Duration	Executing agency	Ground-water component: exclusive or major	substantial (30-50 per cent of the project)	minor
Algeria ALG 9	Natural Resources Surveys, Agricultural Experimentation and Demonstration in the Hodna Region, Central Algeria	1966-73	FAO		X	
Botswana BOT 1	Surveys and Training for Development of Water Resources and Agricultural Production	1968-72	FAO		X	
Cameroon CAM 16	Ground-water Investigation and Pilot Development	1971-74	UN	X		
People's Republic of the Congo CON (B) 2	Survey of the Water Resources of the Niari Valley	completed in 1967	FAO		X	
Dahomey DAH 3	Pilot Development of Groundwater	1967-70	FAO	X		
Ghana GHA 27	Rural Water Supply and Environmental Health	1970	WHO		X	
Ivory Coast IVC 18	Water Supply and Sewerage for Abidjan	1970-71	WHO			X
Madagascar MAG 3	Surveys of the Mineral and Ground-water Resources of Southern Madagascar	1966-69	UN		X	
MAG 14	Agricultural Development of the Morondava Plain	1969-71	FAO			X
Mali MLI 7	Strengthening Government Services for Ground-water Exploration and Development	1968-71	UN	X		
Mauritania MAU 2	Strengthening of the Ground-water Service	1968-71	UN	X		
Mauritius MAR 6	Land and Water Resources Survey	1968-69	FAO			X
Morocco MOR 17	Hydro-Agricultural Development of the Souss Valley	1968-71	FAO		X	
Niger NER 8	Surveys for the Agricultural Development of the Dallol-Maouri	1967-70	FAO		X	
Senegal SEN 9	Establishment of a Master Plan for Water Supply and Sewerage for Dakar and Surrounding Areas	1968-71	WHO		X	
Somalia SOM 4	Mineral and Ground-water Survey, Phase I	completed in 1968	UN			
SOM 10	Water Control and Management of the Shebelli River	1967-70	FAO			X
SOM 14	Mineral and Ground-water Survey, Phase II	1968-71	UN		X	

Ground-water Projects in Africa sponsored by UNDP (continued)

Country and project number	Project	Duration	Executing agency	Ground-water component: exclusive or major	substantial (30-50 per cent of the project)	minor
Sudan SUD 4	Land and Water Use Survey of Kordofan Province	completed in 1966	FAO			X
SUD 25	Savanna Development	1970-?	FAO		X	
SUD 30	Agricultural Development in the Jebel Marra Area	1969-70	FAO			X
Togo TOG 4	Survey of Ground-water and Mineral Resources	1965-70	UN		X	
TOG 11	Ground-water Exploration in the Coastal Region	1971-73	UN	X		
Tunisia TUN 28	Intensification of Ground-water Exploitation in Northern and Central Tunisia	1969-72	UN	X		
Uganda UGA 5	Karamoja Ground-water Survey	completed in 1968	UN	X		
United Arab Republic UAR 49	Pre-Investment Survey of the Northwestern Coastal Region	1965-68	FAO			X
Upper Volta UPV 4	Mineral and ground-water survey	completed in 1968	UN		X	
UPV 10	Hydrological and Railway Studies in connexion with Mineral Development in the Northeast	1969-71	UN		X	
Africa (regional) REG 71	Study of water resources of the Chad Basin	completed in 1970	UNESCO FAO	X		
REG 100	Survey of Ground-water Resources in the Northern Sahara	1968-70	UNESCO	X		

K. Conclusion: general summary and trends

Ground-water prospecting has developed fairly recently in Africa, with a great upswing during the 1950s and early 1960s. This activity, requiring the importation of personnel, equipment and capital from outside Africa, is extremely expensive and was heavily subsidized in a number of countries by bilateral assistance. Bilateral assistance for this type of operation is on the wane, and international assistance, particularly United Nations assistance, is taking up the slack.

The number of working experts and operating rigs is relatively small. However, services specializing in ground-water prospecting, studies and development are being organized in most African countries. African engineers, technicians and specialized workers are being trained in increasing numbers in their own countries or abroad. In view of the high cost of contract drilling of bore-holes and wells, national Governments have established and are continually increasing their own drilling facilities, and national drilling companies have been set up, for example, in Mali and in Algeria.

The most up-to-date methods of ground-water surveying, particularly those using isotopic tracers and analyses and analogue models, as well as detailed hydrogeological mapping, have not yet developed very far in Africa.

The general approach to ground-water prospecting in the French-speaking countries has been strikingly different from the approach in the English-speaking countries.

In the latter countries, climatic conditions are often rather favourable, with generally abundant rainfall, particularly on the plateaux of eastern Africa. The existence of a highly developed drilling-equipment industry in the United Kingdom and the rather long-standing tradition of geophysical research have tended to focus the activities of the water services on direct field searches for promising well-sites. Very often, such sites have been located by a geologist using a geological map and light geophysical-reconnaissance equipment (resistivity instruments). A great many bore-holes have been drilled in this way, very often without leading to any regional survey. Exceptions to this general pattern are found in certain specific cases, such as the artesian basins of northern Nigeria and the limestone-dolomite massifs of South Africa, in which intensive ground-water surveys have been conducted with a view to estimating balances, reserves and yields. In the United Arab Republic, surveys and projects in the New Valley and the Nile delta have been developed to an extent almost unknown elsewhere in Africa.

In the French-speaking countries the high cost of drilling and the relatively great seasonal aridity of the climate, particularly in western Africa, have compelled the technical services to direct their activities towards inventories (requirements, consumption, resources), general reconnaissance (including the preparation of hydrogeological maps at 1:1,000,000 or 1:500,000), small-diameter bore-holes, studies on the hydrogeological characteristics or aquifers, balances and general surveys of basins or regions.

This tendency is even stronger in the Arab countries of northern Africa: the Maghreb, Libya and the United Arab Republic, a country with areas of high population density and a generally semi-arid or arid climate. It is in these countries that detailed hydrogeological mapping has undergone the most extensive development. At the same time, oil exploration in the sedimentary basins of Saharan regions (southern Algeria and the Fezzan) has done much to promote hydrogeological studies.

The present status of available information concerning ground water may be summarized as follows:

In the Arab and French-speaking countries there is a substantial mass of scientific and technical information: inventories, reports, country papers, maps, analysis results; bore-holes are relatively few in number, but their logs and water potentials are usually known in detail.

In the English-speaking countries there are a great many bore-holes, many of them producing, but with little data available on them. Regional surveys and hydrogeological maps are few in number, and hydrogeological documentation is generally scanty.

A middle ground between these two extremes is represented by the integrated operations of United Nations projects (inventories, geophysical studies, bore-holes, pumping and comprehensive reporting). These projects attempt to strike a balance between the diverse activities of organizing national services and training personnel, collecting and utilizing existing data supplemented by additional investigations, sinking pilot bore-holes and wells for exploitation, and formulating programmes for future operations.

The projects are primarily oriented towards economic and social goals; in principle, they should lead to ground-water exploitation under good conditions, and in particular good economic conditions. This approach does not imply that the scientific and technological aspects of ground-water investigation are neglected. On the contrary, United Nations agencies have helped to bring to Africa the most modern and sophisticated methods of ground-water investigation: in some cases hydrogeological maps are prepared. However, these methods constitute simply a means to the ultimate end of assessing the water potential and determining safe yields for appropriate exploitation that is economical and geared to the real needs and potentialities of the countries concerned. Thus action by the United Nations Development Programme and its executing agencies is helping ground-water prospecting to emerge from the academicism or pragmatism in which it might otherwise have bogged down.

II. OCCURRENCE OF GROUND WATER IN AFRICA

A. General

In any country, the natural conditions for the occurrence of ground water depend on three types of factors:

(a) Morphological factors. Some forms of relief are more favourable than others to the infiltration of rain water. On the other hand, the structure of many basins causes most of the water to run off. In other cases, morphological factors favour the evaporating action of the atmosphere;

(b) Climatic factors. The amount and time-distribution of rain and other forms of precipitation constitute a primary factor affecting the water resources available for infiltration into underground reservoirs. However, part of this water potential may be kept from infiltration by the evaporative action of the atmosphere, which itself depends on winds, on pressures and especially on temperatures;

(c) Geological factors. These are the most important. The penetration of water into the ground and the conservation of water quantity and quality, as well as the possibility of mobilizing the water by drainage, well withdrawal and pumping, require certain physical and chemical characteristics in the geological formations involved: the presence of pores capable of holding water; a favourable structure of this porosity permitting the water to circulate easily; and the absence from the rocks of water-soluble chemicals that might change the quality of the water and make it unsuitable for certain uses.

It is clear that the geological factors are paramount, since they form the material basis of the underground reservoir. Thus, some desert regions which have no surface water at all and receive only insignificant rainfall may sometimes be underlain by large ground-water resources. It is not surprising, therefore, that in most cases the large geological units have the same boundaries as the large hydrogeological units or ground-water basins. It should also be borne in mind that the nature and geological structure of the terrain are largely responsible for relief forms, which themselves have a considerable influence on the climate.

For this reason, a knowledge of the geological factors is essential for determining the location and boundaries of ground-water reservoirs and also for estimating their capacity, recharge and yield.

B. Geographical and morphological conditions

Relief

The African continent has an area of some 30,300,000 km^2 (about one quarter of the earth's total land surface), more than two thirds of which lies north of the equator. It is surrounded by seas: the Mediterranean on the north, the Atlantic Ocean on the west, the Red Sea and the Indian Ocean on the east and the waters at the confluence of the Indian and Atlantic Oceans on the south. The Suez Canal, between the Red Sea and the Mediterranean, serves as a conventional dividing line between Africa and Asia. A number of islands, and particularly Madagascar, may be regarded as part of the African domain.

On geographical maps the African continent gives an appearance of massive unity, but this view of Africa conceals two essential facts. Firstly, the Arabian peninsula is a part of the African domain by reason of its structure, geology and climate. Secondly, in many ways the northern part of Africa, and most particularly the Maghreb, separated from tropical Africa by a broad belt of hyperarid deserts, bears a very close geographical, geological, climatic, as well as ethnic, resemblance to the Mediterranean basin. It therefore constitutes a domain very different from tropical and equatorial sub-Saharan Africa.

The mountain regions of Africa are few and relatively small in extent. The topography tends otherwise to be flat, usually low in height (less than 500 m) in western Africa north of a line running from Benguela to Port Sudan, and higher in eastern Africa and southern Africa (1,000 to 1,200 m, and up to 1,500 m in the south).

The elevated regions of the continent, i.e. those with altitudes above 200 m, are associated either with mountain ranges, such as the High Atlas (4,165 m) and Nuweveld (2,800 m), or with isolated, usually volcanic, massifs, such as the Hoggar (3,003 m), the Tibesti (3,265 m), Jebel Marra (3,024 m), Ras Dashan (4,620 m), Mount Ruwenzori (5,119 m), Mount Elgon (4,321 m), Mount Kenya (5,200 m), Mount Uhuru (5,964 m), Mount Aux Sources in Lesotho (3,299 m), Mount Ankaratra (2,644 m) and Cameroon Mountain (4,070 m).

Hydrography

Africa contains four large topographical basins: the Niger basin, the former inland delta of the river of the same name; the Upper Nile basin in the southern Sudan; the Chad basin, at the centre of which lies Lake Chad; and the Congo basin. In addition, the high plateaux of eastern Africa are traversed by vast subsidence troughs, the Rift Valleys, with great elongated lakes lying along the bottom. At the centre of these plateaux lies the immense Lake Victoria, a sort of inland sea.

In northern Africa, usually not far from the coast, there are a number of closed depressions whose bottom lies below sea level and is covered with salt-water deposits; some of these are in southern Morocco, southern Tunisia, northern Egypt (Qattara) and Eritrea (Lake Assal).

The drainage of the continent varies greatly from region to region. The hydrographic network is very dense in the Maghreb, practically non-existent in desert areas, highly diffuse in basement regions and highly ramified in volcanic areas and some parts of the high plateau regions.

Africa has a total of four immense exoreic - drainage to oceans - hydrographic basins (the Niger, Nile, Congo and Zambezi), one endoreic - inland drainage - basin (the Chad basin) and five other major basins (the Senegal, Volta, Orange, Limpopo and Giuba-Scebeli). Among other important rivers, we may mention the Gambia, the Ogooué (Gabon), the Cunene (Angola), the Ruvuma and the Rufiji (Tanzania), the Oum er Rbia and the Moulouya (Morocco).

Conclusion

There are three morphological and geographical factors which favour the creation of ground-water reserves. The first is the existence of mountain ranges and isolated massifs with steep slopes which, by reason of their altitude, receive large amounts of precipitation. Flows are rapid and closely grouped, and this promotes infiltration, especially in arid zones. The second factor is the existence of vast low-lying basins in the centre of Africa. Thus, a large part of Africa's rainfall is not discharged into the ocean; 53 per cent of the surface of the continent has no discharge to the sea. Of this total, however, only 13 per cent consists of endoreic regions, while 40 per cent consists of areic regions - without organized drainage - mostly in the deserts. The third factor is the abundance of tabular forms. These facilitate local infiltration, but in the arid and semi-arid regions they tend to promote evaporation of most of the rain water.

C. Climatic conditions

The equator cuts through the centre of Africa and, even more than in other parts of the world, represents an axis of symmetry between climatic zones, the type of climate depending largely on the latitude. On the whole, the continent lies in the intertropical domain, where hot climates prevail. The seasons north and south of the equator are reversed: when it is winter to the north, it is summer to the south, and vice versa.

Pressures and winds; temperatures

Africa is bounded by the Azores anticyclone in the northern hemisphere and by the South Atlantic and South Indian Ocean anticyclones in the southern hemisphere. From these high-pressure centres, the trade winds blow towards the equator, with a western deviation due to the earth's rotation. In January a dry and relatively cool wind, known as the harmattan, blows from the Sahara towards the west coast of Africa between Mauritania and the Niger delta; at this time all of Africa south of the equator is under a low-pressure régime (less than 700 mm). Conversely, in July a high-pressure régime prevails over southern Africa and a cyclonic depression is centred over the plateaux of Iran. Consequently the wind-flow tends to be eastward, and a south-west monsoon brings heavy rains to the west coast.

The wind generally blows from the sea landwards, bringing rain, but there are some notable exceptions: the harmattan and, at mid-year, certain local winds of the Maghreb which blow towards the Mediterranean, as well as some regular winds which blow towards north-eastern Africa in the direction of the Arabian peninsula. Relief features may block the humid winds; certain depressed areas, such as the rift valleys, receive little precipitation.

In January the areas south of the twentieth parallel (N.) (which stretches roughly from Nouakchott to Port Sudan), except for the Cape area, lie within the 20 °C isotherm, with 30 °C in southern Africa, 35 °C in the Kalahari and 30 °C in the Ogaden, while the northern part of the continent enjoys lower temperatures (below 20 °C). Conversely, in July only southern Africa (essentially the area south of the Tropic of Capricorn) has mean temperatures lower than 20 °C; the northern part of the continent as a whole, except for the coastal areas (other than the Red Sea coast), has temperatures above 30 °C, sometimes 32 °C.

Temperature fluctuations are very small in the equatorial region (1 °C) and become more marked as distance from the equator increases; they range from 20 to 30 °C in the Sahara and the Kalahari.

Precipitation

Precipitation is a function primarily of latitude and secondarily of altitude. The precipitation régime is irregular and varies widely from season to season and from year to year.

The Maghreb and certain coastal areas of Libya and the United Arab Republic, at the north end of the continent, and the Cape area, at the southern end, enjoy a Mediterranean type of rain régime (winter rains).

The very humid equatorial region, between latitudes 10° N. and 8° S. and longitudes 12° W. and 40° E., has two rainy seasons at the time of zenithal maximum - i.e. the time of year when the sun is high over the horizon - lasting generally from March to June and from September to November, with practically continuous rainfall in an area between the Congo River and Lake Victoria and centred about the equator.

Outside this region, the tropical regions have only one rainy season: from May to October in the north, up to about 15° N., and from October to April in the southern part of the continent, down to 20° S., and in Madagascar. This rainy season is even more prolonged in south-eastern Africa; at Durban there are only three months of dry weather.

Lastly, the subtropical desert region - i.e. the entire northern part of the continent except for the Mediterranean domain, the eastern tip (Somalia) and the south-western part south of the twentieth parallel (not including the Cape area) - receives only rare and irregular downpours.

Total annual rainfall is: 2 to 6 metres along the coast of western Africa from Conakry to Abidjan and from the Niger delta to Libreville (Gabon), in the bend of the Congo, in the area west of the great lakes and on the east coast of Madagascar; 1 to 2 metres in some mountainous regions of the Maghreb, on the Ethiopian plateau, south of a line from Dakar to Mogadiscio and north of a line from Moçâmedes to Dar es Salaam, on the east coast of southern Africa and in most of Madagascar; 500 to 1,000 mm in the High Atlas, in the coastal areas of Algeria and Tunisia and in a belt 300 to 500 km wide bordering on the lines indicated above; less than

1 metre in the area north of a line from Nouakchott to Port Sudan (except for the Maghreb), with most of this area receiving less than 20 mm, in Somalia, in some parts of Tanzania, on the west coast of Africa south of the mouth of the Congo, in the Kalahari and, lastly, at the south-western tip of Madagascar.

Climatic zones

The climatic zones, characterized by well-defined types of vegetation, are the following:

(a) Mediterranean zone, dry in the summer (hot season): the northern Maghreb and the Cape area;

(b) Steppe zone, with the following subdivisions:

Areas on the fringe of the Sahara, south of the Maghreb, with drier summers. The climate is sometimes described as "semi-arid Mediterranean". Precipitation is less abundant and the temperature excursions more marked than in the Mediterranean zone;

Areas south of the Sahara, with semi-arid tropical climate of the Senegalese or Sahelian type; they receive more rainfall during the hot season, from June to September;

The steppe zone, a belt 500 to 700 km wide, also includes: (1) all of eastern Africa, except for the coastal regions and the highest plateaux, and the central part of South Africa; and (2) the most humid areas of the steppe belt, i.e. those nearest the equator; these constitute the dry savanna, an area of transition between the steppe zone and the humid-savanna zone;

(c) Humid-savanna zone, or zone of Sudanese tropical climate. In this zone the wet season becomes longer as distance from the equator decreases, but some places may have a continuous dry season of four to five months. The humid-savanna belt has an average width of 500 kilometres. Some coastal areas of eastern Africa (Kenya, Tanzania), South Africa (Drakensberg) and Madagascar (eastern part), over a width of 200 to 300 km, should be considered part of this humid tropical climate area. A high-altitude tropical climate prevails in the high plateaux of Ethiopia and Kenya;

(d) Desert zone, with a Saharan climate (Sahara, Kalahari-Namib, Somalia);

(e) Equatorial forest zone, with a very humid climate, having two rainy seasons or continual rain; it includes, to a breadth of 300 km, the Gulf of Guinea area from Freetown to Accra and from Lagos to Douala, southern Cameroon, and the Congo basin extending to the Rift Valleys;

(f) Coastal fringe zone, a narrow coastal band whose climate is strongly influenced by the coastal currents, which are sometimes very powerful. Cold currents include the Canaries current (north to south), from Tangier to about the twentieth parallel, and the Benguela current (south to north), from the Cape to the equator. Warm currents include the Guinea current (west to east), from Dakar to the equator, the Agulhas current, from the Mozambique Channel to the Cape, and the monsoon current (south to north), from Mozambique to Somalia, with upwelling of cold water near Cape Guardafui.

Aridity and evaporation

The characteristics of climatic zones may also be indicated by using the concept of humidity or aridity index (Thornthwaite), which involves temperature as well as rains and rain distribution and which, in fact, expresses a characteristic relation between the potential evapo-transpiration and the amount of rainfall.

The table below gives some values of potential evapo-transpiration side by side with rainfall values for a number of African climatological stations:

Climatological stations	Annual precipitation (cm)	Potential evapo-transpiration (cm)	Quotient (%)
Arid and hyper-arid zone (rainfall less than 250 mm):			
In-Salah (Algeria)	<0,5	140	-
Biskra (Algeria)	18	133	15
Moudjéria (Mauritania)	17	187	1
Coastal areas:			
Walvis Bay (a South African enclave on the coast of Namibia)	1	78	1
Nouadhibou (Mauritania)	4	116	4
Tarfaya (Morocco)	11	85	13
Zone with rainfall of 250 to 1,000 mm:			
Lugh Ferrandi (Somalia)	36	206	17
Garissa (Kenya)	31	187	17
Luanda (Angola)	33	134	25
Kayes (Mali)	74	187	40
Dodoma (Tanzania)	59	111	50
Catuane (Mozambique)	67	130	50
Algiers: humid Mediterranean climate	76	92	83

Thus, in some areas, a large or even preponderant part of the rainfall is almost immediately taken up by evaporation. Evapo-transpiration is often the largest component of the water balance. Some authors offer the following figures for the various regions of Africa: evapo-transpiration, 40 to 98 per cent; infiltration, 2 to 40 per cent; run-off, 2 to 12 per cent.

The bodies of surface water (lakes), the area of which amounts to 110,000 km^2 (not including the 69,000 km^2 area of Lake Victoria), vary considerably in level because of the imbalance existing in certain years between the evaporation and recharge components of the balance, particularly in Lake Victoria and Lake Chad. The same is true of free ground waters when the piezometric surface is a relatively short distance below ground level. Evaporation phenomena affect - and can be measured by - the concentration of salts in the waters. How deep the effects of evaporation extend is a controversial question. All authors recognize that the effects are perceptible at a depth of a few metres (an average of 5 m, sometimes reaching 8-10 m). Some authors assert that they go much deeper.

Conclusion

The amount of rain water available for recharging underground reservoirs depends on three major climatic factors: the annual amount of rainfall, the time distribution of the rainfall (or how "violent" the precipitation is), and the value of the potential evapo-transpiration, which is essentially a function of latitude, altitude and temperature.

Any one of these three factors may be decisive in a given set of circumstances.

In any area where the rainfall exceeds 1 to 1.20 m per year, neither the violence of rainstorms nor the evapo-transpiration value is of any importance, since a substantial part of the precipitation is almost always available for infiltration, sometimes after run-off. In this case, the total quantity of rainfall is the predominating factor.

For rainfall of less than 250 mm, the central factor is the violence of the precipitation. In fact, it is interesting to note that under conditions of increasing aridity - decrease in precipitation accompanied by an increase in evaporation potential - the violence of the downpours increases to such a point that at times most of the annual precipitation falls within a few hours. Thus, in the Sahara some daily balances may show an excess of rainfall over potential evapo-transpiration, which may be sustained for several days, and so the water has time to infiltrate thereby recharging the local aquifers in certain cases.

In areas where the rain is between 250 mm and 1 m (steppes and dry savannas) the decisive factor is the potential evapo-transpiration, since the rain is more evenly distributed over time. During the rainy season (with rainfall distribution varying greatly from year to year) the potential evapo-transpiration may still have a significant value. However, a highly variable residual amount of water is almost always available for run-off and infiltration. On the other hand, during the dry season, which may last three to six months, some regions of Africa experience semi-arid or arid climatic conditions, even though their annual rainfall is greater than that of some countries in the humid temperature zone of Europe. During the dry season there may be considerable evaporation from surface waters and shallow aquifers.

D. Geological conditions

The mass of Africa consists of crystalline and metamorphic Pre-Cambrian formations. This "African shield" crops out over vast expanses of the continent, including the Sahara region, western, eastern and southern Africa and Madagascar.

Some depressed areas of this "shield" and the coastal zones were affected over the course of geological time by marine transgressions which left sediments that are very thick in some places. At the centre of the continent, however, the depressions have been filled chiefly with continental deposits, which in some cases are the result of tectonic movements accompanied by volcanic activity.

Geological history: Pre-Palaeozoic era

Geologists generally recognize the following chronological divisions of the Pre-Cambrian in Africa:

(a) Old Pre-Cambrian, or Pre-Cambrian I, dating from more than 3,000 million years ago, essentially characterized by granite gneisses that are strongly folded and invaded by granitic batholiths. It is known, *inter alia*, by the following names: Suggarian (Sahara), Dahomean (western Africa), Pre-Mayombé (equatorial Africa) and Basement Complex (eastern Africa);

(b) Middle Pre-Cambrian, or Pre-Cambrian II, between 2,000 million and 3,000 million years ago, also folded and granitized but with less pronounced metamorphism. It is represented chiefly by schists and quartzites and is known by such names as Atacorian and Birrimian (western Africa), Kerdous (Morocco), Mayombé (central Africa), Upper Basement (Zambia), Limpopo (South Africa), and Graphite Series (Madagascar);

(c) Upper Pre-Cambrian, or Pre-Cambrian III, between 1,000 million and 2,000 million years ago, represented by various, more or less metamorphosed, formations: schists, sandstones (quartzites) and conglomerates, as well as granites and volcanic formations (rhyolites, basalts, etc.). This is known as Tarkwaian (western Africa), Great Dyke (Southern Rhodesia) and Witwatersrand (South Africa).

This "African basement" is overlain by a largely sedimentary collection abundant in limestones and dolomites, which are locally very thick but not fossiliferous, except for stromatolites and various "problematical" impressions. This is the Terminal Pre-Cambrian, or Pre-Cambrian IV, likewise known as the Infra-Cambrian. It also contains granitic batholiths, such as the Younger Granites of Nigeria, and eruptive formations. It is known by the names Adoudounian (Morocco), Falemian (western Africa), Katanga Group (central Africa) and Waterberg (South Africa).

Palaeozoic, including Permo-Triassic

Transgressions of Cambrian, Ordovician, Gotlandian, Devonian and Carboniferous seas have covered northern Africa, especially its western part, depositing the following sediments:

Cambrian: limestones and dolomites at the bottom, shales at the top (Morocco);

Ordovician: hard shales and quartzites (Morocco, Hoggar, Mauritania, Guinea, Manding plateau and Bandiagara plateau in Mali);

Gotlandian: softer shales, with limestone nodules or beds (Morocco, Rio de Oro, Mauritania, Guinea, Hoggar, Libya);

Devonian: shales and sandstones, with large limestone beds (Morocco, Mauritania, Tibesti, Ennedi);

Carboniferous: limestones, sandstones and marls (Morocco, western Algeria, Mali in the Taoudenni region, Niger west of the Aïr massif, Tibesti, north-eastern Egypt. To the east the marine deposits grade laterally into continental sandstone deposits).

The Hercynian orogenic movements occurring during the Carboniferous and Permian periods produced the relief features of the Sahara and western Africa: the Hoggar, the Reguibat anticline, the Atacora mountains, and the Tindouf, Taoudenni and Ghana basins.

South of the equator the Palaeozoic outcrops are neither numerous nor very fossiliferous; they occur chiefly in South Africa.

The African Permo-Triassic north of the equator is characterized by generally continental or lagoonal deposits. These deposits often have characteristic red or violet tints; they are found throughout the Maghreb and in the central Sahara, in outcrops, usually of limited extent, containing salt and gypsum.

South of the equator, there was an important glacial period at the end of the Carboniferous era, followed by the deposition of very thick continental sediments (up to 7,000 m) during the Permo-Triassic. These constitute the Karroo, which is found chiefly in southern, central and eastern Africa; Karroo deposits are found at the bottom of the great tectonic troughs or rift valleys. From bottom to top, the Karroo is subdivided into the Ecca formations of alluvial origin; the Beaufort formations which contain sandstone; and the Stormberg formations which contain shale, sandstone and basalt. On the eastern coast of Africa and in Madagascar, Permo-Triassic formations of marine origin have been found (sandstones, shales, limestones). In South Africa, the Karroo is overlain by the basalt flows of the Drakensberg (1,000 to 2,000 m).

Jurassic, Cretaceous, Tertiary

The seas of the Middle Cretaceous covered the northern part of central Africa, now occupied by deserts. The earlier and Post-Hercynian deposits, taken together, have been given the name "Continental intercalaire", a comprehensive series which ranges in age from the Permo-Triassic to the Lower Cretaceous. In the north-eastern part of the continent, the Nubian Sandstones include not only the "Continental intercalaire" but also older sandstones, some of which may date from the beginning of the Palaeozoic era.

The "Continental intercalaire" crops out widely in the southern part of the Maghreb, the central and eastern Sahara, the Sudan, the Chad and Congo basins, eastern Africa and South Africa; it is represented chiefly by sandstones and clays.

The marine Jurassic is extensively present in the form of limestones throughout the Maghreb, particularly the High Atlas and the high plateaux.

Jurassic limestone and marl-and-limestone deposits are also found in Libya, in Egypt and especially in eastern Africa (Ethiopia, Somalia, coastal region of Kenya and Tanzania, Madagascar).

The great marine transgressions of the Cretaceous began with the Albian stage and extended to all of the Maghreb and the central Sahara, down to the Niger in the south (northern Nigeria, the Benue and the lower course of the Niger). They also gave rise to deposits (sandstone, limestone, marl, clay) in coastal sedimentary basins (Mauritania-Senegal, the Gulf of Guinea from the Ivory Coast to Cameroon, Gabon, Angola, Somalia, Mozambique, the west coast of Madagascar).

Palaeogene sediments often overlie those of the Upper Cretaceous; this is the case in the Maghreb, in the Sahara, in Nigeria, on the west and east coasts of Africa and in Madagascar; these sediments are very widespread in Somalia and occupy the entire eastern "horn" of Africa. The deposits include sands and sandstones, sometimes phosphatic, clays and limestones, at times very extensive.

The marine Neogene included phases of marine sedimentation which deposited sandy sandstones, limestones and clays in the Maghreb, on the coasts of Libya and Egypt, in the Canary and Cape Verde Islands, in Senegal, in Gabon, in the lower Congo, in Angola and in various sectors of the east coast of Africa and the west coast of Madagascar.

The continental formations of the Tertiary period are known collectively as the "Continental terminal". They form the vast table-lands of the Maghreb and the Sahara, known as hamadas, which consist of continental red sandstones and marls and of lacustrine limestones, sometimes very thick, the hamadas often being topped by a hard "platform" with karst features.

In central and southern Africa there are extensive continental deposits (sands, sandstones and clays), referred to as "Kalahari" deposits, which are contemporaneous with the "Continental terminal" of the area north of the equator. They stretch from the Congo to South Africa, with thicknesses varying from a few dozen to several hundred metres.

The Neogene was the time of the great geological phenomena that gave Africa the general appearance it has today: the orogeny of the Atlas, basement fractures accompanied by abundant lava flows, subsidence of the Red Sea and formation of the rift valleys of eastern Africa.

Quaternary

At the time of the ice ages in Europe, heavy rains fell on Africa; correlations have been established between the glaciations of northern Europe and the pluvial periods of Africa.

Extensive and thick Quaternary deposits, consisting essentially of sand and clay, are found in the great basins of central Africa: in Chad, in the Congo, in the inland delta of the Niger, in the valleys, deltas and estuaries of the great rivers (Nile, Zambezi), in many coastal regions (Morocco, Mauritania, Libya, Somalia, Kenya, Mozambique) and near the great lakes of eastern Africa.

The sands of the great deserts (Sahara, Nubia) are often described as "Plio-Quaternary".

In tropical Africa the soils of the forest zones generally consist of lateritic clays, while the savanna regions are covered with cemented laterites, whose age is often problematical. In crystalline basement regions, the lateritic formations are particularly well developed.

Geological structure of Africa; volcanism

The African basement and its sedimentary cover underwent large-scale fracturing tectonic movements, but the folds in the northern and southern parts of the continent were produced in different ways. In the north, in the Maghreb, the folds formed the Atlas ranges, alpine mountains which belong to the Mediterranean domain, separated from the African domain proper by the great South Atlas rift. In the southern part of the continent, in South Africa, the folds formed the Cape range, which is lower and less extensive.

Thus, the continent as a whole is compartmentalized by immense fractures into superelevated domes and depressed or subsided basins. The fractures are distributed along two principal directions at right angles to each other, SW-NE and NW-SE; they are much more numerous and fractionated in the eastern part of the continent, delimiting vast subsidence troughs over a length of 4,000 km: the two great rift valleys, which run in a general north-south direction and may reach depths of 2,000 m.

There were important volcanic phases connected with the great fracture lines of the continent during the Miocene, the Pliocene and even the Quaternary. Thus, the principal volcanic units of Africa are situated along the following two fracture zones: the Cameroon-Tibesti trough (including the islands of Fernando Poo and St. Helena) and the rift valleys (the Ethiopian lava sheets, Mount Uhuru, Mount Kenya and Mount Ruwenzori).

In addition, mention should be made of areas outside these two main lines: the Hoggar, the Aïr, the Fezzan (in the Sahara), the Canary Islands, the Cape Verde Islands, Madagascar and the Mascarene Islands, and the mountains of Basutoland.

The African shield includes several vast tectonic basins: the Taoudenni, the Central Sahara (between the Atlas and the Hoggar), the Libyan desert (north of the Tibesti), the Chad basin, the Congo basin, the Kalahari and the Karroo. These basins are separated by areas of basement outcrops which are sometimes quite extensive: the Nubian desert, the Tibesti, the Hoggar, the Reguibat anticline, the dome of western Africa, the high plateaux of Cameroon and eastern Africa and the eastern regions of Madagascar.

Conclusion

A number of geological factors are favourable to the creation of ground-water reservoirs in Africa. Examples of these are the following:

The existence, in most of the coastal regions, of sedimentary basins which include important permeable horizons;

The presence, in the great basins of the African interior, of vast permeable geological formations with a relatively regular structure ("Continental intercalaire", Nubian Sandstones, "Continental terminal");

Vast areas of permeable outcrops; fractured and karstified massifs of limestone or of limestone and dolomite, permeable sandstones, alluvia of the great rivers and of their deltas or estuaries;

Intensive and multiple fracturing of basement regions.

Conversely, other factors are unfavourable. These include:

The limited extent of certain geological basins which form ground-water reservoirs, as in the Maghreb, along the coast;

The unduly high permeability or unduly great depth of certain aquifers, which makes it economically unfeasible to reach and exploit the ground-water resources. In particular, this is true of volcanic regions and islands, Nubian Sandstones, some parts of the Sahara, the "Continental intercalaire" and the formations of the Niger delta; and

Vast areas of crystalline and metamorphic, largely impermeable, formations or desert sands, which provide a more favourable environment for evaporation of the occasional rain than for its infiltration.

The above factors, both those favourable and those unfavourable to the creation of ground-water reservoirs in Africa, are interdependent.

E. Hydrogeological domains; general summary of the principal reservoirs

There are many hydrogeological domains in Africa. Some of them are characteristic and extend over large areas; these are cited and briefly described below. It should be borne in mind that geological factors are preponderant, since in order to contain water, rocks must have a certain "useful" porosity, i.e. voids capable of storing water, allowing it to circulate and releasing it in appreciable quantities.

The Pre-Cambrian shield and its cover

Pre-Cambrian formations generally have very little aquifer capacity, or none at all. They are most often found in the form of low peneplains (western Africa) extending over a wide area, or high plateaux (eastern Africa). Aquifer zones in humid tropical regions are the weathered, fractured or inclusive zones. Thus, ground water has accumulated in:

Surface formations: clay-sand soils and laterites. This ground water is usually temporary and evaporates during the summer;

Weathered layers directly overlying the Pre-Cambrian basement when the basement contains large amounts of quartz components;

Fractures in unweathered rock. These sometimes contain what may be described as "fossil water", at depths that may reach 100 or 200 m;

Inclusions: dikes and sills, intrusive rocks and other geological entities that differ sharply from their surroundings.

These ground-water reservoirs are generally local in extent and are closely related to the surface hydrographic network, particularly to permanent ponds.

Some fractures contain water under pressure.

These hydrogeological conditions prevail over a large part of Africa inhabited by more than 50 million people.

In the Infra-Cambrian and Palaeozoic cover overlying the Pre-Cambrian basement, two major sets of aquifers may be distinguished. Firstly, there are the Infra-Cambrian shale-limestone and limestone-dolomite series. These are widely developed in outcrops south of the equator, in the northern part of the Congo and in the Moroccan Anti-Atlas. They also occur in some parts of western Africa. This aquifer is of considerable importance; in particular, it provides the water supply of Lusaka, the capital of Zambia, and is used to meet the mining, industrial and domestic water needs of the Transvaal. Secondly, mention should be made of the Cambro-Ordovician and Gotlando-Devonian shaly sandstones, which are found mainly in western Africa, in some areas bordering on the Sahara and in South Africa. This kind of rock makes a very mediocre aquifer; it holds water in its fractures, joints etc. Shales, which are more fractured than sandstones, would seem to give a better yield.

Large sedimentary basins of central Africa

The large basins (Sahara, Taoudenni-Niger, Chad, Upper Nile, Congo, Kalahari, Karroo), each highly individualized, contain essentially continental deposits of Palaeozoic age (clayey sandstones of the Carboniferous and the Permo-Triassic, Karroo), Jurassic (Cretaceous, clayey sandstones of the "Continental intercalaire" and the "Continental terminal", sometimes including Cretaceous marine formations) and Plio-Quaternary (sands and clays).

Some sandstone horizons contain abundant water resources, sometimes tapped by artesian bore-holes, such as those of northern Nigeria, in the Chad basin.

In the Sahara, a vast and generally tabular desert region which covers the northern part of Africa and includes the Libyan and Nubian deserts, the following categories of ground water are available:

A semi-deep or deep reservoir called the "Continental intercalaire reservoir", very broad in extent, which also occurs in the (continental) sandstones of the Albian (Algeria) and Nubia (Egypt). A number of fields of artesian wells have been sunk to this reservoir, chiefly in Algeria (the Mzab) and the United Arab Republic (New Valley, Kharga). In addition, some fields of traditional wells are fed by outlets from this immense "fossil" reservoir. However, the creation of the lake behind the Aswan Dam may result in a certain amount of recharge. In the Sudan the sandstones of the "Continental intercalaire" form thin layers over the basement formation, making possible the creation of localized reservoirs;

A reservoir in the Cretaceous limestones, of local importance;

An upper reservoir, called the "Continental terminal reservoir", contained in the lacustrine limestones and the sandstones and the sandstones of the hamadas intercalated in clayey series. In contrast to the "Continental intercalaire", this reservoir is much less rich and may be interrupted by non-aquifer formations;

Reservoirs of alluvia recharged by the violent floods of wadis, after exceptionally heavy downpours;

Reservoirs in dune sand in some locations.

In southern Africa, the Kalahari sandstones and sands (the equivalent of the "Continental terminal") constitute a very extensive aquifer, concerning which, outside of some local exceptions, relatively little is known as yet.

Coastal sedimentary basins

These regions are particularly important; much of the population is concentrated in the capitals and other large cities, together with their industrial suburbs, and hence the coastal basins and the site of much of Africa's economic activity. Ground-water surveys, exploration and exploitation are far advanced in these regions. The principal basins are the following: the vast Mauritania-Senegal basin; the relatively small Ivory Coast basin; the Gulf of Guinea from Ghana to Cameroon; Gabon-Angola; Mozambique; eastern Africa, from Tanzania to Somalia; and the west coast of Madagascar.

The principal aquifer formations found in these regions include Maestrichtian sandstone rocks, Eocene limestones, sand-sandstone rocks of the "Continental terminal", conglomerates, sandstones, sands, limestones and shelly rocks from the Neogene and, lastly, Quaternary alluvium and sand. These formations contain both free and confined ground waters. In a number of cases, these intensively exploited basins are threatened by sea-water intrusions (the Moroccan coastal Sahel, Dakar, Lomé, Mogadiscio, Cyrenaica, Tripolitania, etc.). Special mention should be made here of the zones of the deltas and estuaries of the great rivers, such as the Nile and the Niger.

The Maghreb

The Maghreb, to which we should add certain coastal regions of Libya, belongs, as we have seen, to the Mediterranean domain. Most of this region is occupied by abundantly folded Secondary and Tertiary sedimentary formations, in a semi-humid or semi-arid climatic environment. As a result, the region is divided into many basins, usually with highly individualized features and small in size. The best aquifer rocks are the following:

Jurassic (chiefly Liassic) limestones, in which large springs are found in mountainous areas (the High Atlas, Tunisia) and artesian waters often lie under the valleys and plateaux (the high plateaux of Morocco and western Algeria);

Cenomano-Turonian dolomitic limestones, whose behaviour is similar but whose yields of water are smaller, since the series are less thick; also, in certain cases, Eocene limestones;

Maestrichtian and Eocene sands and sandstones;

Neogene and Quaternary conglomerates, shelly limestones and lacustrine limestones;

Unconsolidated alluvial or sandy formations, alluvial fans and debris.

Mention should also be made of the limestone massifs of the "dorsale rifaine" in northern Morocco and the Infra-Cambrian dolomitic limestones of the Anti-Atlas.

There are a number of other aquifer formations in the Maghreb, but their yields are lower.

In South Africa, the areas near the coast between the Cape and Durban have somewhat similar characteristics from the point of view of climate and relief but not from that of geology; the Palaeozoic limestones, sandstones, quartzites and shales in that region are not very permeable.

Other domains relatively unknown

Vast geological units in eastern Africa are still comparatively unknown in so far as ground-water resources are concerned. These are:

The immense volcanic sheets of Ethiopia and the region of the great lakes, extending to southern Africa, with complex structure and lithology and with highly variable permeability. This region contains many springs, whose yields vary widely; the quality of the water is also subject to wide variations (sulphurous waters, thermal waters, etc.);

The Jurassic-Cretaceous limestone plateaux of Ethiopia and Somalia, which are frequently karstified;

The fill formation of the rift valleys (Karroo and Plio-Quaternary) and the fractured zones. Many bore-holes have been drilled in the lake region, particularly in Malawi, but no general survey has yet been undertaken.

The rudimentary state of present-day knowledge concerning ground waters in this area is due largely to the relative abundance of surface water in some of these regions or to the low population density.

Alluvium

The valleys of the great African rivers constitute a promising hydrogeological domain when the alluvium is of a suitable nature. This is usually not the case, for the alluvium is often clayey, particularly in the case of the Niger and the Nile. In general there has been little incentive for sinking wells in the alluvial terraces or the river banks, since surface water is abundant. However, in providing water supplies for population centres, the sinking of such wells would permit savings in the construction of sedimentation and purification stations.

Islands

Most of the islands surrounding Africa have a relatively high ratio of population to area. They have water problems due to the following causes. In volcanic islands the water infiltrates rather deeply into some excessively permeable formations and is not easily accessible; in areas with impermeable formations much of the water runs off and is lost in the ocean. In limestone islands the storage capacity of the ground is known to be low; the ground water is lost to the ocean through fractures, and pumping often causes an intrusion of salt water.

In short, most of the islands form a special hydrogeological environment which may be summarized as follows: aquifers of limited extent, frequently with poor porosity, surrounded by salt water and often over-exploited.

Conclusion

In Africa the regions with the most abundant rainfall - except for the Congo basin and the volcanic peaks - generally consist of crystalline rocks which have rather low ground-water storage capacities but which are almost certain to be recharged in each rainy season. These regions have a fairly high population density.

On the other hand, most of the large sedimentary basins situated in the heart of the continent, chiefly in the north, have reservoirs which are much larger but whose recharge is uncertain, owing to the aridity of the climate. These regions generally have a low population density; in many cases, ground water is accessible only at considerable depths, and drilled wells yield non-flowing or flowing artesian water.

The coastal sedimentary basins, with most of the capitals and large cities and with a large population, are among the most important hydrogeological units. These regions have been thoroughly surveyed, particularly in subtropical western Africa; they receive abundant rainfall and also benefit from the infiltration water supplied by coastal rivers or even by the great continental rivers.

The waters of the western coasts are of better quality than those of the eastern coasts, which are frequently salty, even at some distance inland.

The Maghreb and, to a lesser extent, the south-eastern tip of Africa, are special domains by reason of the diversity of the geological environment, the fragmented structure of the basins, the intensity of exploitation and the advanced level of regional surveys.

III. AVAILABLE YIELDS FOR THE PRINCIPAL TYPES OF AQUIFERS

The outline map annexed to this report shows the principal aquifer regions of Africa. They may be divided into three large groups according to their type of useful porosity. In this chapter we shall list the yields available from the various formations for as many countries as possible.

It should be noted that these values are given merely as examples; some of the data supplied are probably of doubtful accuracy, and, furthermore, such a listing is far from exhaustive. Despite these limitations, however, it has seemed useful to give a general summary of the available ground waters of Africa. The information below is, in a sense, a supplement to the legend of the ground-water map.

A. Aquifers with interstitial porosity

These are essentially alluvial-sand and sandstone terranes, not including the hard and fine sandstones of the Pre-Cambrian and Palaeozoic eras, which have no interstitial porosity.

1. Extensive sandy areas

In Africa, dune sands cover large areas north of the fourteenth parallel. Little is known about their aquifer behaviour in the Sahara. We do know that the sands themselves, despite their high permeability, cannot constitute an important reservoir in many cases because they give up their absorbed rain water rather rapidly, by drainage or evaporation. The following table gives some examples of the yields and hydrological characteristics of sandy aquifers:

Country	Location	Geology	Yield per well (m^3/h)	Draw-down (m)	S %	K (m/d)	T (m^2/d)
Algeria	Sahara	Sands	-	-	-	20 to 50	-
Madagascar	Southern region	Dune sands	9	3	-	-	-
Mauritania	Plain of Kiffa	Dune sands	5 to 10	-	-	-	-
	Plain of Assaba	Dune sands	5 to 10	-	-	10	-
Senegal	Malika	Clay-bed sands	26	7 to 8	17	-	-
	Cape Verde (Tiaroye)	Dune sands	50	-	-	-	-

S = storage.
K = permeability (hydraulic conductivity).
T = transmissivity.

2. Alluvial fills, deltas, chott deposits, Quaternary formations of the Chad and Congo basins, coastal sedimentary basins

Country	Location	Geology	Yield per well (m^3/h) a/	Drawdown (m)	S %	K (m/d)	T (m^2/d)
River alluvia. These aquifers are among the largest and are of importance to a large population.							
Algeria	Oued Biskra	Sandy gravels	-	-	20 to 30	50	2,000
Congo (both Republics)	Congo (river)	Sandy gravels	(1 to 100 $m^3/h/m$)	-	-	-	-
Madagascar	Tananarive	Clayey alluvia	15 to 40	-	-	-	-
Mauritania	Oued Seguelil	Gravelly alluvia	10	-	-	10	-
Morocco	Doukkala	Sandy gravels	(10 to 1,000 m^3/d)	-	-	-	-
	Tafilalt	Gravelly alluvia	-	-	5	100 to 500	1,000
	Sous	Gravelly alluvia	Up to 360	1	3 to 10	-	2,000 to 6,000
Southern Rhodesia	Sabi (river)	Non-clayey alluvia	60	-	-	-	-
United Arab Republic	Nile	Coarse Plio-Pleistocene gravels	1,000	3	-	200 to 400	-
Coastal alluvia							
Guinea	Rio Nuñez estuary	Alluvia	20 to 50 (subartesian bore-holes: 7)	-	-	-	-
Ivory Coast	Treichville lagoon	Coarse sands	210	3	-	-	-
Togo	Coastal zones	Clayey sands	3 to 5	-	-	-	-
Extensive alluvial fills							
Burundi	Graben of the rift valley	Fill formations	10 to 60	-	-	-	-
Cameroon (Chad basin)	Flats	Fill formations	10 to 80	-	-	-	-
Congo (People's Republic of)	In the Congo basin but away from the river	Fill formations	(1 $m^3/h/m$)	-	-	-	-
Coastal sedimentary basins							
Dahomey-Togo	Coastal region	Cretaceous sands	(1 to 35 $m^3/h/m$; average: 8 to 15)	-	-	-	-
Ivory Coast	Abidjan	Palaeo-Cretaceous sands and limestones	18	80	-	-	-
Libya	Sirte	Miocene limestones and sands	12 $m^3/h/m$	-	-	-	-
Madagascar	-	Cretaceous sandstones	60	-	-	-	-
Morocco	Agadir	Pliocene sandstones and limestones	(5 to 20 $m^3/h/m$)	-	-	-	-
	Plains of Doukkala and Berrechid	-	10 to 100	-	-	-	-
Senegal	Basin (total)	Maestrichtian sandy sandstones	15 to 120 (artesian)	-	-	30 to 100	600 to 2,000
Togo	Afagnagan	Cretaceous sands	(18 (25	(10 (42	-	-	-
Tunisia	Zarzis-Djerba	Upper Miocene sandy sandstones	50 (artesian)	-	0.03	30	3,000
	Various regions	Sandy sandstones:					
		Oligocene	-	-	-	3 to 5	-
		Miocene	-	-	-	7 to 10	-
		Pliocene	-	-	-	0.2 to 2	-

a/ In the column headed "Yield per well", parentheses indicate a specific yield value.

3. Sandstones, conglomerates of the "Continental terminal" (end of the Cretaceous or Post-Cretaceous), Kalahari sandstones and sands (south of the equator)

Country	Location	Geology	Yield per well (m^3/h)	Drawdown (m)	S %	K (m/d)	T (m^2/d)
			"Continental terminal"				
Mali	Gondo	-	(50 to 100, up to 300/d)	-	-	-	-
Mauritania	Trarza	Sandy intercalations	1 to 4	-	-	-	-
	Bennichab	Sandy intercalations	30	23	-	25	250
	Nouakchott	Sandy intercalations	15	8	1	-	-
Senegal	Casamance	Clayey sandy sandstones	(6 $m^3/h/m$)	-	-	-	-
Togo	Lomé-Agouévé	Variegated sandy sandstones	(5 to 40 $m^3/h/m$)	-	-	20 to 40	-
Upper Volta	Bobo-Dioulasso	-	90	-	-	-	-
			Kalahari sands				
Angola	-	Clay-limestone sandstones	2.5 to 4.5	-	-	-	-
Malawi	-	Non-clayey sands	1 to 5	-	-	-	-
	-	Clayey sands	0.5 to 3	-	-	-	-
Southern Rhodesia	-	Sands	Up to 70	-	-	-	-
Zambia	Barotseland	-	Maximum 4 to 8	-	-	-	-

4. "Continental intercalaire", Nubian Sandstones, sandstone Karroo and other Pre-Cretaceous or Cretaceous continental sandstones

Country	Location	Geology	Yield per well (m^3/h)	Drawdown (m)	S %	K (m/d)	T (m^2/d)
Algeria	Ghardaia	Sandstone-clay Continental intercalaire	Variable	-	0.025	5 to 40	1,000
Cameroon	Bénoué-Garoua	Cretaceous sandstones	10 to 20, up to 50	-	-	-	-
Madagascar	-	Clayey sandstones of the Isalo	15 to 40	-	-	-	-
Namibia	Frontier with Botswana	Ecca sandstones (Karroo)	(40 to 4,000 per day - artesian)	-	8 to 15	-	-
Nigeria	Sokoto	Consolidated Eocene sands	High yields (variable)	-	3	150	1,500
Southern Rhodesia	-	Upper Karroo sandstones	3 to 6, up to 50	-	-	-	-
	-	Cretaceous conglomerates	2 to 7	-	-	-	-
Swaziland	-	-	-	-	-	-	-
United Arab Republic	Kharga oasis	-	(3,000 to 4,000 per day - artesian)	20	-	4	4,000
Zambia	-	Lower Karroo sandstones	Low	-	-	-	-
		Grit escarpment sandstones	7 to 10, up to 60	-	-	-	-
		Beaufort formations	20	-	3 to 10	-	-

B. Aquifers with fracture and channel porosity

1. Limestone platforms of the hamadas of northern Africa (Plio-Pleistocene)

The hamadas cover vast areas south of the Atlas Mountains, their surface consists, in general, of a nearly horizontal layer of hard, more or less sandstone-like lacustrine limestones of Plio-Villafranchian age, often overlying some softer sandstone-clay formations. They are generally bounded by an erosion cuesta and have karst characteristics. The scanty rain water that infiltrates into the hamadas circulates rapidly in a karstic network, flows towards peripheral or central depressions and is rather quickly taken up by evaporation. The few wells found on the hamadas are fed by dune or alluvial formations. Drilling operations in search of water have not, in general, yielded positive results. In some cases, however, the hard and karstic formations crowning the hamadas overlie permeable formations and thus favour the infiltration of water into deep underground reservoirs.

2. Karstified limestone reservoirs: Jurassic, Cretaceous (Cenomano-Turonian covering layer of northern Africa) and Eocene

Limestones form either large massifs or extensive covering layers incorporated into less permeable country rock.

Country	Location	Geology	Yield per well (m^3/h)	Drawdown (m)	S %	K (m/d)	T (m^2/d)
Algeria-Morocco	High plateaux	Jurassic limestones	150 (artesian)	-	-	-	-
Algeria	Constantine	Cenomano-Turonian dolomitic limestones	250 to 400	-	-	-	-
Madagascar	West coast	Eocene limestones	40 to 300 - artesian (160 to 200 $m^3/h/m$ when pumping is applied)	-	-	-	-
Mauritania	Trarza	Eocene limestones	0.1 to 1	-	-	-	-
Morocco	-	Liassic limestones	Up to 500 (artesian)	2 to 5	-	-	1,000
	Doukkala	Marly limestones of the Upper Jurassic	10 to 100	-	-	-	-
	Bahira	Dolomitic limestones	150 to 200	-	-	-	-
	Souss	Cenomano-Turonian limestones	Up to 1,200	1 to 2	2 to 3	100 to 500	5,000 to 20,000
	-	Sandstone-marly Cretaceous limestones	1 to 10	-	-	-	-
Senegal	Pout-N'Diass	Palaeocene limestones	100 to 200	1	0.5 to 7	-	-
Tunisia	Djebel Zaghouan	Liassic limestones	2,000 (in 6 springs)	-	-	-	-

These few examples show that the karstified limestones of north-western Africa are capable of providing yields which often exceed 50 m^3 per hour, may go as high as 100 and may even reach several hundred cubic metres per hour in certain cases.

3. <u>Tectonic zones of northern Africa, with complex marly sandstone, marly limestone, flysch, etc., structures of the Jurassic and Cretaceous</u>

The ground-water resources are highly localized; they occur chiefly in the fracture zones in thin limestone or sandstone beds alternating with schists, marly limestones, clays, etc. The available yields are highly variable.

4. <u>Calcareo-dolomitic massifs and plateaux of the Upper Pre-Cambrian and the Cambrian</u>

As was indicated in section 2 above, the calcareo-dolomitic (Upper Pre-Cambrian and Cambrian) sedimentary complex, often very thick, constitutes one of the most important reservoirs of ground water in Africa. A few significant examples are given below:

Middle Katanga dolomites (Zambia): 4 to 10 m^3/h (40 m^3/h on the Mazabuka fault). The town of Lusaka takes 2,000 m^3/d from 10-inch tube wells;

Lubumbashi dolomites (Democratic Republic of the Congo): specific yield, up to 100 $m^3/h/m$,

Dolomitic limestones of the Transvaal - Far West Rand (South Africa). Useful porosity: of the order of 10 per cent at 60 m, 2 to 3 per cent at 100 m and 1 to 2 per cent at 150 m. The Suurbekom pumpings supply water to Johannesburg at the rate of 30,000 m^3/d. The available yield is 30 times this size. Pumping in this region is aimed chiefly at draining the reservoir in the limestones which overlie the gold-bearing conglomerates, with a view to exploitation of the conglomerates. In 15 years, 10^9 m^3 have been pumped;

Dolomitic limestones of Tin Hrassan (Upper Volta) in an arid zone. Transmissivity: 5.10^{-4} m^2/s. Yield: 4 m^3/h, with 10 m of drawdown. Storage coefficient: $1.8.10^{-3}$;

Fissured dolomitic limestones of Atar (Mauritania). Yield: 70 m^3/h, with 4 m of drawdown. Such a yield value is exceptional in an arid zone; it is found here in a river bed into which flood waters infiltrate;

Infra-Cambrian and Cambrian limestones of the Anti-Atlas (Morocco). A number of overflow springs have discharges of 20 to 40 m^3/h, and sometimes as much as 250 m^3/h.

Mention should also be made of the dolomites of Tiara (Upper Volta) and the Gondo, with karstic funnels (Mali), concerning which no numerical data are available.

C. Formations with little or no porosity except locally in certain favourably situated weathered or fissured zones

1. Hard sandstones, shaly sandstones and quartzites of the Pre-Cambrian and Primary eras

Country	Location	Geology	Yield per well (m^3/h)	Drawdown (m)	S %	K (m/d)	T (m^2/d)
Angola	South	Infra-Cambrian quartzites and conglomerates	0.5 to 3	-	-	-	-
Mauritania	Hodh	Cambrian pelite sandstones	Up to 0.2-0.5	-	-	3	-
		Brazer sandstones	2 (maximum)	-	-	7 to 40	-
	Aioun el Atrouss	Infra-Cambrian sandstones	0.2 to 0.3	-	5	5	-
Togo	Bombouaka	Sandstones	0.3 to 7	-	-	-	-
	Dapango	Sandstones	3 to 7 (maximum)	-	-	-	-
			0.5 in the dry season	-	-	-	-
Togo-Dahomey	-	Atacora Quartzites	2 to 3, up to 7	-	-	-	-

2. Schists (chiefly Infra-Cambrian, Primary and Karroo) and clays

When these formations are not completely impermeable, they contain very small amounts of water, chiefly in the fracture zones. Some examples of the yields available per well are given below:

Country	Location	Geology	Yield per well (m^3/h)	Drawdown (m)	S %	K (m/d)	T (m^2/d)
Ghana	-	Voltaian schists	Very small	-	-	-	-
Guinea	-	Gotlandian black shales, slates	Very small in fractures and sills	-	-	-	-
Mali	Nara	Cambrian shists	Very small	-	-	-	-
	Azaouad-Tombouctou	Metamorphosed Pre-Cambrian schists	0.5	-	-	-	-
Mauritania	Atar	Schists under alluvia	20	2	-	-	-
Togo	Sansanné-Mango	Schists	(0.3 to 1 per day)	-	-	-	-
	Buem	Marly sandstone shales	(0.5 to 10 per day)	-	-	-	-
Upper Volta	Banfora	Shaly sandstones	12 (exceptional)	50	-	-	-
Zambia	-	Phyllites, biotite schists, Katanga schists	1 to 4	-	-	-	-

3. Crystalline and metamorphic rocks (basement formations, granites and gneisses)

Crystalline rocks are impermeable, since they have no useful porosity except in faulted, fractured or weathered zones. The best yields are usually obtained when a relatively thick weathered zone overlies a faulted zone. A fairly detailed study is often needed to locate the most favourable sites. In general, however, it may be said that the best prospects are found in the depressed zones of the crystalline basement, which often correspond to tectonized or heterogeneous zones (inclusions, dikes and sills) that have been subjected to erosion.

Moreover, these basin bottoms, often occupied by ponds, marigots or streams, form favoured zones for infiltration.

The nature and structure of the weathered layer vary with the parent rock. It sometimes happens that this layer is almost entirely clayey, and hence sterile. From the hydrogeological point of view, the basement formations may be divided into two major categories:

(a) Orthogneisses, granites, paragneisses poor in ferromagnesian elements

A cross section, from top to bottom, contains the following horizons:

Horizon A: soil (humus) overlying concretionary, more or less lateritic, clays (1 metre to several metres);

Horizon B: more or less sandy clays (variable thickness);

Horizon C: sands, less and less decomposed and less clayey at deeper levels (several metres to 10 m);

Horizon D: fractured rock;

Horizon E: solid rock.

Horizon A is characterized by vivid colours: violet, ochre, red or yellow. This is a sterile zone. Horizon B contains a surface reservoir which is temporary in the savanna zone, since during the dry season the evaporating action of the atmosphere desiccates the land to a depth of 6 to 10 m.

The lower part of horizon B and the upper part of horizon C are often highly fluid, owing to the presence of a kaolinic porridge originating in the decomposition of the feldspathic elements of the substratum. The lower part of horizon C is rich in quartz grains; it is believed that these grains have an absorptive effect on the water in the kaolinic porridge, so that water enters to fill the spaces between the grains. Furthermore, after rain some water percolates through horizons A and B. Thus, there exists at the base of horizon C an aquifer formation which is porous but not very thick and is therefore discontinuous where the topographical and tectonic conditions are unfavourable. Horizon D also contains water and exerts a drainage effect on the upper horizon when tapped by pumping. The water of horizon D is chemically different from that of horizon C. In some cases, horizon D may contain "fossil" water, i.e. when this aquifer is tapped by pumping, recharge cannot be considered certain.

In the Ivory Coast a test basin is being studied at Korhogo; this is a granitic cuvette in which many piezometric bore-holes have been drilled. The piezometric level of the water is recorded frequently, particularly during a season of heavy rains. This level changes quickly in response to any change in the discharge of the outlets but is less affected by heavy rains, particularly when the water table lies at a depth of more than 10 m.

The aquifer horizons are characterized by a fairly light colour: whitish, bluish or greenish.

Certain petrographic discontinuities may help the drain effect already mentioned for the fractures, e.g. quartz veins, which are searched for by geophysical prospecting methods. Unfortunately, it sometimes happens that fractures and veins become clogged with clayey elements, or that the veins are completely crystallized and therefore have no aquifer potential.

It should be noted that the annual evapo-transpiration of the surface water is 500 mm, or 500,000 m^3/km^2, i.e. of an order of magnitude far higher than the rate of local consumption.

(b) Paragneisses rich in ferromagnesian elements (biotites)

The decomposition products of these rocks are essentially clayey, and hence impermeable, except where there are inclusions or interstratified rocks: peridotites and quartz veins. The available yields in such circumstances are much lower than in the previous case.

Rhyolites generally have poor yields in fractured zones overlain by a more or less continuous variable weathered zone. Compact quartz veins may act as impermeable dams blocking the flow of ground water, but they may also behave locally like aquifers.

Examples of available yields per well or bore-hole in crystalline areas

Country	Location	Geology	Yield per well (m^3/h)	Drawdown (m)	S %	K (m/d)	T (m^2/d)
Angola	South	Metamorphic rocks	0.6 (fractured)	-	-	-	-
	Catuiti	Weathered tectonized granites	3 to 30 (up to 80)	-	-	-	-
Chad	Ouaddaï	Granitic sands	2	-	-	-	-
Congo (Dem. Rep. of)	-	Granite-gneisses in weathered and fractured zones	(1 to 10 $m^3/h/m$)	-	-	-	-
Dahomey	Parakou	Fractured granites in tectonic depressions	7 to 8	-	-	-	-
Dahomey-Togo	-	Birrimian schists, quartz veins	3 to 7 (exception)	-	-	-	-
Ghana	-	Granites and granodiorites with quartz veins	(5 to 20 m^3/d)	-	-	-	-
Ivory Coast	Yamoussoukro	Fractured granites	6	-	-	-	-
Madagascar	Various	Weathered gneisses	0.4 to 1.2	-	-	-	-
Malawi	Various	Graphitic gneisses with biotite	2 to 5	-	-	-	-
Mauritania	Fort Gouraud	Mica schists and gneisses with pegmatite dikes and sills	(20 m^3/d)	-	-	-	-
	South-east	Diorites	0.5	-	-	-	-
Mozambique	Various	Rhyolites	Springs: 0.1 to 0.5 (wells 1 m^3/d)	-	-	-	-
	Various	Granites, paragneisses, orthogneisses	4 to 8	-	-	-	-
	Porto Amelia, Vila Pery	Granites, paragneisses, orthogneisses	12 to 20 (up to 25)	-	-	-	-
Namibia	Namaqualand	Gneisses and quartzites	1 to 20 (artesian)	-	-	-	-
Togo	Elavagnon	Mica schists and granite-gneisses	2 to 5	6 to 20	-	-	10 to 20
	Kandé	Chloritic schists with quartz veins	7 to 12	9 to 15	-	-	3 to 20
	Dapango	Alkaline granite-gneisses	(1 to 5 m^3/d)	-	-	-	-
	Palimé	Granites and granodiorites with amphibolites and quartz	(5 to 20 m^3/d)	-	-	-	-
Uganda	Karamoja	Acid gneisses	5 to 50	-	-	-	-
Upper Volta	Various	Mica schists	(less than 1 m^3/d)	-	-	-	-
	Various	Granite-gneisses	1 to 4	10 to 20	-	-	0.5 to 1
Zambia	Kalomo, Choma	Quartz veins	8 to 12	-	-	-	1.5

To sum up, 5 m^3 per hour is a good yield for granites and granite-gneisses; a yield of 1 m^3 per hour is appreciable for schists and mica schists. Better yields are obtained in quartzose zones.

4. Volcanic rocks

Lavas, particularly basalts and dolerites, and certain basic rocks which sometimes have large yields may be classified in a separate category; some examples are given below:

Jurassic basalts (Rhodesia) - artesian water: 8 m^3/h;

Bulawayo (Rhodesia) lavas, tuffs, etc., metamorphosed into greenstones: 8 to 15 m^3/h (70 in exceptional cases); some Rhodesian lavas have small yields, less than 1 m^3/h;

Basalts (Mozambique): 3 to 4, and up to 25 m^3/h, with drawdown of 5 m;

Stormberg basalts (Swaziland): 1 to 2.5 m^3/h;

Fissured dolerites in arid zones - Aioun el Atrouss (Mauritania): less than 0.1 m^3/h; unfractured: 0.2 to 0.3 m^3/h;

Karroo doleritic dikes (Swaziland): 1 to 4 m^3/h;

Basic rocks of Akjoujt (Mauritania): 30 to 45 m^3/h, with drawdown of 13 m;

Basic rocks of Conakry (Guinea): 13 to 72 m^3/h (in a very rainy tropical climate), with drawdown of 20 to 50 m;

Kongolikan (Upper Volta) greenstones, fractured: 3 m^3/h;

Weathered altered basic rocks (southern Angola): 7 to 12 m^3/h.

Volcanic rocks and basalts in particular, also yield considerable discharges, particularly at large springs, in other countries (Ethiopia, Morocco).

D. Conclusion

There is hardly any region of Africa where ground water cannot be found at greater or lesser depths. The largest yields are obtained from clay-free alluvium, continental or marine Cretaceous sandstone and karst limestone.

Most of the ground water is acceptable for human consumption, and certainly for livestock watering. The complicated question of water quality cannot be discussed in this report. In very general terms, however, we may state the following:

The ground waters of the arid zone generally have a calcomagnesian bicarbonate facies in the upstream portion, i.e. near the areas of infiltration from surface run-off. These grade into a sulphate facies, and finally a sodium chloride facies at the downstream end, in regions where evaporation is strong and acts directly on shallow reservoirs. This is true, in particular, of the continental sebkhas in northern Africa, on the edges of the Sahara.

Some geological formations, including in particular Permo-Triassic or Cretaceous formations of lagoonal origin, contain mineral salts which go into solution in the ground water. This is true in northern Africa and Mozambique, among other places.

In the coastal sedimentary basins, often consisting of permeable formations, pumping brings in sea water which tends to contaminate the fresh-water reservoirs.

In the Pre-Cambrian basement, in rainy tropical countries, the water tends not to be mineralized or aggressive.

Hydromineral and thermomineral springs are abundant on the African continent, in the fractured zones. They constitute a rich potential resource, of which only a small part has been explored and exploited.

PART II

GROUND WATER OF AFRICA, ARRANGED BY COUNTRY

GENERAL

A brief monograph has been prepared for each of the countries and territories of Africa, including certain islands, 6a/ and appears below. In most cases it has been divided into three sections: General: location, topography, climate, rainfall and surface hydrology; Geology: brief description of the country's geological features, giving a general idea of the aquifers; Ground water: areas surveyed, results, ground-water resources and their use, structure of government services and operations in progress.

The names of the countries and territories are those normally found on maps in current use. They do not imply recognition of the frontiers or boundaries of States or territories, or of political régimes, particularly in the case of territories under foreign domination or control.

The above disclaimer also applies to the outline map of the ground-water resources of Africa appended to this report.

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The population figures quoted for the various countries are taken from the December 1968 issue of the United Nations Monthly Bulletin of Statistics and refer to the months of June and July 1968.

6a/ Some islands such as the Canary Islands have been included in this study because of their geographical proximity to the African continent, even though the territories concerned come, in the United Nations system, under the Economic Commission for Europe.

ALGERIA

Area: 2,381,700 km^2; population: 12,500,000; North Africa.

General

Algeria is one of the largest countries in Africa and the largest in the north of the continent. Close to the Mediterranean, the relief is mountainous. The southern part of the country, where tabular forms predominate, includes a large section of the Sahara.

Apart from a few small coastal or inland plains, the Mediterranean part of the country is rugged, with an arc of mountains, the Tell Atlas, close to the sea. The range is 1,000 km long, with high peaks averaging between 1,000 and 1,500 m, while some exceed 2,000 m. Further south, a second, narrow arc of mountains, the Saharan Atlas, runs SW-NE and attains heights of 2,000 to 2,200 m. It meets the Tell Atlas in the region of the Aurès and Nementcha mountains. The High Plateaux, which decline towards the east from 1,000 to 400 m, extend between the two mountain chains. To the south lies the edge of the Sahara with vast sandy areas, known as ergs, covered with crescent-shaped dunes, and flat, stony desert areas or regs. Finally, in the extreme south, there are two groups of mountains: the Tassili (2,154 m in the Adrar section) and the Hoggar (3,000 m in the Atakor section).

The central portion of the Sahara region consists of the high Tademaït plateau (900 m), from which the land falls off to the south-west towards the Tidikelt and Taoudenni (Mali) depressions and to the north-east towards the depressions of the Chott Melrhir, the floor of which lies 30 m below sea level.

The coastal region has a semi-humid Mediterranean climate with rainfall of 500 mm (exceptionally 1,000 mm) per year over the whole of the eastern part and in certain areas (Tlemcen) in the west. The western part of the country, the southern slopes of the Tell Atlas, the High Plateaux and the Saharan Atlas are all in the semi-arid zone (rainfall between 200 and 500 mm).

The 100 mm isohyet follows the foothills of the Saharan Atlas and marks the start of the arid Saharan domain. Between the twenty-third and twenty-eighth paralells, the conditions are those of hyper-aridity, with highly irregular rainfall of less than 20 mm per year.

There is little surface water even in the Mediterranean region and its absence is particularly marked in the west. The main coastal rivers are, from west to east: the Tafna, Chéliff, Soummam, Oued el Kebir and Seybouse. On the High Plateaux, the watercourses run towards the flat-bottomed depressions, known as chotts, which are often covered with saline formations. The main Saharan river valley is that of the Saoura in the west.

The paucity of surface water in Algeria makes ground water exceptionally important.

Geology

The granito-gneissic Pre-Cambrian basement outcrops in the west (El Eglab) and the centre (the Hoggar) of the Sahara.

The basement is overlain by Palaeozoic sedimentary formations of mainly marine origin, which are Cambrian to Carboniferous in age and affected by Hercynian orogenesis. These formations outcrop: in the west, on the rim of the Tindouf basin; in the centre, north of the Hoggar, in the "Tassilian Enclave"; in the south-west, on the eastern edges of the Taoudenni basin, and in the north-west, in the Saoura and Béchar basins.

In the lowest-lying areas of these basins, the Palaeozoic sediments are covered by three sedimentary complexes:

The "Continental intercalaire", a comprehensive series of Post-Carboniferous to Ante-Cenomanian age and up to 1,000 m thick. It comprises detrital formations of sands, sandstones and conglomerates with lenticular intercalations of marls. These facies are comparable to the very similar formations, from 50 to 1,000 m thick, exhibited by the continental Albian in the Saharan Atlas and on the High Plateaux. Then come the Cretaceous (marine) and Tertiary formations in the centre of the basins; they form vast platforms - the hamadas - which are often entirely covered by the sandy formations (ergs).

A major tectonic disturbance separates the tabular African domain of the Sahara from the folded Maghreb (or Mediterranean) domain, which geologists also call "Barbary". The Barbary area comprises a geosyncline which was affected by two orogenic phases in the Eocene and Miocene epochs. The geological formations found there are basically Jurassic in the western part of the Atlas and Cretaceous in the east. Along the edge of the Mediterranean, both parts of Kabylia contain small crystalline and Palaeozoic units on the slope of the geosyncline.

The Jurassic beds are as much as 3,000 to 4,000 m thick in places. They consist of argillaceous deep-seas sediments and dolomitic limestones which form thick plateaux and folds in the area of Tlemcen and in the Saïda mountains.

The Cretaceous formations - limestones, schistoid marls, red sandstones and clays - make up three quarters of the mountains. They are thickest (3,000 to 6,000 m) in the Hodna range. The High Plateaux are extensively overlain by continental Cretaceous formations.

The Tertiary (thickness: 1,000 to 3,000 m) is represented by Palaeogene phosphatic limestones, sandstones, marls and schists and by various Neogene formations of lacustrine and continental origin which cover the depressions and particularly the inland plains (Chéliff, Mitidja).

The structural geology of the Barbary area is complex: folds, overthrusts and areas of warping are very numerous and very close together, especially in the Tell Atlas.

Ground water

In Algeria, research into ground water is the responsibility of a special service within the Water Department of the Ministry of Public Works and

Construction, the Service des études scientifiques appliquées à l'hydraulique (SES). This service, which was established in 1942 and also carries out studies in hydrology and agropedology, is responsible not only for ground-water resource prospection and inventory, but also for planning and supervising the construction of such installations as bore-holes and pumping stations, particularly those intended to serve population centres.

The SES has built up a file, which it regularly updates, of wells and similar constructions. It is also responsible for surveillance operations and monitoring of ground-water bodies. Geophysical work and drilling are carried out by specialized companies selected on the basis of tenders; SES has over-all charge of such work and as such is responsible for project design and control.

In 1968, the staff of SES included 22 hydrogeologists and hydraulic engineers, of whom two were Algerian nationals and the rest foreigners. There is a total of approximately 30 water-drilling rigs of widely differing types, some of which are quite old, available in Algeria; they are owned by six companies, one of which is Algerian. The total depth drilled each year is between 5,000 and 15,000 m. The Government has a few light rigs which are used to drill piezometric bore-holes.

In recent years, several bilateral and international aid organizations have taken part in the investigation and development of ground water, the main projects being:

UNDP-UNESCO: Project to survey water resources in the northern Sahara (assessment of the potential of the aquifer in the "Continental intercalaire");

UNDP-FAO: Development study of the Hodna region; a large part of this project is devoted to prospecting for ground water.

France: Secondment to SES of hydrogeological engineers.

USSR: Execution of a water-drilling contract (1964-1967) in the wilayats in the regions of the Oases, the Aurès Mountains, Médéa and Saida; the total depth drilled was 15,000 m. A second phase of operations (12,000 m in three years) got under way in 1969.

In addition, foreign companies have been called in to carry out geophysical prospecting and to make quantitative studies of certain aquifers by means of electrical and mathematical analogues.

The number of hydrogeological studies made in Algeria is considerable. The ground-water bibliography includes 115 regional studies (monographs), which cover all the plateaux, plains and valleys, and over 1,500 reports. The hydrogeological and water-resource maps made include the following:

A provisional 1:500,000 map of ground-water sources (1961); a hydrogeological map of the high steppe plains (1968); a 1:200,000 map of water resources (Constantine sheet; work on other sheets is in progress. Hydrogeological maps at 1:500,000 are now being prepared (sheets for Maghnia, Eghris, Mitidja, the valleys of Kabylia and Annaba).

At present, most urban agglomerations and industrial centres, as well as certain irrigation projects, rely on ground water.

The material presented above shows how crucial ground-water discovery and use are for Algeria. There is thus a need to expand the activities of the services concerned with ground water; this will no doubt entail the training of many Algerian specialists and technicians.

The main ground-water reservoirs and their potential annual yield are shown in the summary table below. The figures are intended merely to give an idea of the size of the main aquifers and of their economic importance.

Description of aquifer	Potential annual yield (millions of cubic metres)	Remarks
(a) Aquifers in Quaternary and Plio-Quaternary alluvium (from west to east)		
Oued Tafna	6	Little used
Maghnia	15	Used from 1969
Bel-Abbès	15	Partially used
Eghris	30	Used (recharge from Upper Jurassic dolomites)
Chéliff	30	Not used
Sersou	15	Little used
Mostaganem	15	Used
Central high plains	26	Little used
Mitidja	250	Partially used
Oued Sébaou	32	Little used
Oued Isser	19	Little used
Oued Soummam	40	Little used
Sétif Plateau	22	Used
Plain of Annaba	50	Little used
(b) Aquifers in carbonate rocks		
Tolga, Eocene limestone	80	Fully used
Dolomites (Aaleno-Bathonian and Senonian) of Chott ech Chergui	60	Not used
Saïda, dolomites (Aaleno-Bathonian)	20	Not used
Jurassic dolomites	(30)	Not used
Aïn M'lila, Cretaceous limestones	23	Fully used

Description of aquifer	Potential annual yield (millions of cubic metres	Remarks
Hamma, Cretaceous limestones	22	Fully used
Miocene limestones	22	Used from 1969
(c) Extended aquifers in the Saharan basin		
"Continental intercalaire"	300	Little used
"Continental terminal"	240	Used

ANGOLA

Area: 1,246,700 km^2; population: 5,300,000; southern Africa, Portuguese administration.

General

Most of the country is occupied by a plateau (elevation 1,000 to 1,500 m) which falls away to the basins of the Congo and Zambezi rivers. In the west there is an upland which strikes north-south; relief is gentle with some summits exceeding 2,000 m. The western slopes are steep, particularly in the Serra da Chela, which forms an escarpment 1,000 m high.

The coastal Namib Desert extends northward from Namibia along the coast of Angola, where conditions are even more arid, to a point 100 km north of Moçâmedes The coastal region immediately inland from and to the north of the Namib Desert has a semi-arid climate. The whole of the country to the east of the highlands lies in a tropical humid zone and has an annual rainfall of from 1 to 1.50 m or more.

Geology

The country comprises three major geological units:

On the coast, a narrow sedimentary basin of Cretaceous-Tertiary age;

In from the coast, over two thirds of the country, the Pre-Cambrian Crystalline basement, which is overlain by formations of the Bembé system;

In the interior of the country, the "Continental intercalaire" and the Quaternary formations, together with continental sediments of the Karroo system, which outcrop locally;

In the centre, Pre-Cambrian formations comprising: the granito-gneissic basal complex; the sandstones and quartzites of the Oendolongo system, producing the highest mountains; and the Bembé system (Terminal Pre-Cambrian or Infra-Cambrian), which has at the bottom a shaly limestone series and at the top a series of sandstones, conglomerates and quartzites.

The Karroo is represented by sandstones and shales (500 m) cut by intrusive dolerites. The Kalahari (Tertiary) is represented by sandstones and ochre sands. The Quaternary deposits are similar to those found in the Democratic Republic of the Congo.

On the coast, the Cretaceous seas developed two gulfs, those of Luanda and Moçâmedes: the corresponding sediments (Aptian-Maestrichtian) are 150 m thick. The area covered by the Tertiary seas was roughly the same in extent (1,200 m of sediments ranging in age from Palaeocene to Pliocene).

Ground water

Prospecting for sources of ground water utilizable by both human beings and livestock has been concentrated mainly in the south-western quarter of the country (south of Lobito), where the climate is semi-arid. In the six years from 1958 to 1964, 1,300 bore-holes were sunk (of a total of 4,400). Of this number, 322 were fitted out as operating wells with a total yield of 1,500 m^3 per hour; most are in the area where the crystalline basement is more or less covered by Kalahari sands. Many of the wells yield between 1 and 7 m^3/hr. Others have higher yields, notably up to 30 m^3/hr at Catuiti, in an area of fractured and tectonized gabbros. One structural study showed that there was a direct link between the rate of flow and tectonic direction (i.e. the strike of fractures). Thus, when the strike is NE-SW, yield is less than 3 m^3/day; for an E-W or NW-SE strike, yield is between 3 and 8.5 m^3/day, and for a N-S strike it is over 8.5 m^3/day.

The depth of the wells is, on average, from 5-7 m to 15-20 m, sometimes 20 to 35 m and exceptionally 40 to 60 m. Initial site selection is made by means of a photogeological survey; the preferred sites are close to watercourses or to geological dislocations which cut across them. Geophysical surveys (electrical and microseismic prospecting) have also been carried out in large numbers. The strata most likely to contain water in the basement are: veins of quartz and basic rocks, the contacts between crystalline rocks of differing texture and composition, areas where fractured granite-gneisses outcrop and the contacts between eruptive and quartzo-schistose rocks.

The Kalahari sands and sandstones can be as much as 600 m thick. In some cases, geophysical prospecting techniques have been employed to seek for fossil valleys in sandstone-limestone sedimentary formations overlain by Kalahari sandstones (Cune River region).

In the coastal sedimentary basin, the best and practically the only aquifer consists of the white, argillaceous alluvial sandstones which fill the fossil valleys. The water, which contains few dissolved solids, is sometimes tapped by means of underground barrages.

Drilling has revealed the presence of artesian water beneath certain flat areas of sands and clays covered with savanna vegetation known as chanas.

BOTSWANA

Area: 570,000 km^2; population: 600,000; southern Africa.

General

The Republic of Botswana occupies a vast desert plateau, the average height of which is 1,100 m above sea level. Some raised groups of hard rocks, covered with dense, spiney steppe vegetation, run in a narrow band along the eastern border. The bulk of the population lives in that area, it being the least barren part of the country. To the west stretch large desert steppes which slope down towards the Kalahari depression, which is covered with red sands.

The north-west of the country has a tropical climate. It contains the vast, swampy inland delta of the Okavango River, which is the terminal point for several rivers flowing from the plateaux of Angola. The overflow from the Okavango runs off into the great Makarikari salt-pan, which lies downstream. To the south, the frontier of the country follows the courses of two major rivers, the Limpopo and the Molopo.

In most areas of the country, rainfall is less than 250 mm per year. The most arid regions of the Kalahari receive less than 100 mm of rain per year.

Geology

The main formations which outcrop along the edges of the Kalahari sand desert are: Pre-Cambrian granite-gneisses and schists, dolomitic limestones of the Terminal Pre-Cambrian, Waterberg conglomerates and sandstones (2,000 m; Terminal Pre-Cambrian) and thick formations of Karroo shales and sandstones.

The Kalahari sands (of Plio-Quaternary age) are as much as 40 m thick.

Ground water

Attempts to develop and utilize ground water began in Botswana many years ago. Since 1929, when the Government sank the first bore-hole, more than 2,200 wells have been drilled. A similar number of wells has been sunk by private companies.

The interest in ground water results from the fact that over huge areas of the country there is practically no surface water, since rainfall is very slight and the ground is covered with highly permeable (Kalahari) sands. Prior to 1964, all towns of any size and the country's only major industry (an abattoir and canning plant) relied entirely on ground water. Although dams have been built recently in the Gaborone and Lobatse regions, it is estimated that at least 75 per cent of both the human population and livestock still depend wholly or largely on ground water.

Since 1955, the Botswana Geological Survey has considerably increased its activities with regard to ground water and, in April 1959, it was made responsible for the Government drilling service. The Geological Survey has also undertaken to promote the development of ground-water studies, particularly in the following fields: ground-water reserves, permissible pumping rates, recharge and improvement of geophysical prospecting techniques. Its specialized staff includes two hydrogeologists, five to seven scientific assistants and junior personnel.

The Government drilling service sinks approximately 100 to 130 wells per year, using three high-speed compressed air rigs and seven percussion rigs. Most of the wells are drilled at the request of the Government or local authorities or, at their own expense, at the request of livestock farmers. It is planned to drill and equip 75 wells under the Borehole Repayment Scheme. The cost will be covered by loans from the National Development Bank to farmers who, either as individuals or in groups, offer adequate guarantees.

Some 12 to 14 drilling rigs belonging to private firms or individuals are currently operating in Botswana, drilling 100 bore-holes per year. Recently, the growth in the population, improvements in living conditions and agricultural development techniques and the possibility that large-scale mining industry will be established have led to an enormous increase in the demand for water. To meet this demand, it is proposed to increase the number of drilling teams by 50 per cent in the next few years. Ground water in Botswana is generally associated with secondary porosity resulting from weathering and the formation of joints, fissures, indurated contact surfaces, faults, dikes and sills. This means that flows are generally modest: only 17.4 per cent of the wells produce more than 8 m^3/hr, while 27.8 per cent produce 0.4 to 2 m^3/hr.

Storativity and transmissivity are thus very low. The best aquifers in Botswana are decomposed granitic rocks, including: the heavily folded metamorphic rocks of the crystalline basement, all the stages of the Transvaal system, the folded sandstones and conglomerates of the Waterberg system, the schists and quartzites of the Ghanzi formation, the Karroo sandstones (Ecca), and the contact between the lavas of the Drakensberg and the sandstone horizons of the Stormberg series (Karroo), this last aquifer being one of the best.

The bore-holes drilled by the Government currently yield a total of more than 4,000 m^3/hr. Modern (geological and geophysical) methods of determining favourable sites for future wells are now being employed by the Geological Survey, raising the percentage of productive wells from 45 per cent to 71 per cent, while the average yield has increased by some 25 per cent. Wells yielding less than 400 litres/hr are considered to be dry. Even though drilling operations have been extended to the most difficult areas, drilling rates continue to rise.

Geophysical prospecting is carried out by the resistivity and spontaneous potential, magnetic and seismic (reflection and refraction) methods. New methods for quantitative interpretation of the resistivity data have recently been introduced.

Hydrogeological investigations will proceed as rapidly as the staff and funds available permit. The long-term objective is to produce an accurate and detailed map of Botswana's ground-water resources. This is particularly necessary for long-term economic planning, since vast areas of the country have no surface water at all and there is little potential for further development of that which is found in the east.

Detailed ground-water studies are now in progress in the Lobatse, Molotoana, Mosomane, Serowe, Francistown, Ghanzi, Orapa and Letthakeng and Morwamosu areas. Particularly detailed studies are in progress at Serowe and Lobatse, dealing especially with the relationships between water levels, withdrawal rates and rainfalls. Automatic level-recording devices have been installed at a number of wells. Ground-water dating studies have been made using tritium and have given important information on storage capacity, recharge areas and flow rates in the Serowe and Lobatse regions.

Radio-carbon dating in the Kalahari indicates an age in excess of 25,000 years, showing that the current recharge rate is very low. This confirms the evidence of laboratory studies that there is no recharge of the underlying horizons when the sandy overburden is more than 7 m thick.

At Lobatse, detailed studies over a period of more than 15 years have made it possible to assess the storage capacity, increase by 100 per cent the output of the Nuane barrage and provide the town with an emergency supply sufficient for eight months.

At Serowe, research has shown that there is at present no noticeable decrease in resources, although there will be a serious water shortage in the future when consumption, which is at present 5 litres/day for 97 per cent of the population, rises.

In addition, scientifically conducted pumping tests have been carried out at Orapa, Selebi-Pikwe and Lobatse to determine storativity and transmissivity values. Observation bore-holes have been installed in the north and central Kalahari and piezometric contours have been mapped, so that the direction of underground flow can be determined. It is intended to acquire an electric logger. Regular chemical analyses are made of water samples and temperature readings. New (geophysical and other) prospecting methods are also being tried out. Legislation such as the Borehole Proclamation of 1956 and the Water Act of 1967 make it obligatory to provide the Geological Survey with soil samples taken every 3 m in wells, and with the results of pumping tests. It is also laid down that all extraction of ground water is subject to official authorization, unless the water is intended for domestic use.

BURUNDI

Area: 28,000 km^2; population: 3,300,000; central Africa.

General

Burundi is a small, heavily populated and mountainous equatorial country, bordering on Lake Tanganyika. It is crossed by a river, the Kagera, which flows into Lake Victoria and whose source is considered to be the source of the Nile. The country's average elevation is 1,500 m, and the annual rainfall exceeds one metre in all areas.

Geology

To the west is Lake Tanganyika, which lies in a huge subsidence trough between two large faults. The whole of the country consists of the crystalline formations of the Pre-Cambrian basement with, in the south-east, the Infra-Cambrian dolomitic, shale and sandstone formations of the Malagarasi series.

Ground water

The main geological formations tested by trial bores are the gravels, sands and detritus which fill the subsidence trough and give specific yields from 0.2 to 15 l/s per metre of drawdown. Some bore-holes in the Infra-Cambrian limestones and sandstones have yielded 0.2 to 2 l/s/m.

Bore-holes have been sunk in the plains of the Ruzizi River (150 wells to supply the local population and for livestock), Lake Tanganyika (50 wells) and the Mosso district (100 wells).

The main water requirements which must be met in the immediate future are: 1 million m^3/yr in the plain of the Ruzizi, where the quality of the ground water gives rise to some difficulties; 5 million m^3/yr for the town of Bujumbura, its port and industries; 1 million m^3/yr for the plain in the dry Mosso district, an area covered by laterites and carbonate rocks; and 1 million m^3/yr for the plain to the east of Lake Tanganyika. Finally, approximately 10 small urban centres, including Gitega and Ngozi, each require some 100,000 m^3/yr.

CAMEROON

Area: 475,400 km^2; population: 5,500,000; central Africa.

General

Cameroon extends for 1,500 km between the Atlantic (shoreline: 350 km) and Lake Chad. Through it runs a chain of mountains, the Massif de l'Adamaoua (1,500 to 2,500 m), which divides the country into the northern savanna region (altitude 300 to 500 m) and the southern plateau region (700 to 1,000 m), which is covered by equatorial forest. The coastal plain is dominated by Mt. Cameroon (4,070 m). The south of the country is drained by the Sanaga and the Nyong which flow into the Gulf of Guinea; the north is drained by the Bénoué, a tributary of the Niger, and the Logone, a tributary of the Chari. The latter flows into Lake Chad and periodically floods the northern part of the country.

Rainfall in Cameroon is among the highest in Africa (more than 2 to 4 m per year in the south, and from 0.5 to 0.7 m in the north).

Geology

The Pre-Cambrian basement outcrops over most of the country, exhibiting the following: the Lower Pre-Cambrian (crystalline schists and older granites); the Middle Pre-Cambrian (amphibolitic schists, lavas, quartzites and granitic bodies), and the Upper Pre-Cambrian (shales, tillites, sandstones, andesites, rhyolites and granitic bodies).

The ancient basement is overlain by the Jurassico-Cretaceous formations of the "Continental intercalaire" with marine episodes, which outcrop locally in the west and north; there are shales and sandstones, mottled clays, marls and limestone lenses.

The marine Cretaceous (1,000-2,000 m of sandstones and limestones) is found in the Douala coastal basin and in the Upper Bénoué.

The Eocene-Oligocene is very thick (1,500 m) in the Douala region.

A series of large parallel fissures runs across the country from north-east to south-west, forming in particular a trough (a sort of rift valley) bordered by faults, with scarps as much as 1,000 m high. Along the centre line of this trough there are large volcanic massifs of varying age and composition in a remarkable chain which extends as far as the volcanic islands of Fernando Póo and São Tomé in the Gulf of Guinea.

In the extreme north of the country are the sedimentary sands and clays of Tertiary and Quaternary age of the Chad Basin.

Ground water

Most of the ground water investigations in Cameroon have been carried out in the regions north of the Adamaoua mountains (north of the eighth parallel). Since 1962 there has been a water office at Garoua; this was preceded by a hydrogeological mission established in 1953. In May 1969, a federal hydrogeological service was set up, with headquarters at Garoua. It is responsible for keeping an inventory of ground-water sources, for making a systematic survey of aquifers and a hydrochemical study of the water found and for protecting water resources by controlling their use.

Several large-scale regional surveys have been made in northern Cameroon since 1961, each of them covering a particular hydrogeological unit of this region where 1,200,000 inhabitants are scattered over an area of 150,000 km^2. The surveys concerned:

The reservoirs which lie at the base of the crystalline massifs and flow NNE in the direction of Lake Chad, the reservoirs of the great flats (alluvial plains) and dune lines and the surface reservoirs in the piedmont area;

The Mandara Mountains, an area of denuded crystalline massifs on the Nigerian border where there is insufficient water for the very dense population;

The sedimentary basin of the Bénoué river, which is mainly composed of Cretaceous sandstones, and three less extensive sedimentary basins which strike depressions oriented east-west in the crystalline shield. In 1966-1967, 20 bore-holes were drilled to a maximum depth of 420 m;

The Chad Basin, where geophysical prospecting has shown the southern limit of the area of artesian water to correspond roughly to the 250-300 m isobath of the crystalline basement. Many flowing wells have been drilled in this Basin in Nigeria, close to the border with Cameroon. One bore-hole has been drilled in the Waza National Park, three at Logone Birni to the north-east of Waza and two at

Fort Foureau as part of the FAO-sponsored hydrogeological project in the international Lake Chad Basin.

The areas of surface water on the Logone-Chari-Chad alluvial plain, where the establishment of watering points will permit settlement for the purpose of cultivating cotton. This study was completed in June 1969.

A maximum of 100 wells per year is drilled in the northern districts. The Government Water Bureau drills an average of 150-250 exploratory bore-holes per month. Official records list a total of more than 2,000 modern wells.

Generally speaking, most of the major population centres in the crystalline basement region suffer from a shortage of water, particularly in the Mandara Mountains. Recent surveys have determined the siting of several thousand new wells.

The search for water in the crystalline formations, which constitute nine tenths of the country, and the formations of the Chad Basin is hampered by the nature of the aquifers (fracture zones, gravelly and sandy lenses intercalated in a mass of mainly argillaceous deposits). The best aquifers are the sandstones of the Bénoué Basin, where wells 50 m deep (at Garoua) have yielded 50 m^3/hr for a drawdown of 10-15 m.

Elsewhere, both in the Chad Basin and the crystalline basement, the yield from wells is often of the order of 2-5 m^3/hr at most. From 1954 to 1960, a hydrogeological mission made 30 local studies (concerning water for population centres) in the southern part of the country, within the tropical humid zone. In 1968, France's Office de la recherche scientifique dans les territories d'outre-mer set up a hydrogeological mission to study the thermal and hydrothermal springs in Cameroon and particularly on the Adamaoua plateau. No hydrogeological study has yet been made in the département of Mbam or in the north of the Federal State of West Cameroon, although the problem of supplying their inhabitants with water is just as acute as in the northern portion of the country as a whooe.

In 1970, Cameroon had no operating motor-driven drilling rigs. Two hydrogeologists were in service at Garoua.

CANARY ISLANDS

Area: 7,800 km^2; population: 1,100,000; archipelago off the north-west coast of Africa; Spanish administration.

General

The Canaries archipelago comprises seven volcanic islands, five in the west, ranging in height from 1,500 to 3,000 m and receiving 300 to 500 mm of rain per year, and two in the east, with no major relief features and rainfall of only 50 mm. Despite the low rainfall, fog is frequent and the high level of atmospheric humidity has led to forest development and the growing of tropical and Mediterranean crops. There is no perennial watercourse in the archipelago.

Geology

The Islands' basement consists of doleritic basalts of Cretaceous age overlain by lava flows of varying ages: Nummulitic (rhyolites), Miocene (trachytes, phonolites and tuffs), Pliocene (plateau basalts) and Quaternary (basalts). There appears to have been a marine transgression in the Miocene, depositing sediments, some outliers of which have been located.

Ground water

Ground water drawn from wells and drainage galleries, which are often over-exploited, 7/ is the only reliable source of water on the Islands, since surface water supplies are scarce and intermittent. The situation in the Islands may be summed up as follows:

Grand Canary, with a population of 500,000, has 2,800 wells, 360 galleries and 10 springs, for a total yield of 5 to 6 m^3/sec; a fifth of these sources are affected by the intrusion of salt water. The piezometric surface is falling rapidly in some areas. Water requirements amount to approximately 35 million m^3/yr. It is proposed to install a desalination plant;

Tenerife, with 400,000 inhabitants, has 73 wells, 485 galleries and 54 springs; it has an adequate supply of good-quality ground water;

Lanzarote, which has 40,000 inhabitants, has insufficient water of good quality and a desalination plant has been built. The same will have to be done on Fuerteventura, an island with 17,000 inhabitants, where the water contains between 0.5 and 2 grammes of sodium chloride per litre. At present, drinking water has to be brought in from Las Palmas.

The ground-water potential of the Canary Islands has not yet been studied in any great detail. A UNESCO expert undertook a short preparatory mission for this purpose in 1967. The Government also requested UNDP assistance for a study of the hydrological balance of the Islands, and this project, which is being carried out by UNESCO, was started in 1970.

CAPE VERDE ISLANDS

Area: 4,033 km^2; population: 250,000; archipelago lying 400 km off the west coast of Africa; Portuguese administration.

General

The group comprises 15 volcanic islands having rugged terrain. Annual rainfall is, on average, from 200 to 450 mm, but exceeds 800 mm on the mountain peaks. Both temperature and evaporation are high.

7/ On Grand Canary, recharge is estimated at approximately 100 million m^3/yr, whereas the withdrawal rate is almost double that figure.

Geology

The Cape Verde Islands contain the following geological formations: Upper Jurassic (limestones); Lower Cretaceous (metamorphic limestones (250 m), marls, clays and basalts); Eocene (marls); Miocene (basalts, trachytes and phonolites ejected during a major volcanic phase); Upper Miocene (limestones overlain by Pliocene and Quaternary basaltic lava flows).

Ground water

Most of the geological formations are permeable. Water which does not evaporate filters rapidly downwards and flows to the ocean, making extraction difficult.

Near the coasts there is evidence of the progressive intrusion of salt water, particularly in the permeable limestones, which are over-exploited in certain areas. The ground water becomes softer during the rainy season. The main towns are supplied by means of wells and galleries. The entire archipelago suffers from a shortage of water.

CENTRAL AFRICAN REPUBLIC

Area: 623,000 km^2; population: 1,500,000; central Africa.

General

This land-locked country comprises a large plateau 500 to 700 m high, bordered in the south by the Bomu and Oubangui rivers, the latter being a tributary of the Congo, and in the north by the River Chari, which flows into Lake Chad. Two low mountain groups rise from the plateau; they are: in the north, the Yadé mountains, which reach 1,400 m (Mt. Gaou), and in the north-east, the Massif des Mongos (1,400 m). Equatorial forest is found only along the southern edge of the country.

The climate is hot and humid, with 0.8 to 1 m of rain per year in the north and 1 to 1.4 m in the south. There are two dry seasons, from November to March and from June to July. There are numerous watercourses, most of which are tributaries of the Oubangui.

Geology

Pre-Cambrian formations are widespread. They include: the ancient Pre-Cambrian with granite gneisses and migmatites; the Middle and Upper Pre-Cambrian with schists and quartzites, and also young granites (Yadé and Mongo massifs); the Lower Terminal Pre-Cambrian: shaly limestones with stromatolites; and the Upper Terminal Pre-Cambrian with quartzites and sandstones, in the south of the country.

The Lobaye basin, to the west of Bangui, is lined with argillaceous and conglomeratic sandstone formations attributed to the "Continental intercalaire" (Cretaceous). Further east, to the south of the Massif des Mongos, the

Ouadda-Ndélé plateau is composed of thick sandstone formations which are contemporaneous with those mentioned above; the upper part seems to be the equivalent of the Batéké sandstones of the People's Republic of the Congo, which belong to the "Continental terminal".

Ground water

A very small number of local surveys has been made with a view to providing a water supply for the population centres of Fort-Crampel, Berbérati and Bambari and for a factory at Bangui. Some deep wells have been sunk in the Birao area. In view of the abundance of surface water, it has not been thought worthwhile to undertake any large-scale activity in respect of ground water. Hydrogeology comes within the purview of the Department of Mines and Geology (Direction des mines et de la geologie), but there is no ground-water specialist serving in the Central African Republic.

From 1967 to 1969, approximately 400 wells were built with the aid of the Fund for Aid and Co-operation (Fonds d'aide et de coopération), as part of the French bilateral aid programme, and with the support of the European Development Fund.

Ninety per cent of these wells were productive. They encountered phreatic water at a depth of between 3 and 15 m, depending on local conditions, in the weathered layer above the crystalline basement.

In the M'Baïki series (argillites and sandstones, fissured quartzites), the results were less successful; the water body here is generally deep (25 to 28 m). Seasonal variations in the water-table can be as much as several metres; the level is highest in November, at the end of the rainy season.

No measurements have been made of yields, but there is no case in which local consumption exceeds the capacity of a well. The water requirement of the villages is estimated at one well per 200 inhabitants, at a cost of $US 14-28 per metre for a well dug by hand.

One drilling company is based at Bangui.

CHAD

Area: 1,285,000 km^2; population: 3,400,000; central Africa.

General

The Republic of Chad occupies the eastern part of the Chad basin, which contains Lake Chad in its south central portion. The western frontier of the country passes through the middle of Lake Chad.

From south to north, this vast country is divided into three zones which differ greatly in relief, climate and population.

South of Lake Chad (12,000 km^2) extends a tropical zone with an area of 400,000 km^2 and a population of 2 million, in which rainfall is abundant (1.2 m at

Fort Lamy and 600 mm at Fort Archambault). Lake Chad is fed by an important inland river, the Chari, and its tributary, the Logone. The altitude in the southern part of this zone is less than 500 m; it reaches 1,200 m at Mount Guéra, about 350 km east of Fort Lamy.

Further north lies the Sahelian zone, with an area of about 400,000 km^2 and a population of more than 1 million. This is flat country (250 to 300 m), rising in the east to the Ouaddai plateaux (500 to 700 m).

Lastly, the northern part of the country is dominated by the great Tibesti massif (3,415 m) and the high plateaux of the Ennedi (1,450 m); it has a population of about 100,000 pastoral nomads, who live in a very dry region (less than 200 mm of rainfall).

Geology

The Pre-Cambrian basement crops out along the Chad basin edges, which for the most part lie outside the frontiers of the country. Within the territory of the Republic of Chad, the basement is found only in the Ouaddai and, in rare and limited outcrops, between Lake Chad and Lake Fitri, where the basement appears in the form of rhyolites and granitic rocks.

The bottom of the Chad cuvette is occupied by sandstone formations of the "Continental intercalaire", which crop out along the southern edge. The higher horizons in the north contain Cretaceous marine deposits of a thickness estimated at about 400 m, and above this the "Continental terminal", which is also very thick. The thickness of the sedimentary formations, which exceeds 1,000 m in the Bornu area of Nigeria, is unknown in Chad. Much of the country is covered by aeolian sands or Quaternary formations.

The Tibesti-Borku and the Ennedi are plateaux of Palaeozoic sandstones resting on the Pre-Cambrian basement. They include the following assemblages: the Cambro-Ordovician, consisting of 500 m of more or less hard or weathered sandstones; the Gotlandian, containing argillaceous sandstones of the Borku; and the Devonian-Carboniferous, with calcareous sandstones. They have been marked by violent eruptions, the most important of which took place during the Quaternary, with basalt deposits covering 60,000 km^2. Quaternary lacustrine limestone formations have been found in the Tibesti.

Ground water

In the crystalline areas there are local aquifers known as "rock" aquifers, underflow aquifers or alluvium aquifers.

The structure of the aquifers in the Chad basin is extremely complex. In this region the "Continental intercalaire" is the equivalent of the Nubian Sandstones. It includes sandy clays in a lenticular arrangement, overlain in the south by the Chad series (Post Eocene).

The piezometric surface of the ground water, sometimes under a small head, varies from sector to sector. It generally lies at a depth of 10 to 20 m. While it sometimes rises almost to outcrop level, it may also lie at a depth of more than 100 m. Perched water exists in some locations.

At Fort Lamy artesian aquifers have been found by means of borings into the siliceous sands and silts. All of the semi-deep aquifers are under some head and are exploited by bore-holes equipped with pumps. The first flowing artesian well (6 m) was drilled as part of the FAO project north of Fort Lamy.

The development of hydrogeological studies, particularly in the Upper Chari and the Logone area, dates chiefly from the period after 1960.

A 1:500,000 hydrogeological map of the part of the country south of the eighteenth parallel has been prepared (individual sheets on the Aouk-Salamat, Moundou, Fort Lamy, Bongor, Batha, Mao, Largeau and Lowlands areas). Studies have also been made in connexion with transhumance trails in the central, eastern and southern parts of the country.

In 1969 Chad had a total of 1,000 wells and 78 exploitation bore-holes, including 32 for the city of Fort Lamy.

In 1966, sites were located for 165 wells in the Chari-Baguirmi, 51 in the Batha, 13 in the Ouaddai and 18 in the Biltine area. These wells have been constructed with the aid of the European Development Fund (FED), which also financed the initial geophysical surveys and reconnaissance bore-holes (116 bore-holes in 1963). In Kanem prefecture 153 additional wells will be constructed by FED beginning in 1970.

A United Nations hydrogeological mission has been studying the Melfi-Likkine area (east of Fort Lamy) since October 1968 and has prepared a five-year hydraulic development plan. Execution of the UNESCO-FAO project providing for a survey of the water resources of Chad and the three other countries bordering on Lake Chad was begun in 1967; the centre of operations for the project is at Fort Lamy. UNESCO has prepared a comprehensive hydrogeological survey of the Chad basin, while FAO is investigating the potential utilization of its water resources.

Several sources of hot water inventoried in the Tibesti, in particular at Soborom, may be related to local faults.

The fossil valley of the Bahr el Ghazal, extending from the Tibesti to Lake Chad, contains some local reservoirs of potable water in the alluvia or sands. Towards the north it acts as a natural drain for the general ground-water reservoir of the basin ("Continental terminal"). There are also other drainage zones of this kind towards the north.

In 1970 the Chad Government employed one foreign hydrogeologist, who had six drilling rigs of various kinds at his disposal. Most of the drilling work is done by foreign companies. Two drilling companies have their headquarters at Fort Lamy.

COMORO ISLANDS

Area: 2,000 km^2; population: 220,000; archipelago between the African coast and Madagascar; French administration.

General

The Comoro archipelago comprises four islands, Grand Comoro, Anjouan, Mohéli and Mayotte, all of which are volcanic in origin. Grand Comoro is dominated by Mt. Karthala (2,361 m), an active volcano. The climate is tropical. Annual rainfall is 1 to 2.5 m along the coasts, but increases rapidly with altitude (up to 2.5 m or even 6 m and more on the mountain peaks). There is sufficient surface water available on Anjouan, Mohéli and Mayotte, but not on the rock of Dzaoudzi, a small island close to Mayotte and the former capital of the archipelago. There is no surface water supply on Grand Comoro, where the inhabitants collect rain water in cisterns installed in each house. There are also a few small springs at high altitude.

Geology

The islands probably lie on a crystalline base. They are made up of volcanic rocks. There were several volcanic phases separated by repose periods during which erosion occurred. The most common rocks, except on Grand Comoro, are basaltic lavas and some acid rocks.

Ground water

A large part of the population is concentrated on the coasts, particularly at Moroni, the capital of Grand Comoro, and in nearby villages. Wells have been sunk 2 km from the shore to reach the fresh water lens which lies on top of sea water. The chloride content is of the order of 200 ppm. 8/ The yield is 200 m^3/hr for a drawdown of only 10 cm, for the permeability of the basalts is very high. Financial support for the production and distribution facilities comes from bilateral and international sources (from France and the European Development Fund respectively).

It is also intended to install a water supply system for the other coastal population centres.

Work has been started on a UNDP/FAO project to make the bottoms of the craters impermeable, with a view to using them as rainwater storage areas.

DAHOMEY

Area: 112,600 km^2; population: 2,500,000; West Africa.

General

The country lies on a north-south axis between Togo and Nigeria and is wider in the north (350 km) than the south (125 km coastline on the Gulf of Guinea). The maximum altitude is between 500 and 800 m in the Atacora range in the north-west.

8/ The abbreviation "ppm" stands for "parts per million", e.g. milligrammes per litre.

The hydrographic network comprises two basins: the southern, containing the coastal rivers (Mono, Couffo, Ouémé, Okpara), and the northern, containing several tributaries of the Niger and part of the Niger itself, forming the north-east frontier with the Republic of the Niger. Rainfall is of the order of 1 m (1.25 m in the centre of the country and 750 mm in the north).

Geology

As the geological structure of Dahomey is very similar to that of Togo, reference should be made to the section concerning that country.

Pre-Cambrian basement formations

The Lower Pre-Cambrian (Dahomeyan), consisting of granite-gneisses and mica schists, extends over the whole of the country except the north and south.

The Middle Pre-Cambrian (Atacorian), consisting of quartzites, is found in the Atacora range, which runs across the north-west of the country.

The Upper Pre-Cambrian (Buem) occurs in the form of a narrow belt lying alongside the Atacora range in the west.

Sedimentary basins

The Oti basin, which is composed of intercalary Cambrian sandstones and shales, such as the Kandi sandstones, is situated in the north-west of the country.

The southern sedimentary basin has the same structure as the corresponding basin in Togo.

Ground water

Hydrogeological reconnaissance and geophysical prospecting (both electrical and seismic) have been carried out in the densely populated areas since 1958. Efforts have been concentrated mainly on the granitic sand aquifers, the fracture zones and the coastal sedimentary basin; the latter, as well as the major towns, whose water supply has often posed serious problems, has been the subject of detailed surveys.

The most important of the recent surveys include:

1961: geophysical (electroseismic) prospecting in the area of Savé, Dassa-Zoumé, Savalou and Djougou, where the crystalline basement lies just below the surface, with granitic sand aquifers and fractures having a low yield;

1961-1962: hydrogeological and geophysical prospecting in the north-west aimed at establishing watering points;

1963: hydrogeological survey (with United Nations technical co-operation) of the north-east, particularly the Kandi region;

1964: geophysical reconnaissance mission in the centre and north-east of the country (United Nations technical assistance).

The main purpose of these surveys was to inventory the ground-water sources in rural areas. The studies showed that the granitic sand or fracture zone aquifers are capable of producing more than 100 m^3/day per well in the rainy season and several tens of m^3 in the dry season; yields are higher in the Kandi sandstones.

1966-1968: construction of 275 rural wells in the central and northern region (European Development Fund) and the execution of 85 electrical soundings and 420 exploratory bore-holes;

Since 1967: UNDP/FAO ground-water development project to determine the amount of ground water in the northern and southern sedimentary basins and to seek for areas suitable for the installation of water points to serve towns.

The main results of these surveys may be summed up as follows:

In the coastal sedimentary basin, the crystalline basement lies at a depth which increases rapidly from 100 to 800 m as one moves further south. The characteristics of the aquifers in this zone are well known and the problems associated with the exploitation of the water are relatively simple.

The yield per well from the sands of the "Continental terminal" can vary from several m^3/hr to several tens of m^3/hr; the confined aquifers in the Maestrichtian sands and sandstones are capable of yielding 45 to 100 m^3/hr.

In the north-eastern sedimentary basin, trial borings have shown the basement to lie at a depth of more than 300 m (at Bodjecali). Yields are low (30 to 40 m^3/hr); the water is held in sandstones.

In the crystalline areas in the centre and north, yields from the fractures and granitic sands are low and are often intermittent. The provision of a water supply is generally very difficult in the northern areas.

DEMOCRATIC REPUBLIC OF THE CONGO

Area: 2,345,500 km^2; population: 16,500,000; Central Africa.

General

The Democratic Republic of the Congo lies on the equator and is a large, land-locked State which occupies most of the Congo basin; it opens onto the Atlantic Ocean through a very short coastline (40 km) north of the mouth of the River Congo.

To the west, in the bend of the Congo, which encloses a swampy area of equatorial forest crossed by very large streams, the country is flat and lies 300 to 400 m above sea level. The ground rises in the south towards the Kasaï (500 to 700 m) and Katanga (1,000 to 1,500 m) plateaux. In the east, along the rift valley containing Lakes Tanganyika, Kivu, Edward and Albert, there are chains of mountains 1,500 to 2,500 m high, with the Karisimbi (4,508) and the Rwenzori (5,119 m) Mountains being the highest. Finally, in the north, there are plateaux 500 to 1,000 m high which are extensions of those in Sudan and the Central African Republic.

The country has a very humid tropical equatorial climate. Average annual rainfall is 1.50 m in general for the country but there are areas, such as the mouth of the Congo and the mountains in the east, where rainfall exceeds 2 and 3 m. In the south, it rains from October to April. In the equatorial region rain falls throughout the year, with peaks in October-November and March-April.

Geology

The Pre-Cambrian basement outcrops extensively in the south-west, east and north of the country (gneisses, phyllites and quartzites). It is also found near the mouth of the Congo in the Mayombe range (schists, gneisses, quartzites, conglomerates, tillites). In the latter region, the crystalline and metamorphic basement is overlain by Infra-Cambrian sedimentary formations: dolomitic limestones with stromatolites, shaly limestones and shaly sandstones.

In the south-east, the Katanga group includes three systems: at the bottom, the Roan system (1,000 to 2,000 m of conglomerates, dolomites, limestones, shales and sandstones); above it, the Mwashya system (1,000 m of tillites, shales and "grands conglomérats"); and, at the top, the Kundelungu system (1,500 to 3,000 m of calc-schists and limestones with stromatolites, shales and sandstones).

To the east and north, along the edge of the crystalline basement, formations have been found which are similar to those of the Katanga group. In the centre of the Congo basin, the Pre-Cambrian basement is overlain by a sedimentary layer which outcrops at its edges and which is thought to be as much as 4,000 m thick. The layer includes, in addition to the Pre-Cambrian dolomites and limestones, the following formations:

Shaly sandstones, tillites and clays of the Karroo (more than 500 m);

Sandstones, argillites and green and red mottled shales of Jurassic and Cretaceous age. This group comprises the "Continental intercalaire", with some limited marine episodes (500 to 700 m); and

More or less consolidated, polymorphous sandstone (Nummulitic, 100 m thick) and red sands (Neogene). This is the Kalahari system.

The Quaternary formations deposited during the pluvial periods form a thick and complex assemblage which includes sands, gravels and clays, sometimes cut by volcanic intrusions.

A Cretaceous-Neogene marine sedimentary basin has been recognized along the coast, west of Boma, where limestones predominate.

Ground water

A 1:5,000,000 hydrogeological outline map of the Congo has been made by Mr. J. Snel. It gives an idea of the main hydrogeological subdivisions of this vast country.

The main aquifers are:

Surface formations of sands and sandstones (Tertiary and Quaternary). These are found in the following areas: coastal zone, Kwango plateau (south of the Kasai River), the Congo valley from Kisangani to the swamp areas (near Mbandaka) and the central basin, the graben of the great lakes, and the Kasaï and Katanga plateaux;

Weathered layer and fracture zone of the crystalline and metamorphic rocks of the Pre-Cambrian basement, especially near the northern borders in the coastal region and on the Kasai and Katanga plateaux; and

Permeable limestones and dolomites (Terminal Pre-Cambrian and Infra-Cambrian) in the large fractures running NE-SW: plateaux of the Kasai, Katanga and Moyen-Congo regions.

Details of the wells are given in the following table:

Nature and age of the aquifer	Location	Depth of well (m)	Specific yield (l/s per metre of drawdown)	Hydraulic conductivity (permeability) in m/s
Alluvium (Quaternary sands and gravels	Kinshasa	10 to 60	0.2 to 20	10^{-5} to 10^{-1}
"	Lubumbashi	5 to 60	0.2 to 22	10^{-5} to 10^{-3}
"	Central basin	Up to 100	0.2	10^{-5} to 10^{-4}
"	Bas-Congo coastal plain	Up to 100	0.1 to 2	10^{-4}
Alluvium with granitic sand and laterites	Bas-Congo	Up to 30	0.1 to 20	10^{-4} to 10^{-1}
"	Kivu alluvium	Up to 100	0.2 to 2	10^{-3} to 10^{-5}
Alluvium (lacustrine formations)	Uvira and Ruzizi River plain (graben)	Up to 60 (20 in laterites)	0.1 to 2	10^{-3} to 10^{-5}
"	Lake Albert plain	Up to 30	0.1 to 2	10^{-3} to 10^{-5}
Weathered zone in Pre-Cambrian basement area	Province Orientale	25 to 100	0.2 to 2) 0.1 to 1)	10^{-3} to 10^{-5}

Nature and age of the aquifer	Location	Depth of well (m)	Specific yield (l/s per metre of drawdown)	Hydraulic conductivity (permeability) in m/s
Pre-Cambrian basement area	Maniema	-	0.2 to 2	10^{-4} to 10^{-5}
Weathered zone in Pre-Cambrian basement and fractures	Bas-Congo	40 to 100	0.2 to 2	10^{-3} to 10^{-2}
Kasai limestones	Gandajika		(Artesian conditions)	
Limestones and dolomites	Lubumbashi	Up to 100	Up to 20	10^{-1}

Hydrogeological surveys have been made with a view to providing a water supply for towns and villages, particularly in the following regions: Kinshasa, Lubumbashi, the whole of Katanga, the Ruzizi River and Lake Albert plains, Kivu, central basin, Kasai-Kivu, Maniema and Equateur. A total of approximately 2,000 wells has been drilled on the basis of the information obtained during these local surveys.

The main ground-water requirements of the Democratic Republic of the Congo may be summarized as follows:

Kinshasa: surface water (Congo River) is plentiful but of poor quality. The city requires a total of 20 million m^3/yr;

Bas-Congo: the water is of poor quality, being mineralized. The ports, villages and livestock require a total of 15 million m^3/yr;

Lubumbashi and Katanga: surface water is scarce during the dry season. Most ground water comes from wells and springs in the limestones and dolomites. It is estimated that 50 million m^3/yr are required for the mines and for irrigation;

Ruzizi River plain: the surface water in this region, where industrial crops (cotton and sugar cane) are grown, is not potable. Approximately 10 million m^3 of water are required each year;

Kisangani and Mbandaka: water is required to supply the cities and industries;

Babua, Azande, Gemena, etc.: supply needed for rural centres in areas where the surface water is polluted.

In 1968, the Democratic Republic of the Congo had available to it for ground-water surveys, exploration and development a number of experts (four foreign hydrogeologists and two Congolese students, one foreign geophysicist, and 24 drillers, of whom four were foreigners) and the following equipment: approximately 20 drilling rigs, mostly from the United States, allocated to various Ministries and State bodies and used according to demand.

No regional surveys or ground-water development programmes are envisaged at present.

EQUATORIAL GUINEA

Area: 26,000 km^2; population: 200,000; Central Africa.

General remarks

The mainland portion of the country is bounded on two sides by Gabon and has an Atlantic coastline of nearly 200 km. It consists of a plateau (500 to 1,000 m) lying inland from a narrow coastal plain and, in the south, a long line of high ground, including Mt. Mitra (1,200 m), running from east to west and forming a sort of headland in the Atlantic. The country is crossed by two coastal rivers, the Benito and Utamboni rivers. Rainfall is high (2 to 3 m per year). The country also includes the volcanic island of Fernando Póo.

Geology

Most of the country consists of an extension of the Pre-Cambrian basement formations of Gabon and Cameroon, i.e. of a granito-gneissic basal complex overlain by the mica schists, schists and quartzites of the Ogooué system.

Along the coast lie the formations of the Cretaceous and Tertiary coastal sedimentary basin of Gabon, which becomes increasingly narrow towards the north (see the section on Gabon).

Ground water

Little information has been published concerning ground water in this country. The main towns and most other large population centres are situated on the coast and have no difficulty in obtaining their supplies from ground-water sources.

The administrative centres and the few large villages in the interior require small amounts of water and are able to obtain adequate supplies from a few wells.

ETHIOPIA

Area: 1,222,000 km^2; population: 23,500,000; East Africa.

General

Ethiopia is a large, mountainous country in eastern Africa between the Sudan and Somalia. Most of the country lies at an elevation of more than 1,000 m and there are many peaks of over 3,000 and even 4,000 m; the highest point, Ras Dashan Mountain, is 4,620 m above sea level.

The country is essentially land-locked. The maritime province of Eritrea, which lies on the Red Sea, does not provide the country with any major point of access to the outside world. Most sea traffic is handled through the port of Djibouti, capital of the French Territory of the Afars and the Issas, which is linked to Addis Ababa by railway.

In the east, the country forms a sort of spike extending into Somalia; this is the Ogaden plateau (elevation 500 to 1,000 m), which drops down towards the east.

Generally speaking, Ethiopia has a tropical humid climate; rainfall exceeds 1 m (up to 1.5 and 2 m) in the western part, which is mountainous and has many watercourses (such as the Blue Nile, which flows out of Lake Tana) and lakes (7,000 km^2),

In contrast to this, the province of Eritrea and its hinterland the Danakil desert, which contains depressions below the level of the Red Sea, as well as the Aoussa region, have an arid or even hyperarid climate (less than 100 mm of rain per year on the coast). In the Ogaden region, annual rainfall is between 200 and 500 mm.

Geology

In terms of geology, the country is divided into three main areas: the Abyssinian plateau in the north and west, the Somali plateau in the south and, between the two, the tectonized Afar region, which is bounded by very pronounced faults and cliffs and is narrow in its south-western part and broader in the north-east.

The high plateaux of Abyssinia are widely covered by a thick layer of volcanic lavas - mainly basalts and rhyolites - of end-Cretaceous-Lower Eocene age. These lavas rest on a basically calcareous Jurassico-Cretaceous stratum which outcrops extensively in the Harar highlands and the Somali plateau, across which run the Webbe Shibeli and Juba rivers. In the Ogaden region, argillaceous Eocene limestones lie conformably on the Cretaceous series.

The Jurassico-Cretaceous complex lies directly over the Pre-Cambrian metamorphic basement (schists and granite gneiss), which outcrops widely in the northern part of the country (Asmara region), along the western and southern borders and in the upper basin of the Juba and its tributaries.

Ground water

A joint Ethiopian-United States project, intended to solve the water-supply problems of urban and rural communities, began in 1954. The aim of the project was to improve the conditions of supply by drilling wells equipped with the necessary pumping and storage facilities.

Most of the towns and villages in Ethiopia are built on mountain tops. This, together with the absence of surface and spring water, meant that attention had to be focused on ground-water development. A total of 372 wells were built in the priority areas and in other parts of the country where the water was readily accessible. Many Ethiopian technicians and workers received training in water-well drilling.

In 1960, following the completion of the project, the Ethiopian Government continued the well drilling programme on its own, using only Ethiopian personnel. Considerable effort has been put into the programme. Ground-water potential is determined by the resistivity method. Because of a lack of funds, no over-all survey has been made, but a certain amount of data has been collected. The immediate and main aim of this activity has been to solve the pressing water-supply problems affecting certain localities.

Preliminary hydrogeological reconnaissance has shown that the ground-water "provinces" of Ethiopia correspond roughly to the main geological divisions of the country, which are the following:

(a) The plateau areas covered by effusive volcanic rocks (Somali and Ethiopian plateaux);

(b) The rift valley area (Danakil depression, Awash valley, Galla lakes area);

(c) The areas of Jurassic limestones;

(d) The areas of Triassic sandstones;

(e) The areas of the Pre-Cambrian crystalline basement.

In the plateau areas, ground-water occurrence is directly related to the lithology of the volcanic rocks. The subdivisions shown are based on geographical criteria. The yield from wells is generally low to moderate.

In the rift valley, the Aden volcanic series and the fluvial and lacustrine material constitute the best aquifers; the yield from them varies widely, depending on their nature and the degree of consolidation. The subdivisions shown are based on recharge and drainage conditions. In the Danakil depression, there is only a very small amount of recharge and no steady drainage. In the Awash valley, recharge is moderate as the river flows all year round. The central, or Galla lakes region experiences heavy rainfall but is endoreic (a closed basin). Some wells in the rift valley have a high yield.

In the limestone areas, the water table generally lies very deep. The perched aquifers contain only limited amounts of water. The yield from most of the wells tapping the fracture aquifers is often very low and the water tends to be quite hard.

On the whole, the sandstones are dense and fine-grained. Yields are generally low, except in specific rock areas, such as the conglomerates.

In the Pre-Cambrian areas, the degree of alteration of the substratum is usually moderate. This, together with the impermeability of the substratum, limits the occurrence of ground water to joints, cracks and fractures, with the result that wells drilled in these areas usually have a low yield. In many cases, the quality of the water is poor. The level of dissolved solids is high and varies considerably from place to place.

In recent years some local studies have been carried out in the more accessible areas. They include a brief survey of the environs of Addis Ababa in which Japanese specialists took part. There are four foreign hydrogeologists in Ethiopia, three of them working in the Department of Water Resources and one in the Ministry of Mines. One Ethiopian hydrogeologist is abroad on a fellowship and there are 15 nationals working as well drillers for the Government. Five water-drilling companies (Meketa, National Boring, Rampi Odone, Rodio and Watenco) operate in Ethiopia; some are not fully equipped. Both rotary and percussion rigs are used.

A total of 35 wells is drilled each year for various purposes.

The water supply for most towns comes entirely from ground-water sources, particularly from shallow wells dug by hand.

It is not possible to quote typical rates of flow since insufficient data are available on yields from the various types of aquifer.

FRENCH TERRITORY OF THE AFARS AND THE ISSAS

Area: 23,000 km^2; population: 90,000; north-eastern Africa; French administration.

General

This Territory forms an enclave between Ethiopia and Somalia; it has a sea-coast at the exit from the Red Sea to the Gulf of Aden. The relief of the country is marked by sharp contrasts, with secondary volcanic chains and plateaux separated by deep valleys. It includes several closed basins whose bottom is occupied by salt lakes or dry lakes. The highest point of the relief is Mount Moussa Ali, with an altitude of 2,063 m.

Half the population is concentrated at Djibouti, the capital, an important seaport and the terminus of the Addis Ababa railway, which is the main artery for Ethiopia's foreign trade.

The Territory has a tropical desert climate, with average temperatures of 26°C in winter, 36°C in summer and peak values exceeding 45°C; the rainfall is of the order of 30 mm in the plains areas, with maximum values in the mountain areas that may reach 500 mm in wet years. There are no permanent streams, the rains are short and violent and are followed by torrential flows in the wadis.

Geology

Volcanic formations (basalts, rhyolites, etc) of various ages cover the entire country. In the eastern part, near the Somali frontier, there is an outcrop of a Jurassico-Cretaceous series which includes limestones of marine origin (Upper Jurassic), 250 m thick, overlain by 300 m of sandstones similar to the Upper Nubian Sandstones (Cretaceous).

The salt lakes occupy sunken areas bordered by well-defined faults; the depressions contain lacustrine sediments of Pliocene and Quaternary age. A coastal plain 10 to 20 km wide extends along the entire northern coast; in this plain the basals are overlain by 15 m of Quaternary limestones.

Ground water

The springs found at the base of elevated features yield saline water, sometimes highly mineralized, at temperatures which are often very high, approaching the boiling point.

Alluvial fills, which collect infiltration water following the rains, are traditionally the main source of water. The town of Djibouti obtains its water from a network of drains constructed in this type of formation; this network also taps the hot water rising from deep formations through faults. In the coastal zone the water is brackish or salty. A number of recent hydrogeological reconnaissances have indicated the existence of large reserves of fresh water.

GABON

Area: 267,700 km^2; population: 480,000; central Africa.

General

Gabon lies on the equator and has an Atlantic coastal region 800 km long which varies in width from 50 to 150 km. The elevation of the coastal region is less than 200 m. The central part of the country contains mountainous uplands, including the Crystal Mountains (1,000 m) in the north, the Chaillu Mountains (1,575 m) in the centre and the Mayombé Mountains in the south. There is a lower (300 to 600 m) and less rugged plateau area further east.

The climate is hot and wet; rainfall decreases as one moves away from the coast (where it is 3 m) into the interior (1.3 m). The dry season lasts from June to September.

The greater part of the country is occupied by the basin of a major river, the Ogooué; two thirds of the land area is covered by equatorial forest.

Geology

The interior of the country belongs to the Pre-Cambrian basement domain; the basement rock is overlain in the coastal region by sedimentary formations of Cretaceous and Eocene age.

The basement formations include the following subdivisions:

Lower Pre-Cambrian: granite-gneisses cut by intrusive rocks. It takes the form of an extensive peneplain in the north and centre of the country;

Middle Pre-Cambrian: schists, mica schists, quartzites, volcanic rocks, found widely in the upper basin of the Ogooué in the east and the Mayombe area in the south;

Upper Pre-Cambrian: in the north, in the Ogooué region, it consists of argillaceous schists and sandstones (300 to 400 m);

Terminal Pre-Cambrian: this is represented in the south, in the Nyanga syncline by various sediments: glacial tillites, (dolomitic) shaly limestones and shaly sandstones (a total of almost 1,000 m).

The coastal sedimentary basin, as much as 150 km wide, contains the following formations:

Lower Cretaceous: basaltic sandstones, clays and marls (800 to 1,000 m);

Marine Cretaceous: marls, sandstones, shales and dolomitic limestones (3,000 m);

Middle Cretaceous: sandstones, clays, sands, marly limestones, marls and sandstones (1,600 m);

Upper Cretaceous: sands, sandstones and phosphatic marls (1,500 m);

Palaeocene-Eocene: limestones, marls and clays (1,500 m);

Miocene: marly clays, with limestone lenses (1,100 m);

Pliocene: fluviatile sands (2,000 m).

Ground water

Since the population is small and surface water is plentiful, there have as yet been few ground-water surveys. Those which have been made concentrated mainly on the areas of Libreville and Port Gentil, with a view to providing the towns with potable water. Libreville used to take its water from springs and wells yielding 4,400 m^3/day. During the dry season the water-table would drop rapidly and the supply sometimes dried up completely. For this reason, a diversion dam has been built at Ntoum; it provides 10,000 m^3/day. Port Gentil is supplied by a network of 86 wells divided into four groups and yielding some 4,000 m^3/day. Because of the rapid rise in water demand, it is planned to build a fifth group of wells (20 in all) in the near future, to yield 1,000 m^3/day. Longer-term plans include the drilling of deeper holes and the possible construction of a diversion dam 40 km away on the Ogooué.

As most of the towns are close to watercourses, measures have been taken to provide them with a supply of surface water which has first been treated in purification plants. As for the villages, few are permanent and their positions change frequently. The Government is making a major effort to regroup the scattered population in rural centres equipped with modern water supply systems.

Agriculture has been relatively little developed in Gabon and it makes no appreciable use of ground water. The water for the Moanda manganese mine is drawn not from ground-water bodies but from a nearby stream.

Many surveys have been made of surface water in Gabon because it is so plentiful. On the other hand, practically no work has been done on ground-water sources. It would, however, be possible to use those sources to supply urban and rural centres; that would, indeed, be preferable to the present system, which seems to be very costly, since only one urban water-supply system can be built each year. The country does contain geological formations which constitute exploitable aquifers.

GAMBIA

Area: 11,300 km^2; population: 350,000; West Africa.

General

The Gambia, a narrow country lying astride the lower reaches of the river of the same name, is almost entirely surrounded by the Republic of Senegal. The maximum height above sea level in the eastern region is approximately 50 m. Annual rainfall is between 1 and 1.2 m.

Geology

The country generally consists of the argillaceous sandstones, marly limestones and sands of the marine Oligo-Miocene, which outcrops in the west; in the east, these formations are covered by the argillaceous sands of the "Continental terminal", of varying colours and turning locally into sandstone; the argillaceous sands are themselves overlain by a lateritic carapace and Quaternary formations (see the section on Senegal).

Ground water

The largest body of ground water occurs in the argillaceous sandstones and sands of the "Continental terminal". Much of the water comes from the Gambia River. The wells have a specific yield of 5 m^3/hr/m. Except for a few individual wells, those located away from the estuary and the coast yield water which contains few impurities (less than 0.2 gr/l), the most common being calcium bicarbonate.

GHANA

Areas: 238,500 km^2; population: 8,200,000; West Africa.

General

Ghana has a 500-km long coastline on the Gulf of Guinea. In the east, it is separated from Togo by hills rising to 700 to 800 m. The western central area, the region along the frontier with the Ivory Coast and the north-western part of the country consist essentially of a plateau varying in height from 300 to 500 m above sea level. In the centre and south-east is the depression occupied by the valley of the Volta River, where the Akosombo Dam forms one of the largest artificial lakes in the world. The western coastal region is also low-lying.

Average rainfall is: 1 to 1.5 m on the coast (heavier towards the west), 1.5 to 2 m in the western central area, 1 to 1.5 m over the rest of the country and 0.75 to 1 m in the north-west.

The south-west of the country is occupied by rain forest; the north-east forms part of the Sudanese dry savanna domain.

Geology

The Lower Pre-Cambrian (Dahomeyan), with its granite gneisses, occupies the south-east. The Middle Pre-Cambrian (Birrimian), comprising schists, phyllites and graywackes, outcrops over a sixth of the country in long belts running NE-SW, particularly in the west. The Upper Pre-Cambrian (Tarkwaian) is found in two synclines striking NE-SW. One forms a sort of lowland in the south; between Kumasi and Tarkwa; the other, further north, lies between the elbow of the Black Volta and the Ivory Coast. The gold-bearing Tarkwaian comprises conglomerates, sandstones, quartzites and shales. Its total thickness is 3,000 m. In the east, along the border with Togo, there are outcrops of the Buem series (conglomerates, sandstones and dolerites), which is considered to be Terminal Pre-Cambrian. The Voltaian (Cambro-Silurian) occupies that half of the total area of Ghana which constitutes the Volta basin (syncline). It contains mainly sandstones and conglomerates and also exhibits shales, jaspers and limestone lenses (Oti limestones); the total thickness is approximately 800 m.

Some sandstones and shales attributed to the Devonian crop out near Accra. In the eastern and western coastal regions, there are two small sedimentary basins which contain, reading downwards - as was shown by an 800 m trial bore which did not reach the Pre-Cambrian - the following: "Continental intercalaire", Eocene sands and sandstones, Cretaceous limestones and Cretaceous clays.

Ground water

Ground-water development in Ghana is in the hands of government services and is undertaken mainly in order to provide population centres with potable water.

By 1970, approximately 2,000 wells had been sunk by mechanical means and 10,000 (shallow) wells dug by hand.

A 1:1,000,000 diagrammatic map of ground-water resources made in 1969 shows that most of the geological formations in Ghana are aquiferous and likely to provide yields sufficient to meet the requirements of rural communities, provided that well sites are carefully chosen. The Volta basin is perhaps the only exception to the rule, for the area is thinly populated and few surveys have yet been made there.

Until recently, hydrogeological surveys were the responsibility of the Government's Geological Survey. Since 1965, however, the Water and Sewerage Corporation, a public agency, has employed hydrogeologists and geophysicists to carry out hydrological investigations and supervise drilling operations. In addition, the Water Resources Research Institute of the Council for Scientific and Industrial Research has a ground-water hydrology section.

In the crystalline basement regions, ground water is most likely to be found in the fracture and weathered areas. The wells sunk in these areas are usually 10 to 15 m deep and 90 per cent of them yield enough to supply the villages with drinking water; yields are not sufficient, however, to justify the use of motorized pumping devices. It is hoped that geophysical surveys carried out prior to the selection of well sites will reveal the most favourable areas and thus permit higher yields to be obtained. An estimated three quarters of the wells could then be equipped with motor-driven pumps.

In the areas where sediments predominate there are approximately 200 wells with a depth of around 100 m. The quantitative hydrological characteristics of the aquifers (transmissivity, storage coefficient) are not yet known. However, two main aquifers have been identified in the south-eastern coastal sedimentary region: sands and gravels (of Cretaceous-Tertiary age) capable of yielding 8 to 12 l/s per well, and limestones with a potential yield of 15 l/s.

The classic problem of the intrusion of salt water has already arisen in both sedimentary basins; there is also some fear of over-exploitation. To date, there has been no regional ground-water survey. A general reconnaissance was made in 1964 and repeated in 1969-1970 with the help of a private firm. A WHO project to study water supplies for rural centres is scheduled to begin in 1971. This project will include local hydrogeological surveys.

In 1970, the government services had on their staff two hydrogeologists and two water-drilling engineers.

Drilling for water is carried out by the drilling section of the Ghana Water and Sewerage Corporation, which has 12 rigs (five rotary and seven cable-tool percussion).

A local firm installed several wells for the Government between 1964 and 1968.

The current rate of drilling is approximately 150 wells per year. Ground water is used mainly for domestic purposes and as drinking water; hardly any is used for irrigation or in industry. Ground water accounts for about 70 per cent of the total requirements of the villages, and the same is true in the case of a number of large towns such as Ho, Bolgatanga, Bawku, Akim Oda and Keta.

GUINEA

Area: 246,000 km^2; population: 3,400,000; West Africa.

General

Guinea has an Atlantic shoreline 300 km long. Inland from the narrow coastal plain, the ground is relatively high and has varied relief. The Fouta Djalon massif, 200 km from the sea, consists of sandstone plateaux between 500 and 1,500 m high and is the source of many watercourses, such as coastal rivers, the Gambia and tributaries of the upper Niger.

To the south and east, along the frontiers with Sierra Leone and Liberia, is another complex of highlands (Mts. Loma and Nimba and the Béro and Tétini massifs), with elevations also ranging between 500 to 1,500 m. Between the two arms of the mountains lies the upper basin of the Niger, which rises in Guinea on Mt. Loma (1,800 m).

The country lies in the humid tropical zone. Rainfall exceeds 3.5 m per year on the coast and 1.5 m over most of the country.

Geology

Most of the interior is composed of the following Pre-Cambrian formations:

Lower Pre-Cambrian (Dahomeyan): granite gneisses (south and east of country);

Middle Pre-Cambrian (Atacorian, Birrimian): schists, quartzites, metamorphic rocks and granites in the north-east (in the Kankan-Siguiri area);

Upper and Late Pre-Cambrian (infrequent): conglomerates, shales and jaspers.

The coastal region consists mainly of asyncline of Primary rocks:

Infra-Cambrian: red limestones, quartzites, argillites (1,500 m);

Cambrian: shales, dolomitic limestones, jaspers (200 m), "Mali shales", doleritic rocks (1,000 m);

Ordovician: cross-bedded sandstones (500 m);

Gotlandian: black shales and sandstones;

Devonian: argillaceous shales (300 m).

There are also dolerites in superimposed layers.

Ground water

Ground-water surveys are made in Guinea for the sole purpose of meeting the water requirements of the large towns and population centres.

Most studies carried out from 1948 to the present day have concentrated on the Kaloum peninsula with a view to finding water for the capital, Conakry. The best yields per well are in the range of 10 to 30 m^3/hr (exceptionally 70 m^3/hr).

Studies were also made between 1955 and 1957 with a view to providing water for other towns and population centres, particularly in Basse-Guinée (the towns of Boffa, Coyah, Forecariah, Kindia, and Labah and the port area of Kamsar).

Since 1960 a Hungarian hydrogeological mission has been investigating possible sources of water for population centres in the interior (Mamou, Dinguiray, Siguiri, Quéckédou, Koundara, N'Zerekore and Macenta). The yields obtained are high (10 to 70 m^3/hr). The Hungarian team comprises a hydrogeologist, a drilling engineer and three technicians with a mobile rig capable of reaching a depth of 150 m.

No over-all regional survey of Guinea has been made so far. The country has numerous springs, particularly in volcanic terrain, where the ground-water potential is probably greatest.

GUINEA (BISSAU)

Area: 36,000 km^2; population: 530,000; West Africa; Portuguese administration.

General

This small territory is low-lying, generally not more than 70 m above sea level. It opens onto the Atlantic with an area of swampy estuaries of several large coastal rivers; just off the coast are the Bijagós Archipelago. Annual rainfall is of the order of 2 to 3 m on the coast (1.2 to 1.5 m in the north-east).

Geology

The hinterland and the coastal region to the south of the capital, Bissau, consists of soft, level Primary terrain composed mainly of Gotlando-Devonian shales and Cambro-Ordovician sandstones, tillites and limestones.

North of a line Bissau-Sare-Bácar is the Gambia-Casamance sedimentary basin where the marine Oligo-Miocene marls and clays are covered by lateritic argillaceous sands of the "Continental terminal".

Ground water

No information on ground water has been published (or sent to the secretariat for the International Hydrological Decade).

As the geological formations are the same as those of southern Senegal, some idea of what their yield might be can be gained from the section on Senegal.

IVORY COAST

Area: 322,400 km^2; population: 4 million; West Africa

General

The country is generally flat but rises regularly from the south to the north, reaching a height of 300 m in the east and 450 m in the west. There are some mountainous areas: the Main Mountains (1,200 to 1,700 m) in the west near Liberia and the Odienné region (800 to 900 m) in the north-west.

Four main watercourses cross the country from north to south. They are, from east to west, the Comoë, Bandama, Sassandra and Cavally Rivers. Annual rainfall is from 1.5 to 2 m on the coast and in the south-west, from 1.2 to 1.5 m in the west and from 1 to 1.2 m in the north-east.

The south of the country lies within the tropical forest region; the north-east is part of the Sudanese zone (dry savanna with sparse vegetation); between the two lies the "transitional" zone of the humid savanna.

Geology

No trace has been found in the Ivory Coast of the granite gneisses of the (Dahomeyan) Lower Pre-Cambrian. The Middle Pre-Cambrian (Birrimian), represented by schists and quartzites which include large granitic batholiths (granites Baoulés), constitutes the rock foundation of the country. The Man "massif" is formed of hypersthene granites, or charnockites; it lies at the eastern extremity of a complex which extends into Guinea.

The Upper Pre-Cambrian (Tarkwaian), made up of conglomerates, sandstones and arkoses, is found in the centre (Fettekro and Yaouré) and east (Agnibilékrou, Bondoukou) of the country and occurs in hills 750 m high. The Cretaceous and Tertiary seas deposited sediments in the coastal zone; the outcrops form a belt 320 km long and 35 km wide.

Bore-holes have intersected the basement at a depth of less than 200 m near Abidjan. There is, however, a major collapse running parallel to the coast in the south; in the depressed zone the depth of the basement may be as much as 3,000 m.

The Lower Cretaceous is argillaceous; the Middle Cretaceous is represented, in the Cenomanian-Turonian, by a limestone slab 30 m thick.

The sediments of the Upper Cretaceous and the Eocene are generally sandy. They are overlain by the argillaceous sands of the "Continental terminal", which are in turn covered by laterites.

Ground water

The coastal sedimentary basin is the best aquifer; some shallow wells have been sunk in it, in the Quaternary and the argillaceous sands of the "Continental terminal". The deep-lying water is fresh where it is protected against the intrusion of sea water by a screen of clays. Fresh-water lenses resulting from the direct infiltration of rain water have been recorded in the coastal region, at Treichville; they overlie salt water.

In the western section of the interior there is quite a number of wells which, in the granitic areas, reach a maximum depth of 15 m; the beds are coarse-grained and quite thick but of low permeability. The wells are often capable of yielding 2 m^3/hr, but rarely more than 5 m^3/hr.

The aquifer lies at the substratum contact in those zones where the granites have already crumbled without the feldspars becoming kaolinized; above this are loose clays, and then sandy clays from which the kaolins have been leached, giving rise to a certain degree of channel porosity; the water here is polluted, however.

The depth of the substratum can be determined by geophysical techniques, such as seismic reflection, and also by electrical logging when the kaolinized zone is thick and electroconducive.

The Government's Water Department (Service hydraulique) has five well-construction teams. The teams operate mainly in the granite areas which occupy most of the western part of the country; they build 50 wells per year.

In the east, the ground is more often schistose, with diaclases that are frequently filled with clays; where they are filled with quartz or pegmatites, the diaclases contain small amounts of water. The main supply of water comes from the small storage dams built on watercourses.

Water is scarcest in the northern part of the country, particularly in the area around Korhogo, where geophysical prospecting has been carried out to study in detail the granitic sand cover.

In 1969, the Ivory Coast had, for a total of 8,000 villages, 1,150 modern water points, including 700 equipped with mechanical extraction devices, of which half were in good condition.

A provisional 1:1,000,000 hydrogeological map and hydrogeological maps of départements (1:200,000) were made in 1964.

Two hydrogeologists (of whom one is a national) are serving in the country.

Five drilling companies (one from the Ivory Coast, 3 French and 1 Italian) are based at Abidjan.

The main hydrogeological surveys made in recent years are: in 1964, a general reconnaissance of the country (1:200,000 maps) and a geophysical and hydrogeological survey of the north-west; from 1964 to 1966, a hydrogeological survey of the schists in the east; in 1968-1969, a hydrogeological survey of the Adiake region, in the south-east of the country on the border with Ghana, with a view to establishing a table-water industry.

It is planned to study the possibility of exploiting the water body at Abidjan, to establish new villages for the resettlement of the population following the construction of the Kossou dam and to set up development zones in the San Pedro region.

KENYA

Area: 582,700 km^2; population: 10 million; East Africa.

General

Kenya opens onto the Indian Ocean over 500 km of coastline and also has access to Lake Victoria, the largest lake in Africa. The equator runs through the centre of the country. The ground rises from east to west. The western half of the country lies at over 1,000 m above sea level and the region to the north-west of Nairobi at 2,000 m. The highest point is Mt. Kenya (5,200 m).

Rainfall averages 250 mm per year in the arid regions and exceeds 2.5 m in the mountainous areas. The 700 mm isohyet marks the eastern limit of the humid region, where there are numerous watercourses and springs. To the west of the Aberdare Range, the Great Rift Valley extends to the north and south, draining many watercourses which feed lakes of various sizes. Further west, the watercourses flow into Lake Victoria.

To the east, the water system includes the large Tana and Galana rivers which rise on Mt. Kenya; the north-eastern region is crossed by stream beds which are often dry and which run out into plains in alluvial deposition zones which turn swampy in the rainy season.

Geology

The Pre-Cambrian crystalline basement occurs throughout the central and western areas of the country. It consists of schists, quartzites and cipolins of Archaean age and conglomerates, slates, feldspathic sandstones, volcanic rocks and quartzites of the Middle and Upper Pre-Cambrian.

The sandstone sediments of the Karroo, of Carboniferous-Triassic age, outcrop parallel to the coast in a band 80 km wide.

Jurassic formations outcrop in the coastal areas and in the north-east of the Mandera region, at Wajir, near the border with Somalia.

Cretaceous (calcareous) and Tertiary (calcareo-argillaceous) formations of marine origin also cover extensive areas in the east. The Great Rift Valley, formed in the Tertiary period, is lined with continental sediments.

Volcanic activity in the Miocene produced beds of basaltic, phonolitic and rhyolitic lavas which are more than 100 m thick. These volcanic formations cover more than a quarter of the country to the north and east of Nairobi.

Ground water

No systematic survey has yet been made of ground-water resources, for their potential is often far in excess of existing needs, except in the area of the capital, Nairobi, where conservation measures have been taken. Since 1927, some 3,600 bore-holes have been sunk, of which 75 per cent have been successful. The water-table often lies at a depth of more than 80 m and this may reach 200 m in volcanic rocks. Data on the bore-holes are carefully collected with a view to preparing regional studies. Because of the small number of hydrogeologists in service, it has not yet been possible to carry out such studies or compile ground-water maps. There is a need, however, for documents showing the location, potential and quality of water resources, particularly in the case of regions like Turkana, an arid, volcanic area between Uganda and Lake Rudolph. During the dry season in a large part of the eastern and north-eastern regions women will walk as much as 20 km in order to obtain water.

The Pre-Cambrian formations contain localized ground-water bodies whose position it is difficult to pinpoint. The eastern sedimentary basins contain worthwhile, but limited, amounts of artesian water. The rift valleys contain considerable potential resources. It is, however, difficult to develop ground water in the volcanic rocks. Most of the aquifers are subartesian.

In recent years there has been a considerable increase in the use of ground water, coinciding with the expansion of small-scale farming.

Drilling for water is now (1970) almost entirely carried out by private firms, which are required by law to submit a report and bore-hole samples to the Government. The exact location of each bore-hole is shown on 1:50,000 scale maps and a large number of water analysis reports is available.

Regional surveys have been made of the Nakuru (1957), Nairobi (1964) and Laikipia (1964) areas, and of the coastal region.

A total of 81 bore-holes was sunk by the eight local companies in 1969, using 12 percussion rigs. The Water Development Division has one percussion and two small combined rotary-percussion rigs.

Ground water is used by many population centres.

Some specific yields, expressed in litres per minute per metre, are the following: upper Athi series (Nairobi), 5 to 25; other volcanic areas, 5 to 10; crystalline basement, 1 to 4. The yield from the sediments in the coastal region is highly variable.

LESOTHO

Area: 30,300 km^2; population: 890,000; southern Africa.

General

Lesotho is an enclave within the Republic of South Africa. It is a small mountanous country of which all parts are over 1,000 m, half is 2,000 m and the highest point is 3,350 m above sea level. Rainfall often exceeds 1 m per year. Temperatures are moderate.

Geology

The formations of the Stormberg series (Upper Triassic) cover the whole of the country. They comprise four superimposed "groups": these are, reading downwards: the Drakensberg volcanic formations (basaltic lavas 2,000 m thick); the white feldspathic cave sandstones; the red beds (sandstones and clayey shales (500 m)); and the Molteno beds (sandstones and clayey shales (500 m)).

An assessment of ground-water resources on a regional basis was made as part of a UNDP-FAO project (1970-1971).

There are no hydrogeologists, geophysicists or well drillers in Government service.

Wells are sunk mainly to meet the domestic requirements of the rural communities or individual families; approximately 12 wells are drilled each year. The Hydrological Survey has two percussion rigs; some wells are built by private concerns. Some towns, including Butha Buthe, Teyateyaneng, Mafeteng, Mohales Hoek and Quthing, draw part of their water supply from underground sources.

There are no extensive aquifers in the country and most of the formations are more or less impermeable. Low yields, which sometimes reach 1.5 l/s, are obtained in dikes, sills, contact zones, fractures and faults.

A total of some 200 wells has been drilled in Lesotho, but there are no systematically collected data available on water-tables and their fluctuations.

LIBERIA

Area: 117,400 km^2; population: 1,100,000; West Africa.

General

The whole of the country lies within the tropical rain forest belt, where annual rainfall is at least 3 m and exceeds 5 m on the coast. There are no major relief features and the ground rises steadily from the coast towards the interior, reaching a height of 500 to 1,000 m; the Nimba Mountains, on the border with Guinea, are 1,700 m high.

Geology

Almost the whole of the country is made up of ancient basal formations, i.e. granite-gneisses and granites extensively overlain by lateritic deposits. There is a small, narrow sedimentary basin in the coastal zone.

Ground water

No regional survey has been made to date. Ground water is used on a large scale only to supply the capital, Monrovia, which has 110,000 inhabitants. Until recently the city relied on a system of drains yielding 4,000 m^3/day and located in a thick sandy formation. Drilling programmes have been carried out in the vicinity of the capital, but none has revealed any areas of appreciable yield. This inadequate yield has been increased twofold by the use, since 1957, of the waters of the Saint Paul River. It is estimated that total consumption will reach 100,000 m^3/day by 1985. There are no plans for further development of ground-water supplies at Monrovia, since the full potential seems already to have been achieved.

The other towns are supplied by means of shallow wells less than 10 m deep.

A firm of consultants has recently investigated the resources and methods which could be employed to supply various urban and rural centres with water. The wells to be drilled will be approximately 80 m deep.

LIBYAN ARAB REPUBLIC

Area: 1,760,000 km^2; population: 1,750,000; North Africa.

General

The Libyan Arab Republic is a vast desert country which borders on the Mediterranean between Tunisia and Egypt.

The Fezzan plateau, which is an average of 500 to 700 m above sea level, covers over half the country in the south-west. It slopes down towards the north-east in the direction of the Libyan sand desert, through which the frontier with Egypt runs directly from north to south.

The Fezzan is separated from the western (Tripolitania) and eastern (Cyrenaica) coastal regions by the vast, flat, rocky area known as the Hamada el Homra, which is often around 1,000 m above sea level (highest point: 1,200 m).

In Tripolitania, inland from the coast, there is a small mountain arc known as the Jebel Nefusa (970 m); another important mountain group, the Jebel al Akhdar (880 m), lies close to the coast of Cyrenaica. It is these two regions which receive the heaviest rainfall, between October and April; amounts occasionally reach 400 mm in Tripolitania and 600 mm in Cyrenaica. The rainiest areas on the coast have 200 to 400 mm per year. However, the 100-mm isohyet, which marks the northern limit of the desert proper, runs very close to the coast and in fact meets it on the Gulf of Syrte, where it more or less follows the thirtieth parallel. There are no perennial watercourses in Libya; torrential streams flow through the dry wadi beds following storm showers, but in some regions the latter do not occur every year.

The largest wadis are found in the Fezzan; they run westwards and are dotted with clumps of palm trees. However, most of the areas under cultivation are concentrated along a few stretches of the Mediterranean coast, where there is some scope for irrigation using shallow ground-water sources.

Geology

The Fezzan lies in a large basin, where Nubian Sandstones overlie a Palaeozoic series in which the Carboniferous is represented by sandstones and limestones, the Devonian by sandstones and the Gotlandian by schists; the latter outcrop from Serdeles to Edri, in an anticlinal position, and thus mark the northern edge of the Fezzan, which rises in the south towards the Tibesti and Hoggar massifs. Thus, the Fezzan forms an artesian synclinal basin. In the north, the Nubian Sandstones are overlain by the extensive Cretaceous tablelands of the Hamada el Homra. In the east, starting from Mursuk, there are other flat areas consisting of marine Eocene limestones (200 m) covered by (lacustrine) calcareous sandstones of the "Continental terminal" and the extensive volcanic basalt and phonolite flows of Haruj el Aswad. There are also signs of volcanism in the north-west, in the Jebel Sayda and in the Jebel Gharyan - at the eastern end of the Jebel Nefusa.

In northern Tripolitania, running east from the Tunisian border, there is a Permo-Trias-Jurassic series which includes: Permian sandstones, Muschelkalk limestones (100 m), Upper Triassic and Liassic gypsum and dolomites (200 to 300 m) and cherty limestones of Jurassic age. The series is overlain by sandstones and clays of the "Continental intercalaire", outcrops of which are widespread. To the east, the coastal plains are composed of Tertiary marine formations, mainly limestones, of Eocene to Miocene age. The limestones are karstified, particularly in Cyrenaica.

Ground water

The extent and number of the permeable formations are factors favourable to the accumulation of fossil water in the basins, whose structure is that found in areas of artesian flow. On the other hand, given the low rainfall over the country as a whole and the high potential evaporation, it is not surprising that the shallow aquifers are generally small and scattered and contain water of poor to bad quality.

There are, however, the wadi beds and large areas of sands and basalts through which water is able to filter rapidly after heavy downpours. This results in the formation of local water bodies which are tapped by wells and drains and may even support small springs.

The coastal aquifers, particularly those in the Tertiary limestones, contain limited amounts of water and are subject to sea-water intrusion. Indeed, most ground water in Libya, including that of the oases of the Fezzan, contains between 300 and 2,500 ppm of dissolved salts and sometimes more. The shallow water in the plain of Jeffara and the Jebel al Akhdar and that in certain deep aquifers of the Fezzan Traghan and the wadi el Ajal is of very high quality (less than 500 ppm of dissolved salts).

Libya, which produces oil from which it derives considerable income, has been able to devote large sums to ground-water exploration. Studies have been made not only of the yield of aquifers but also of their recharge, particularly in the coastal plains around Tripoli and Benghazi, where most of the population is concentrated. Recharge is ensured by the use of various spreading devices, including dams built on some of the wadis.

There is intensive exploitation of the coastal aquifers in the Tripoli region between the Tunisian border and Misurata, particularly in the Gefara plain, where the following formations can be found:

At the surface: Plio-Quaternary sands (several metres), followed by sandstones and limestones at Tripoli (40 m) and near Sabratha (up to 130 m);

Then: Tortonian white limestones (80 m), Helvetian clays and limestones (up to 400 m; yield some water at 200-250 m), and Lower Miocene sands (80 m), which represent the best aquifer close to the coast.

In the Fezzan syncline, the formations are the following:

Tertiary and Quaternary (acolian) sands;

Nubian Sandstones (equivalent to the "Continental intercalaire"). Pressurized water occurs at the base of this formation. The piezometric head is below ground level. The water runs into depressed areas filled with alluvial material;

Carboniferous sandstones and limestones (with intercalations of impermeable (shales?) schists and quartzites);

Sandstones of the (External) Tassilis series, of Lower Devonian age, with schistose intercalations;

The last two formations support the springs at Brak (30 l/s); the Obru artesian well, drilled at Brach, yields 105 l/s of flowing water;

Silurian shales with graptolites (200 m). This bed becomes thinner towards the east; and

Sandstones of the Internal Tassilis series, of Lower Silurian age (500 m);

The permeable formations outcrop on the edges of the syncline in relatively humid zones. Thus, artesian water has been found in the Fezzan at a depth of 700 m.

The water contained in the Nubian Sandstones flows into the region of the sebkhas, where it evaporates. It is probable that the water in the Koufra oasis further east comes from the Nubian Sandstones.

The major towns receive their water supply from drainage galleries or drilled wells.

After the Second World War there was a great deal of drilling for water, which was needed to support oil-drilling operations; some attempts were also made to find water in the vicinity of foreign air bases.

Through the Geological Survey, a United States bilateral assistance programme (Agency for International Development) has sent several hydrogeologists (2 to 4 per year since 1950) to Libya, where they have taken part in investigations in several areas, particularly near Benghazi.

Since independence in 1951, Libya has mounted a large-scale campaign to identify and develop ground-water sources to supply its towns. Much research has also been done into the possibility of using brackish water for irrigation.

In recent years, over-all water resources surveys have been made in the following areas: Benghazi, Derna, Agedabia (geophysical survey), wadi Soffejin, Misurata (Dafnia, Kararim, Tummina), wadi Caam, wadi Gatara and wadi Meganin.

Geophysical reconnaissance work has been carried out at Al Marj (Barce), Ras Jadu and Jardas-el-Abiol. Several wadis have been the subject of hydrogeological surveys.

In 1970, there were 12 hydrogeologists and five drilling engineers in Libya. Approximately 150 wells are drilled each year. The country has 28 water drilling rigs. The following table gives the specific yields obtained from various aquifers:

	Shallow aquifers (l/s/m)	Deep aquifers (l/s/m)
Tripolitania	1 to 10	1 to 3
Cyrenaica	1 to 6	0.5 to 2
Fezzan	1 to 20	1 to 20
Libyan Desert	1 to 30	-

MADAGASCAR

Area: 587,000 km^2; population: 6,400,000; large island in the Indian Ocean, separated from mainland Africa by the Mozambique Channel.

General

The island forms a "small continent", with a length of 1,500 km and a width of 400 to 500 km.

A high plateau (800 to 2,000 m, with some peaks over 2,000 m) occupies the centre of the country. It drops down rapidly towards the east in high, cliff-like steps to the narrow eastern coastal plain. In the west, the gradient is far less steep and the coastal plains and plateaux are a good deal more extensive. In the north, the structure is more complex and the terrain is rugged; the coast is deeply indented and there are numerous off-shore islands.

The rainy season lasts five months, from December to March inclusive, with annual rainfall amounting to 3 m in the north, 1 to 2 m on the plateau and in the north-west and 0.50 m in the south, where the climate is arid.

The central highlands have a tropical mountain climate. At the centre of the island there is a virtually straight-line watershed 50 km from the east coast, which is itself practically straight.

The coastal rivers on the eastern slope have very small basins and beds with steep and irregular gradients. The large rivers in the west also have a young profile made up of steps linked by abrupt escarpments. The central plateau contains some large lakes. The rivers often flood but they are not all perennial.

Geology

The greater part of the island, particularly in the centre and east, consists of a Pre-Cambrian gneissic base supporting a more recent layer of metamorphic rocks with injected Hercynian granites. to the west, the crystalline and metamorphic basal complex is overlain by a thick sedimentary series which constitutes a vast, gently-sloping monocline. From the base to the top the series contains:

The Karroo, a complex of sandstones, conglomerates, clays and limestones of continental origin;

The Upper Jurassic, of marine origin, represented by limestones and marls;

The Cretaceous, a complex of marls, sandstones and sands;

The Maestrichtian and Eocene, basically limestones;

The Upper Eocene and the Neogene, clays, sands and sandstones; and

The Quaternary: weathered layers, dune sands and abundant alluvial deposits in the deltas.

There were frequent effusions of volcanic rocks during the Cretaceous, Miocene, Pliocene and Pleistocene ages.

Ground water

The topography, the high rainfall, the thick and extensive formations of permeable rocks in the sedimentary basin, the gently and evenly-dipping strata, the degree of fracturing and the presence of a karst phenomenon are all factors favourable to the accumulation of very large amounts of ground water.

The very thick weathered gneiss zone in the crystalline massif also constitutes an important reservoir, of which use is made in the traditional system of rice-growing.

Hydrogeological investigation began in Madagascar in 1928, in the arid southern region. It was then extended to cover other areas, the main aim being to find water for the big population centres. In 1959 the Government set up a hydrogeological service with a staff of between 5 and 7 geological and hydrogeological engineers. In 1966, the service became part of the Water Supply Division of the Ministry of Energy. Its main task was to carry out local surveys with a view to finding sources of potable water for urban and rural centres. Until 1966 most of the surveys were made in the southern part of the country. They included the recording of 800 local watering points; geophysical prospecting (a few programmes in the south in 1959-1960) and the sinking of bore-holes (a total of 150, of which 110 were drilled after 1960).

Three water drilling rigs have been supplied by the United States Agency for International Development, and one by the Special Fund under a United Nations project which got under way in 1966.

Approximately 50 aquifer tests have been made, as well as a small number of general surveys, most of which concerned the southern part of the country.

Little information is available on water-table fluctuations or on the chemical quality of the water.

The main aquifers are the following:

Quaternary limestones, sandstones and dune sands;

Sands and certain lacustrine formations of Pleistocene age;

Dolomitic limestones of Eocene age. These give rise to springs and also contain water under pressure in the Befandriana (artesian yields of up to 70 l/s) and Majunga basins;

Limestones and sands of Maestrichtian and Upper Cretaceous age, containing confined fresh water (Morondava basin);

Dolomitic limestones and sandstones of Infra-Cretaceous age containing confined fresh water;

Upper Jurassic limestones (fresh, artesian water);

Continental sandstones of Liassic age (Isalo group);

Continental sandstones of Upper Triassic age (Sakamena group): confined water under high pressure;

Fracture zones in the basement.

It is not known whether the basalts contain water.

Drilling for oil has revealed deep-lying aquifers.

Specific yields (in litres per second per metre of drawdown) during pumping tests were as follows:

Dune and coastal sands, 0.7 to 1.5;

Alluvial deposits and loamy sands, 1.5 to 6;

Alluvial deposits and sands free from clay, 6 to 10;

Quaternary limestones, 100;

Eocene limestones (Majunga), 40 to 60;

Eocene limestones at Befandriana and Neogene formations, 3 to 6;

Cretaceous sandstones, 0.2 to 4;

Sands and sandstones of the Isalo group (Karroo), 0.3 to 0.6.

The rate of artesian discharge from one of the bore-holes drilled as part of the United Nations project was as much as 70 l/s. The project involved the study of a number of water bodies between Tuléar and Morondava.

The Eocene limestones, which have been eroded and are recovered by Neogene clays, constitute the best aquifer. It is possible that there may be sufficient ground water within the coastal sedimentary basin to permit the large-scale development of irrigation agriculture.

From 1967 to 1970, regional surveys were made in part of the Majunga basin and east coast. Four hydrogeologists (two from abroad) are serving at Tananarive and two Malagasy geologists, a drilling engineer and 10 skilled drillers are receiving training in France. There are in Madagascar 10 drilling rigs belonging to the Drilling Section of the Directorate of Mines and Industry and 15 other rigs belonging to two companies.

MALAWI

Area: 119,300 km^2; population: 4,200,000; southern Africa.

General

This land-locked country forms a narrow belt along the western shore and to the south of Lake Malawi. The whole country lies in a rift valley dominated by the escarpments of the high plateaux (1,300 to 1,500 m). The overflow from Lake Malawi runs into the Zambezi via the River Shire which flows through the southern part of the country. There is an area of lakes and swamps in the east.

Annual rainfall is between 0.80 and 1.50 m and is heaviest on the high plateaux in the west. The depressed zones receive little rain and have a semi-arid climate. The dry season lasts from May to September.

Geology

The northern part of the country to the west of Lake Malawi represents the eastern arm of the Pre-Cambrian basement areas of eastern Zambia (granite gneiss). There are some outcrops of shales, sandstones and limestones thought to be of Cambrian age; of argillaceous shales and sandstones and basalts of the Karroo (floor of the rift valley, shoreline of Lake Malawi); of conglomerates and arkoses; and of sandstones of the continental Cretaceous ("Continental intercalaire") in the south of the country.

There are some Quaternary deposits on the shores of the lakes, but they are more frequent in the Shire valley.

Ground water

Despite the relatively high rainfall and the abundance of surface water, there is a shortage of water in some parts of Malawi. This is because rainfall varies considerably from one year to the next and does not occur evenly throughout the year, the dry season being quite long.

For this reason, the Water Development Department, which is concerned mainly with the development of ground water, was established in 1931. From 1931 to 1965 some 900 wells were sunk, at an annual rate during the last few years of 130 to 150. The average depth is between 30 and 40 m and the mean yield approximately 3 m^3/hr, rising to 8 m^3/hr in the town of Dowa. A well is considered to be productive - and thus to justify the installation of a pump - when the yield reaches 1/2 m3/hr; judged by this standard, four wells out of every five are productive.

The water is used for human needs and for livestock; there is practically no irrigation.

The inhabited areas where the development of ground water sources is being given priority are those of Lilongwe (surface water polluted by livestock), Bwanje, Palombe (to the south of Lake Chilwa) and Balaka.

Other less densely inhabited regions could be developed if sufficient use were made of ground water. This is true of Chikwawa, in the south-west of the country, of Rivi, to the south of the Malombe River, and of Lisungwe.

In 1958 artesian wells were sunk in the Zomba district to the south of Lake Chilwa and encountered filling deposits: gravels, sands, silts and clays. There is an occasional shallow body of saline water in clays which lie above gravel beds containing fresh water.

Six drilling rigs are used for this work and well sites are selected by a geologist and a geophysicist. The results are summarized in the following table:

Formation	Depth of wells (m)	Yield (m^3/hr)
Biotite gneisses	60	5
Gneisses with dolerites	30	0.5
Graphitic gneisses	45	4
Gneisses of the basal complex	25 to 40	1.2 to 3.6 (average 1.8)
Weathered zone of gneisses, sand and clay	25 to 45	1.2 to 5 (average 3.5)
Weathered zone of gneisses, mainly clay	25 to 40	Average 2
Dambos (temporarily flooded areas, bottoms of ponds)	30 to 50	1 to 4
Thick alluvial deposits	30 to 50	1 to 5
Thick sands	30 to 60	1.2 to 3.6
Thick gravels	35	5
Argillaceous sediments	35 to 60	0.5 to 6 (average 2.5)

MALI

Area: 1,202,000 km^2; population: 4,700,000; West Africa.

General

Mali is a land-locked African State with extensive tablelands, plains and plateaux of a height of 200 to 500 m. The lowest-lying areas are in the north (170 m above sea level in the Taoudenni depression) and west (46 m at Kayes in the Senegal valley). The ground is higher in the north-east, in the Adrar des Iforas (1,000 m), in the centre of the country, south of the Niger River on the Bandiagara plateau and in the Hombori mountains (1,550 m), and in the south-west in the Manding mountains on the border with Guinea.

The climatic zones are as follows:

Sudanese zone in the south-west and west, with a climate of the humid savanna type (up to 1 or 1.25 m of rain);

Sahelian zone further north, crossed by the River Niger, and having less and intermittent rainfall (250 to 600 mm);

Saharan zone above the seventeenth parallel.

Most of the population is concentrated close to the major rivers: the Senegal, the Niger and its tributary, the Bani, in the south-western area.

Geology

Mali occupies the eastern part of the vast Taoudenni sedimentary basin.

The Pre-Cambrian basement outcrops:

In the west, in the Kayes-Yélimané region;

In the east, in the Adrar des Iforas: Lower Pre-Cambrian or Suggarian (quartzites, cipolins, amphibolites, lamellar gneisses, the whole being granitized); Middle Pre-Cambrian (volcanic products, schists, conglomerates, granitic batholiths);

In the bend of the Niger: Lower Pre-Cambrian (Dahomeyan), granite gneisses; Middle Pre-Cambrian (Birrimian), schists, quartzites and greenstones; and south of Bamako.

As one moves from these outer regions towards the centre the following formations are found:

Infra-Cambrian: sandstones and dolomitic limestones with stromatolites;

Cambrian: conglomerates, shales, dolomites, jaspers and pelites;

Ordovician: sandstones, quartzites and coarse-grained sandstones; less distinct (Cambro-Ordovician) in the west, where the complex constitutes the Nara-Sotuba (1,300 m) and Bandiagara (600 m) series;

Gotlandian: sandy clays and argillites;

Devonian: sandstones;

Carboniferous: limestones, sandstones and red (lie-de-vin) clays.

The marine Carboniferous is overlain by the sandstones of the "Continental intercalaire" (Lower Cretaceous) and the lacustrine sandstones, argillaceous sands and mottled clays of the "Continental terminal".

The depressed areas of the basin contain the saline deposits of the sebkha, which have been worked for centuries as a source of salt. In the north, there are extensive areas of dune sands.

Ground water

The main hydrogeological units are: the Mali-Niger basin in the east, bordered by the mountainous areas of the Adrar des Iforas and the Hoggar, and the Ténéré desert in the north, which borders on the Pre-Cambrian zones of west Africa to the south and the Gourma region (Infra-Cambrian) to the east. Three aquifers have been identified within the basin: the first in the "Continental intercalaire", the second in the Upper Cretaceous and the third in the "Continental terminal", a sedimentary complex which lies on the Pre-Cambrian shield and is a total of 1,500 to 2,000 m thick. The maximum thicknesses of the three formations are 1,500 m, 400 m and 100 m respectively. There are also up to 100 m of sterile Tertiary sediments. Many of these sediments are argillaceous. The water-bearing horizons are represented by sandstones and conglomerates with some limestone passages (Cretaceous).

The least mineralized water is found in the "Continental intercalaire" (700 ppm of dissolved solids) and to the south and east of the Adrar des Iforas. Elsewhere, the amount of dissolved solids may exceed 5,000 ppm.

The "Sudanese Strait" constitutes a special area; it consists of a subsidence trough - bordered by faults with big throws - 100 km wide and 2 km deep; the aquifers in the strait receive part of their water from the Niger between Bourem and Ansongo and then are drained by it between Ansongo and Niamey. The aquifers concerned are the following:

That in the interior delta of the Niger. The water is contained in formations of the "Continental terminal" which are generally overlain by more recent formations, particularly dune sands. The aquifer is 100 m thick and is fed mainly by the Niger and its tributaries, up to 130 km from the bed of the river in the area of Lake Faguibine, 80 km at Tombouctou, 30-50 km between Gourma-Rarous and Tosaye and up to 15 km at Gao. The rate of feed probably amounts to several m^3/s;

Those in the Taoudenni basin. The water is (or is likely) to be found in the Cambro-Ordovician sandstones (not yet tested), the Tournaisian Carboniferous sandstones (artesian, but saline water) and the recent formations, particularly the sebkhas;

Those in the Gondo area, which is surrounded by impermeable formations and constitutes a closed basin. The aquifers are: the sandstones at the edge of the area, the fractured Infra-Cambrian dolomitic limestones (Irma), the sandstones at Sarniers-Ouolo and the clays and sandstones of the "Continental terminal". Wells in the area are 35 to 75 m deep.

Formations in the Gourma area. They constitute an Infra-Cambrian peneplain of folded rocks where there are small, localized water bodies with irregular recharge;

The aquifer in the western Palaeozoic sedimentary basin. The main formations are the Cambrian shales at Nara, which contain intercalations of sandstones, quartzites and jaspers, and the Ordovician sandstones at Nara. Ground water occurs in small, localized bodies in fractures and thin surface dune formations;

The granito-gneissic basement (Birrimian), in the south. It contains small amounts of water in weathered and fracture zones.

Hydrogeological investigation was first undertaken by the French West African Water Service (<u>Service hydraulique de l'Afrique occidentale française</u>), and later with the aid of French technical co-operation. In recent years it has been linked with mining investigation under the National Mining Research Company (<u>Société nationale de recherches minières</u>, SONAREM). A team of Soviet and Hungarian hydrogeologists has been assigned to SONAREM. Artesian wells have been sunk in the east and north of the country. More recently, UNESCO has provided the services of a hydrogeological expert.

The main aims of a United Nations project which began in 1968 are to organize a ground-water service within the Department of Water and Power (<u>Direction de l'hydraulique et de l'énergie</u>), to test various aquifers by drilling and pumping in areas where the need for additional water is most urgent and to produce a general study concerning the search for and development and use of ground water in Mali.

MASCARENE ISLANDS

Volcanic archipelago in the Indian Ocean to the east of Madagascar.

Réunion

Area: 2,500 km^2; population: 415,000; French administration.

The island is dominated by two volcanic mountains 2,500 to 3,000 m high, one of which is active. It consists of basaltic rocks; no sedimentary rocks have been found.

Mauritius

Area: 1,800 km^2; population: 755,000.

This island, which is also basaltic, is lower (highest point: 825 m) and the volcanoes are eroded.

Rodrigues

Area: 200 km^2; population: 20,000; dependency of Mauritius.

The island is also basaltic, but has a coral limestone plain in the south-west. Annual rainfall is of the order of 1 m.

Ground water

Réunion suffers from a shortage of water. The volcanic formations are highly permeable and contain no perched aquifers. The water is contaminated by brine along the coasts, for there is excessive pumping in the inhabited areas. A complete hydrogeological survey of the island was made in 1963 by the Bureau of Geological and Mining Research.

A pilot agricultural development project which FAO has been carrying out since 1967 includes among its objectives the surveying of ground-water resources in Mauritius.

MAURITANIA

Area: 1,030,000 km^2; population: 1,100,000; West Africa.

General

Mauritania is a large country, the major part of which is occupied by the Sahara. It has an Atlantic coastline some 500 km long stretching north from the Senegal River, the lower reaches of which form the southern border with the Republic of Senegal.

The country contains extensive flat or subtabular areas which are largely covered by dune sands. Elevation increases fairly steadily towards the east to reach 200 to 400 m close to the southern and eastern frontiers. The highest point is an isolated peak, the Kediat Idjil (917 m), which rises over an iron deposit.

Maximum rainfall is 600 mm per year in the extreme south, but it is less than 200 mm over two thirds of the country so that there is little evidence of any drainage system other than at the foot of certain cuestas. Mauritania has no perennial watercourse apart from the Senegal River.

Geology

The Pre-Cambrian basement outcrops in the centre of the country and occupies almost all of the northern region (the Dorsale Regueibat). It forms a sort of crest or ridge between two synclines: the Senegal-Mauritania sedimentary basin (of marine origin) to the west and the continental Taoudenni basin to the east.

The formations of the African Pre-Cambrian shield found in the country are:

Lower Pre-Cambrian: gneisses with intercalations of quartzites, cipolins and amphibolites; and

The ancient Akjoujt series, sensulato, which is composed of a variety of rocks (schists, cipolins, sandstones and quartzites), the ages of which vary from Pre-Cambrian to Cambro-Ordovician depending on the region. The whole series was affected by orogenesis and the resultant folded formation is known as the "Mauritanian complex".

The Taoudenni basin, which is in fact one of the world's largest synclines, includes the Infra-Cambrian (up to 1,000 m of dolomitic limestones with stromatolites) and the Cambro-Ordovician (500 m of pelites, jaspers, quartzite pebbles, more or less quartzitic sandstones, coarse-grained sandstones and shales).

These two formations, where they are not hidden by overlying sandy formations, cover almost the whole of the eastern part of the country, particularly in the south (plains of the Hodh area, massif de l'Assaba, Tagant sandstones, Adrar plateau). They are succeeded by: the Gotlando-Ordovician (sandstones with intercalated clays and limestones (500 m)); the Carboniferous, in the centre of the syncline (limestones and sandstones); the "Continental intercalaire" (argillaceous sandstones), and the Quaternary, which is mainly represented by sands.

The coastal sedimentary basin consists for the most part of sandy formations with intercalated clays of Maestrichtian, Eocene and Mio-Pliocene ("Continental terminal") age.

The Quaternary formations include mainly continental sands and alluvium.

Ground water

There has been intensive activity in the field of hydrogeological surveys since 1950. Several hydrogeological maps have been published. The aggregate depth of bore-holes sunk is approximately 3,000 m.

The formations or areas in which ground water is found are:

Crystalline formations. Water occurs in fractures and weathered zones. Amounts are very small and the water is often mineralized;

Primary rocks in the Taoudenni basin. There are few water bodies in the north, although there may be some artesian water in the sandstones. In the south, water is found in the fractures in shales and sandstones, into which it filters after rain;

"Continental intercalaire" and "Continental terminal" in the extreme south-east. This complex takes the form of argillaceous sandstones which extend without interruption into Mali and Algeria. The "Continental intercalaire" contains several superimposed aquifers, from the topmost of which water is currently being extracted in the extreme south-east of the country. These water-bearing horizons extend throughout the basin within Mauritania and are also found in Mali and Algeria (Albian aquifer).

Coastal basin. In areas where the sedimentary succession is most complete, i.e. near the coast, this subsidence basin contains as many as three superimposed aquifers separated by less permeable strata. The aquifers within the basin include:

The phreatic and semi-confined aquifers in the sands and argillaceous sandstones of the "Continental terminal", which are currently exploited by means of the 600 traditional wells in the area. Water is also withdrawn from these aquifers through wells drilled to supply the country's three main urban centres: Nouakchott, Nouadhibou and Akjoujt. The specific yields obtained depend closely on the lithology of the formations concerned and vary from 0.5 to 3 l/s per metre of drawdown. The salt content of the water is generally low;

Intermediary (Eocene) aquifer, composed of limestones and argillaceous sandstones;

The lower or Maestrichtian sands, where the water is under pressure at some points.

The most widely exploited of the extensive ground-water bodies is that in the coastal basin.

The piezometric surface of the phreatic aquifer is below zero at almost all points; it drops down towards the north-east, reaching -35 approximately 120 km east of Nouakchott. It is probable that the aquifer contains fossil water and now receives a very small and inadequate amount of water from the Senegal River. The best yields are obtained from the sands and sandstones of the "Continental terminal", namely 10 to 60 m3/hr for a drawdown of between 5 and 15 m (or 1 to 2 l/s per metre of drawdown). Almost all areas of the country contain surface water or water lying at shallow depths which is quite strongly saline. Some large lenses of fresh water have been discovered. One of these is pumped to provide water for Nouakchott, 30 km away. As the yield is insufficient, a large seawater desalination plant is now under construction at Nouakchott.

A United Nations project got under way early in 1969. Its purpose is to train local personnel in the techniques of searching for ground water, to test a number of formations which are thought to contain water by taking soundings and sinking wells and to prepare a general study of the country's ground-water resources.

MOROCCO

Area: 445,000 km^2; population: 13,500,000; North Africa.

General

Morocco is the only country in Africa to have a shoreline on both the Atlantic and the Mediterranean. The relief is highly contrasted: two chains of high mountains, the Rif and the Atlas, form an arc open to the west, dividing the country into two parts: Atlantic Morocco to the west and Saharan Morocco to the east and south. The Mediterranean section of the country forms a narrow belt to the north of the Rif mountains and in the area of Tangier.

The High Atlas chain, which runs SW-NE, is one of the loftiest in Africa; its high point is Mt. Toubkal (4,165 m). The southern part of the chain is paralleled by the high plateaux of the Anti-Atlas, while the northern section is prolonged by the vast limestone plateau of the Middle Atlas (1,500 to 2,000 m).

The Rif chain follows the Mediterranean coast and contains peaks between 1,800 and 2,000 m high. The Rif and Middle Atlas meet in the Taza-Guercif region, which forms a sort of gap between Fès and Oujda; the crescent formed by the mountains in this area encloses the Atlantic coastal plains, which are drained by several large rivers: the plain of Loukkos, which is drained by the river of the same name; the Saïs and the Gharb, drained by the Sebou and its tributaries, the Ouerrha and Beth; the Tadla area, the plain of Berrechid and the Chaouia and Douakkala regions, drained by the Oum er Rbia river; the Haouz and Abda regions, drained by the Tensift, and the Sous region, which is drained by the river of the same name and lies between the Atlas and the Anti-Atlas.

All the major towns are located in the Atlantic portion of the country, with the exception of Oujda, the capital of eastern Morocco. To the east of the High Atlas lie the high plateaux, which merge into those of Algeria.

To the south of the Anti-Atlas is the region of the vast, rocky uplands (500 to 1,000 m high) known as hamadas. It includes the hamadas du Dra and du Guir and the Atlantic coastal plains of Tarfaya.

In the high mountains, and particularly in the Rif, the climate is humid, with annual rainfall exceeding 1 m; the coastal plains have 300 to 600 mm of rain per year, with more falling in the north and on the coast itself than in the south and inland.

Rainfall to the east and south of the Atlas Mountains is less than 100 mm while the potential evapo-transpiration is of the order of 2 m.

Geology

The Pre-Cambrian basement outcrops along the centre-line of the Anti-Atlas and in the western High Atlas. In the Anti-Atlas, the crystalline and metamorphic rocks are covered by very thick layers of Infra-Cambrian limestone and dolomite rocks. The central area of the Atlantic plains consists of Primary rocks covered by shallow Tertiary or Quaternary sedimentary deposits. The Gharb and Saïs areas in the north and the Sous region in the south are subsidence basins or gaps which contain thick beds of Tertiary and Secondary material. The central High Atlas and the Middle Atlas consist mainly of limestones, particularly of Jurassic age.

The Mediterranean face of the Rif, the ridge of which is composed of limestones, consists of (Primary) shales. The southern slope is made up of deposits of Jurassic, Cretaceous and Tertiary (Miocene) flysch, largely clays and marls.

To the south of the Atlas Mountains there are extensive Primary formations, mainly of shales and sandstones.

The eastern high plateaux consist of Jurassic limestones and dolomites overlain by Tertiary or Quaternary clay and sandstone formations.

Ground water

The first ground-water surveys were made in the 1930s. They concentrated on the southern parts of the country, from which there had been large-scale migration of the population towards the north in 1937 because of periods of drought. In 1963, the Hydrogeological Service had a staff of 18 engineers. The main aquifers are the following:

The limestones and dolomites (hard, fine-grained or oolitic) of Infra-Cambrian, Cambrian, Jurassic (particularly Upper Jurassic) and Cretaceous (Cenamano-Turonian) age. In the Atlas Mountains these formations contain many springs and they also feed the aquifers of the neighbouring plains through subsurface contact. The Liassic alone covers 10 per cent of Morocco and yields one third of the spring water ($25m^3/s$ from some springs); it supports 80 bore-holes yielding 1.5 m^3/s each. The Jurassic limestones contain artesian water in the high plateaux and their northern extension, the Triffa-Angad, and beneath the plain of Saïs. They also carry water on the Phosphate plateau;

The sandstone formations contained in the Primary series, which have far more limited potential;

Of the Tertiary and Quaternary formations, the Oligo-Miocene conglomerates of the piedmont areas; the Eocene limestones and sandstones; the Miocene and Pliocene limestones and coquina of the Atlantic coast; the Plio-Quaternary lacustrine limestones, sandstones, conglomerates and marly limestones of certain plains (Gharb, Saïs, Tadla, Benguerir, Berrechid, Sous, Tiznit, Tafilal and Haouz, Doukkala), which are tapped by numerous wells and drains and, when possible, by artesian wells. Sometimes, particularly in the arid southern regions, these formations are the only aquifers.

Most of the ground-water basins in Morocco have been developed, but overpumping is rare. The Atlantic coastal zone, between Mohammedia and El-Jadida, is the area most seriously threatened with contamination by brine, which is very far advanced in some places.

On the other hand, there has been a rise in the water tables in areas which are once again being irrigated by surface water (obtained from recently-built dams) and this has necessitated the installation of drainage systems. This has been the case in some parts of Triffa, Tadla, Gharb and the Doukkalas, areas where the ground-water bodies have inadequate outfalls. Various methods of drainage have been tried out in these areas, including pumping followed by injection into deep aquifers and the use of surface collectors. Some areas of Morocco, particularly certain limestone massifs, the areas of marl and flysch in the Rif, the regions where there are outcrops of crystalline or Primary shales and sandstones (central Morocco, south-east of Rabat, Bani), the hamadas du Dra and du Guir and the Tarfaya plains, contain very little ground water.

The water tends to be safe for human as well as livestock use, except in some desert areas where sediment concentration is high and in the outcrops of saliferous and gypsiferous Permo-Triassic formations. The water is often very hard. A map of the country's saline water deposits has been published.

Within the Water Department of the Ministry of Public Works, there is a service which specializes in the study of water resources. Known as the Water Resources Division (Division des ressources en eau), it has a staff of 450, including 27 engineers, 22 of whom are hydrogeologists and geophysicists. The national monitoring network comprises 135 hydrological stations and 2,100 piezometers. Some 700 major technical reports were prepared between 1958 and 1968. Numerous hydrogeological monographs have been published and a series of region-by-region studies of water resources is now being printed. A total of 2,424 million m^3 of ground water is used each year, while a further 1,040 million m^3 are lost into the sea, across the borders or through evaporation.

MOZAMBIQUE

Area: 783,000 km^2; population: 7,200,000; territory in south-east Africa opposite Madagascar; Portuguese administration.

General

From the south as far north as Beira the country consists of a large plain lying between 200 and 500 m above sea level and dominated in the west by the high plateaux of Natal, Swaziland, the Transvaal and Southern Rhodesia. The coastal zone is swampy.

In the centre, along the Zambezi, one of the longest rivers in Africa, the country forms something of a wedge between Southern Rhodesia and Zambia in the high plateau region; in the north, to the east of Lake Malawi, it declines fairly steadily towards the Indian Ocean over a distance of 400-500 km from a line of peaks, many of which are over 1,500 m high, overlooking the rift valley to the coast.

Several large rivers cross the country from west to east. They are, from north to south: the Ruvuma, Lurio, Zambezi, Save and Limpopo.

Except for certain areas in the south, all parts of the country have more than 500 mm of rain per year. In regions close to the coast and in the north, especially near Lake Malawi, rainfall exceeds 1 m.

Geology

The Pre-Cambrian basement covers an area of 500,000 km^2, or almost the whole of the country north of the Zambezi and a belt of plateaux along the border with Southern Rhodesia, with the gneisses, granites and granite-gneisses of the "basal complex". The Middle Pre-Cambrian, which is the most widely represented, exhibits schists and quartzites. The Terminal Pre-Cambrian includes sandstones and quartzites, but not the limestones which are found in Southern Rhodesia.

The Karroo system is represented by a narrow band of outcrops in the west, along the borders, at the edge of the high plateaux; it is composed of conglomerates, sandstones, shales and basalts.

Cretaceous and Eocene formations outcrop in the western sector of the coastal plains, which are narrow in the north and wide in the south; such formations comprise marine or continental sandstones which are argillaceous or calcareous and often conglomeratic. The Miocene is represented by marine limestones and the Upper Pleistocene, which occurs extensively along the coasts, by argillaceous aeolian sands of various colours.

Ground water

The search for ground water has been concentrated, particularly since the end of the 1950s, in the south and far north of the country, where the problems associated with providing an adequate water supply are greatest. Work has begun on a comprehensive inventory of water resources and the first regional hydrogeological survey has been undertaken in the area south of the Save, with the aid of a team of hydrogeologists from a consulting firm.

In the south, the unconfined aquifer is very extensive and continuous, since it is fed by considerable quantities of rain water filtering directly into it. However, the water often contains quite large amounts of minerals, except at points where there is surface sand cover. The Cretaceous and Tertiary sandstone-clay formations are relatively impermeable and this in terrain where evapo-transpiration is high. The alluvial aquifers contain large amounts of readily-exploitable fresh water.

Water with low mineral content is found in fractures in the karstified Miocene limestones which cover some 25,000 km^2 to the south of the Save, and yields per well are high. The piezometric surface lies at a depth of 50 m. Further south, the water body is also continuous and mainly exploitable in the extensive area of recent dunes. The chemical composition of the water, which has a low mineral content, is complex and variable; it is not directly dependent on the nature of the formations holding the water.

In the areas containing crystalline metamorphic and eruptive rocks (the areas of the basal complex, Upper Karroo and the Pre-Cambrian), yields from wells are as follows:

In the orthogneisses, granites and paragneisses which contain only small amounts of iron and magnesium and have a thick surface weathered layer, yields average 4 to 8 m^3/hr and as much as 10-12 m^3/hr (occasionally 25 m^3/hr). The water has a low mineral content (less than 300 mg/l).

In the highly ferromagnesian paragneisses, which are generally impermeable, it is only certain inclusions (quartz veins, peridotites) which yield water and then in small amounts. The weathered zone itself is argillaceous and barren; and

In the rhyolites, which contain small amounts of water in fractures and at occasional points support springs yielding a few hundreds of litres per hour, wells yield an average of 1 m^3/hr. The same is true of the basic and ultrabasic rocks. However, some bore-holes in basalts are capable of yielding as much as 25 m^3/hr.

In the Karroo and post-Karroo areas in the interior, where the tillites, shaly sandstones and argillaceous sandstones are largely impermeable, the best wells yield a few m^3/hr.

The northern coastal sedimentary basin contains a number of springs at such places as Cabo Delgado, where 43 have been recorded for a total yield of over 100 l/s. Bore-holes are capable of yielding a few m^3/s.

The fault zones in the rift valleys and the alluvial deposits of the major rivers contain unknown but probably large amounts of water.

On the whole, knowledge of the ground-water resources of this vast land, which has a relatively small and unevenly distributed population, is still at the inventory and reconnaissance stage. Because of the relatively widespread occurrence of saline water containing more than 1 g of NaCl per litre, particular attention has been paid in Mozambique to hydrochemical and geophysical (electrical logging) surveys. There can be no doubt that ground water represents a considerable potential natural resource, particularly in the south.

NAMIBIA

Area: 824,000 km^2; population: 600,000; southern Africa; South African administration.

General

The central area consists of a large plateau over 1,000 m above sea level, with peaks approaching or exceeding 2,000 m. To the west of the plateau lies the coastal Namib desert, a sandy strip 50 to 80 km wide and 1,500 km long, and to the east, the western part of the Kalahari desert.

Temperatures on the plateau are high (30 to 35°C). They are often lower on the coast, which is frequently covered by dank fog. Annual rainfall is less than 250 mm in the Kalahari and reaches a maximum of approximately 450 mm on the plateau at Windhoek. The coastal zone is very arid, having less than 50 mm of rain per year. The country contains no perennial watercourse.

Geology

The main geological units are: in the west, Pre-Cambrian formations: granite-gneisses, schists, conglomerates and sandstones; in the east, the sandy (continental) formations of the Kalahari; in the centre, and extending south and east, Infra-Cambrian dolomitic series; and locally, particularly in the Karroo, some basaltic formations.

Ground water

The main aquifers, and those most heavily exploited, are the alluvial fills of streams. This only applies in certain specific cases, since such alluvial water is sometimes saline.

In second place are the dolomitic limestones. They have been the subject of much preliminary reconnaissance work, but their true potential is still largely unknown. They contain fresh water not far from Windhoek, in areas where karstification is far advanced.

Many trial bores have been made in other formations, such as the Pre-Cambrian crystalline and metamorphic basement and the Karroo sandstones, but when pumped these have generally yielded only brackish water.

NIGER

Area: 1,267,000 km^2; population: 3,000,000; West Africa.

General

The greater part of the country lies within the Saharan region. The southern part, on the border with Nigeria, lies in the Sahelian zone. The country is generally flat, with altitudes varying in most cases between 250 and 450 m above sea level. The northern central region is occupied by the Aïr mountains, the highest point of which is 2,000 m above sea level. In the north-east are the Mangueni and Djado plateaux, which form uplands (500 to 700 m) connecting the Hoggar-Tassili and the Tibesti mountains.

The only major watercourse is the Niger River, which runs through the south-western corner of the country. The frontier in the south-east runs through Lake Chad. A narrow strip of land in the south has more than 400 mm of rain per year, whereas the northern half of the country has less than 100 mm.

The country is largely devoid of surface water, so that ground water is of vital importance.

Geology

The Pre-Cambrian shield outcrops in the south-western part of the country as far as the Niger valley and also occurs less frequently in the Zinder area. It is overlain by the following sedimentary formations:

Sandstones and clays of the "Continental intercalaire": Agadem and Tagama formations;

Marine Cenomanian: hard limestones;

Marine Turonian: yellow, sandy, dolomitic limestones overlain by sandstones;

Upper Cretaceous clays; and

Palaeocene-Eocene chalky limestones and schists.

This sedimentary complex is extremely thick (several thousands of metres) in the central area of the subsidence basin, to the north of Tahoua. To the east of the Aïr massif, in the Ténéré-Chad subsidence basin, the sedimentary series is less well known. In the north-east, in the Mangueni-Djado region, there are extensive, flat outcrops of Primary rocks, including Ordovician sandstones and limestones and Carboniferous and Devonian clays and calcareous sandstones. The "Continental terminal" outcrops over extensive areas to the north-east of the Niger as far as the Tahoua region. The north-west and the east of the country are covered by sandy formations, particularly in the Ténéré-Bilma region, which is one of the most inaccessible in Africa.

Ground water

Systematic hydrogeological investigation, based on geophysical techniques, began in the country soon after the Second World War with the making of a geological reconnaissance map and the sinking of the first bore-holes. The activity reached its peak in 1963.

Work is currently being carried out by the Government's Hydrogeological Service, by consulting firms, by the United Nations family of organizations, by a Government-owned ground-water enterprise known as the Office des eaux de sous-sol (OFEDES), and by mining and oil companies. There are a number of companies which build wells or bore-holes, and in particular four drilling companies (not counting the oil companies) which are currently sinking wells, some of them as much as 1,000 m deep. The techniques used in well or bore-hole construction and management are primarily the responsibility of OFEDES.

The results of all the investigations into and exploitation of ground-water sources, including the geophysical surveys, are summarized in a hydrogeological monograph which the Government published in 1969. It contains a description of all currently known aquifers and attempts to set the course for future work.

The country's aquifers include:

The eruptive and metamorphic formations attributed to the Pre-Cambrian, where the water is contained in weathered zones, fractures, crush zones, sills, dikes and contacts;

The Palaeozoic formations in the north, on either side of the Aïr massif. These contain very large bodies of water, which the oil companies have tested by means of bore-holes penetrating to the Pre-Cambrian and have occasionally exploited (areas of artesian flow). Particularly detailed studies have been made of the Primary formations near the western edge of the Aïr massif;

The basal formations of the "Continental intercalaire". These contain water bodies of which one promising example is situated west-south-west of the Aïr massif;

The "Continental intercalaire-Continental hamadien", which represents the largest water system known in the country, extending from Mali to the Djado plateau and Chad and as far south as Dahomey and Nigeria. This aquifer, which is an average of 500 m thick, contains promising areas of flowing water in the west and south-west of the country;

The Middle and Upper Cretaceous and the Palaeocene. They form a complex which is an average of 600 to 700 m thick and is basically argillaceous, although it also contains some limestones, sands and silts which may hold water. The quantity of such water is, however, always limited and the salt content is often too high for the water to be usable. Some water bodies are, however, found in these deposits near near the Pre-Cambrian rim of the basins;

The "Continental terminal", which occupies an extensive syncline in the west of the country, containing a series of promising superimposed aquifers which yield artesian water in some areas;

The Quaternary, which is particularly widespread in the east of the country, where the Chad formations, several hundreds of metres thick, also contain superimposed aquifers, one of which is artesian and has been exploited since 1962. The fixed dune sands and the alluvium of the water network, where this is fossilized or in the process of becoming so, also contain readily exploitable water bodies which are recharged each year, although the reserves are limited. In particular, the alluvial deposits in areas where there is no raised ground, and thus no slope, are, with few exceptions, thin and highly argillaceous.

With the exception of the Niger and Lake Chad, perennial surface water is extremely scarce in the interior and occurs only in small quantities. In this area, life is only possible thanks to large numbers of wells and pits, both old-fashioned and modern, and to bore-holes, some of which are more than 800 m deep.

Recently, a study was made of the water requirements of the country south of the fifteenth parallel; another study now in progress concerns the area between this parallel and the true Saharan regions. The latter areas contain known reserves of ground water which are plentiful by comparison with the requirements of their few inhabitants.

NIGERIA

Area: 924,000 km^2; population: 61,500,000; West Africa.

General

Nigeria is the largest and the richest country in West Africa. It is also the most populous of the African States, containing approximately 18 per cent of the total population of Africa. The country opens on to the Bight of Benin in the Gulf of Guinea over a coastline 800 km long, half of which is taken up by the vast delta of the Niger, one of the continent's longest rivers, which flows through the western part of the country. In the north-east, the frontier runs through Lake Chad.

The entire country rises steadily from the coast towards the northern border, where the altitude is of the order of 400 m. In the east are the Cameroon highlands (which average between 800 and 1,400 m but rise to as much as 2,400 m) and the Mandara mountains. In the centre, the vast bulk of the Jos Plateau (1,781 m at its highest point) dominates the broad surrounding plains. In the west, there is the Niger River and in the east, its main downstream tributary, the Benue. In the north-east, an ill-defined river system provides some degree of drainage to Lake Chad. The southern half of the country has from 1 to 1.5 m of rain per year, and more in the south-east. The drier regions, along the northern border, have 0.5 m of rain per year.

Geology

The entire country is made up of the Pre-Cambrian formations of the "basement complex", which outcrop over half of its total area. There are zones of gneisses, mica schists, schists and amphibolites heavily penetrated by ancient granitic batholiths, which are hard, extensively tectonized rocks uplifted in Mounts Goura and Kagora on the Jos Plateau, and younger granitic batholiths.

In the centre, in the Niger-Benue basin, the ancient shield is overlain by occasionally saliferous marls, sandstones and clays of the "Continental intercalaire" (500 m), which in turn are covered by the marine Upper Cretaceous consisting of thin beds of Cenomano-Turonian limestones and of clays and coal seams. The thickness of the Cretaceous sediments increases towards the south, in the direction of the vast coastal subsidence zone.

The Eocene is represented in the southern sedimentary basin; it contains up to 1,000 m of clays. In the south-west and south-east, the sediments are less thick (100 m) and include layers of phosphatic sandstones and sands.

The marine Eocene has also been found in the north (Sokoto province).

The "Continental terminal" is widespread in the north-east and north-west, namely in the Chad and Sokoto basins, with 700 m of argillaceous sands, sandstones, diatomites and lignites. In the south, the "Continental terminal" comprises two formations: the lignite group (lignitic sandstones and clays 25 m thick), overlain by argillaceous Benin sands of Plio-Pleistocene age (250 m).

Some areas of volcanic basalt of indeterminate age - but not old - occur in the centre and east of the country.

Ground water

The ground-water bibliography of Nigeria for the period 1930-1963 includes nearly 250 unpublished reports. These are mainly drilling logs, local inventories and technical notes. There are several local geological monographs which include a section on hydrogeology. However no comprehensive hydrogeological map has yet been published. General reports have been written on the ground-water resources of each region. The Israeli firm, Tahal, in particular has surveyed the southern part of the country.

The main aquifers occur in the following zones:

The fracture and weathered zones of the crystalline and metamorphic basement;

The water-saturated sandstones of the Cretaceous sedimentary basins of the Niger and Benue;

The sandstones of "Continental terminal" (Post-Eocene) age in the delta, where artesian wells have been sunk in the Oji district near Onitsha;

The sandstones of the "Continental terminal" and the Quaternary cover sands in the Chad basin.

Ground water plays an important role in the life of Nigeria. Although the country is humid, there are large areas where there is insufficient surface water to meet local needs. This is particularly true of the provinces of Kano, Katsina and Sokoto in the north, of Zaria and Bauchi and of the Benue and Niger valleys at some distance from the rivers and their major tributaries.

Exploration for water has been carried out by the ground-water section of the Government's Geological Survey, which has a staff of five hydrogeologists, by a hydrogeological mission from the (United States) Agency for International Development in the north and by technical co-operation missions, including a United Nations mission to the Cross River basin in 1963-1964. Some 15,000 traditional wells have been recorded in the north-east.

In 1968, there were more than 700 lined wells and over 300 deep bore-holes in Nigeria.

Most of the wells have been sunk into the basement formations. Each supplies about 500 inhabitants. Some of the bore-holes are situated in the delta areas where the water-table cannot be reached by means of wells, since the aquifer closest to the surface often lies at a depth of over 200 m.

Most of the bore-holes are in the Chad basin. The drilling equipment available includes: the rigs belonging to the water drilling section of the Geological Survey; the rigs of the private Balakhany company, which works for the Government, and equipment made available to Nigeria, together with the necessary technical personnel, by the (United States) Agency for International Development.

In the Bornu region, which covers 30,000 km^2, artesian bore-holes yield between 0.4 and 20 m^3/hr. The depth at which the water lies increases from the rim of the basin (120 m) towards the centre (400 m). The major activity in the area is livestock raising. Development of the artesian water has obviated the need to move the cattle to the watering points, which are an average of 20 to 30 km from the grazing areas. Each artesian well is capable of providing water for 5,000 head of cattle per day.

The western part of the basin holds non-artesian water which is currently under study.

A joint UNESCO-FAO-UNDP project, which covers the whole of the Chad basin, is intended to determine the best method of developing this aquifer and the grazing areas.

Artesian water has been found in the north-west, in the Sokoto basin, by bore-holes sunk into the "Continental hamadien" and the "Continental terminal".

In the south, near the Niger, in the region of Nsukka to the north-east of Onitsha, wells have been drilled down to the deep-lying aquifers since the area contains no ground water at shallow depths.

In basement areas, the search for ground water is based on extensive geophysical prospecting, using mainly electrical techniques.

PEOPLE'S REPUBLIC OF THE CONGO

Area: 342,000 km^2; population: 860,000; central Africa.

General remarks

The People's Republic of the Congo lies along the right bank of the Congo and of its tributary, the Oubangui, and has an Atlantic coastline 150 km long. The equator runs through the centre of the country, which has a hot, tropical humid climate.

The Batéké plateau (average elevation 700 m) rises behind the coastal plain and the Mayombé chain. Further north is the basin of the Congo and the Oubangui Rivers, which is swampy in parts and contains equatorial forest; the altitude, between 300 and 500 m above sea level, increases towards the west and north.

The country has an average annual rainfall of 1.2 m; the dry season, from May to September, is more marked in the west.

Geology

The old basement outcrops in the Mayombé chain and all along the country's northern border. The crystalline, "crystallophyllian", conglomeratic and sandstone and quartzitic formations form the Nyanga syncline, which strikes NW-SE and is filled by sediments from the Terminal Pre-Cambrian: tillites, lustrous schists, argillites, schistose and dolomitic limestones (with stromatolites) and feldspathic sandstones.

The Batéké plateau sandstones are equivalent to the Kalahari formations, having at their base, polymorphous sandstones ("Continental terminal" of Eocene-Oligocene age) and at the top aeolian sandy loams (100 m).

On the coast there is a sedimentary basin of Cretaceous-Eocene age which is linked to that in Gabon; it does not exceed 50 km in width. In it, the Aptian is represented by sandstones and limestones and the rest of the Cretaceous by sandstones and marls. The Maestrichtian and the Eocene are represented by phosphatic sands.

The basin of the Congo and the Oubangui Rivers contains the formations of the "Continental intercalaire" and "Continental terminal" described in the section on the Democratic Republic of the Congo.

Ground water

In the People's Republic of the Congo, ground water has been little studied; the only investigations which have been made concerned local problems such as that of the water supply for the town of Pointe-Noire and its industries, particularly a brewery. In the Niari River valley, the UNDP (Special Fund) project executed by FAO and completed in 1967 found ground water suitable for irrigation. A search was also made for ground water on the Batéké plateau (Koukouya) with a view to assessing the potential water supply for the growing of cash crops.

Some rural areas have insufficient water to meet the needs of the local population. The Government has no plans, however, to undertake any hydrogeological surveys; in 1970, it had no form of bilateral assistance for work on ground water.

The hydrological characteristics of the geological formations in the People's Republic of the Congo are probably similar to those in areas in neighbouring countries where geological and climatic conditions are about the same; this would include, in the Democratic Republic of the Congo, the Infra-Cambrian basement, limestone and dolomite regions, the Kalahari formations and the interior sedimentary basin of the Congo.

RWANDA

Area: 26,300 km^2; population: 3,300,000; central Africa.

General

Rwanda is a small, densely populated country bordering on Lake Kivu. It is an equatorial, mountainous land. Mt. Karasimibi, in the north of the country, is 4,507 m high. The country lies at an average height above sea level of 1,500 to 1,800 m and contains a number of lakes. Rainfall exceeds 1 metre per year throughout the country. Some eastern regions have dry seasons in the winter and summer.

Geology

To the west, Lake Kivu lies in a subsidence trough -- the graben of the great lakes -- which is crossed from west to east by the Virunga Mountains, a chain of basaltic volcanoes of Miocene age, some of which are active. Pre-Cambrian basal formations lie to the east of the graben.

Ground water

From 1952 to 1962, drilling for water was carried out with an average of two to four rigs belonging to the Government, largely for the purpose of providing urban and rural centres, including Kigali, Gisenye, Kagera, Bugetsera, Butare, Ntiaza, Nyanza and Gitemero, with water. Most of the wells were sunk in Quaternary, lacustrine or fluvio-lacustrine formations (sands, gravels and granitic sands) and in Tertiary volcanic centres. The dewatering coefficient was 0.1 to 2 l/s per metre of drawdown.

There are very few publications and maps relating to ground-water resources. Construction work has included the building of dams intended to increase the amounts of water flowing into the small alluvial aquifers and the building of several hundred modern wells.

The main demands made on ground-water resources are as follows:

Bugetsera: 2 million m^3/yr, and Kajesera: 1 million m^3/yr for the inhabitants of the rural areas, livestock, the mines and the tourist park. The region has no surface water;

Gisenye and Burgoye: 5 million m^3/yr for the rural and urban population and livestock. In this area, ground water is extracted from the lacustrine and fluviatile alluvial deposits and the piedmont of the Virunga Mountains;

Kigali: approximately 10 million m^3/yr for a large urban and rural population, mines and livestock. Ground water is extracted from the Nyawarongo system; and

Butare and the centre of the country: 10 million m^3/yr for a large urban and rural population, mines and plantations. The area contains marshes in the low-lying valleys which have no drainage. The ground water is drawn from the Akanguru alluvial deposits.

SENEGAL

Area: 196,000 km^2; population: 3,700,000; West Africa.

General

Senegal is situated in the extreme west of Africa and has an Atlantic coastline 550 km long. It is a flat country, the altitude being generally less than 50 m. Some volcanic mountains in the south-east reach a height of 445 m.

Rainfall increases steadily from the north (300 mm) to the south (1.3 to 1.5 m), and is approximately 600 mm at Dakar. Two large rivers cross the country: the Senegal in the north and the Gambia in the south. The Senegal, whose main tributary is the Falémé, flows into the Atlantic through a huge, marshy estuary, which contains numerous sand bars and receives the overflow from the lac de Guiers: this shallow lake is fed by floodwater from the Senegal.

Geology

The formations of the Pre-Cambrian basement outcrop in the south-east; they include granitized schists of Birrimian age which are overlain in the south-east, along the border with Guinea, by Infra-Cambrian sandstones, quartzites and limestones and in the west by a Cambro-Ordovician series of sandstones and limestones.

However, almost the entire western part of the country consists of a sedimentary coastal subsidence basin of Secondary and Tertiary age, which is depressed in the central area of the country and rises in the west in the Cap Vert area. The latter region contains the faulted anticline of N'Diass and the Cap Vert peninsula, which is itself covered in the west by basalt flows. Outcrops of the following formations are found:

Maestrichtian: basically sandy, with sandstone and sandstone-limestone beds grading, to the west, into more argillaceous facies (thickness: 1,800 m at Rufisque and 900 m at Diourbel);

Palaeocene: limestones (50 to 100 m), with layers of sandstones and marls;

Lower Eocene (100 to 400 m): marls and clays, with some intercalated limestones;

Middle Eocene (200 m): limestones at the bottom and local deposits of clay at the top;

Oligo-Miocene: limestones, marls and clays covering the south-west of the country; and

"Continental terminal", of widely varying thickness (up to 150 m): sands containing sandstones and clays, overlain by a lateritic carapace.

The Quaternary is represented by several different formations: lacustrine limestones in thin surface layers in the north-west, fixed or mobile dunes, marine oozes and sands, and fluviatile alluvium, including both sands and loams and sands and clays.

Ground water

Of all the French-speaking countries in Africa, Senegal has been the subject of the most intensive ground-water studies. These were stimulated in the first place by the need of the city of Dakar for large quantities of water and also by the considerable ground-water potential of the Maestrichtian sedimentary basin.

The main aquifers are as follows:

Cap Vert Peninsula

Quaternary aquiferous sands, 50 to 80 m thick, covered in the west by basalts, from which 32 bore-holes and wells draw 25,000 to 30,000 m^3/day. The water contains 400 ppm of dissolved salts and leaves ferruginous deposits;

Maestrichtian sands and sandstones at N'Diass;

Palaeocene limestones at Sebikotane in the west and Pout in the east (7 bore-holes supply the city of Dakar with 50,000 m^3 of water in each 24-hour period); the water contains 400 ppm of dissolved solids.

In 1970, as part of a UNDP Special Fund project executed by WHO, an investigation was made into the amounts of ground water available in the Dakar area for municipal use.

Surface aquifer covering whole of country

The water is contained in very varied geological formations. The piezometric surface is at a negative level (-50) in the centre of the basin. It is higher in the west along the coast (+10 to +20) in the Niaye sands and especially locally in the Thiès area (+60); it also rises in the north (zero throughout the valley of the Senegal River), in the east (+30 to +50) along the edge of the Cambro-Ordovician outcrops and in the south in the Casamance area (+20).

The best water-bearing strata, both in terms of yield and of water quality, are found in the areas around the Ferlo River (sands of the "Continental terminal", Eocene limestones), the Niaye sands, the Diourbel area (Eocene: the yield is as high as 50 m^3/hr per well) and the area between Nioro du Rip and Koungheul near the border with Gambia (specific yields of the order of 6 m^3/hr/m).

In the delta areas, the argillaceous strata have a low yield and contain brackish water.

In the area around the ancient eastern massif, there is very little ground water other than in the more suitable formations, such as alluvial deposits.

Deep Maestrichtian aquifer

This aquifer extends through most of the country. It is currently exploited by approximately 100 bore-holes. The water is contained in 200 to 250 m of sands and sandstones and lies above saline water of Cretaceous age. It is pressurized by clayey marls and argillaceous sandstones of the Eocene and "Continental terminal". The piezometric surface is higher in the south. The water is used mainly for domestic purposes and for livestock. Three types of well are used: the "puits-forage" which comprise a deep bore-hole of small diameter combined, with a well from which water is taken manually (cost: $US 40,000); wells drilled for pastoral use (cost: $US 55,000, at 7 cents per m^3) and wells drilled for urban use (cost: $US 65,000, at 2 cents per m^3).

For a drilled well yielding 400 m^3/hr, the cost price of the water is estimated to be 4 CFA 9/ francs (1.5 cents) per m^3.

The water in the Maestrichtian aquifer does not have a uniform chemical composition; sediment concentration increases from the interior (500 ppm) towards the north-west (2,000 to 2,500 ppm).

SIERRA LEONE

Area: 71,700 km^2; population: 2,500,000; West Africa.

General

Sierra Leone, like Liberia, is part of Guinea's tectonic foreland on the Atlantic coast, with 350 km of highly indented coastline and many islands. The coastal plain is fairly wide (50 to 100 km) and covered in the south by equatorial jungle. Towards the northern and eastern frontiers, the elevation reaches 1,000 m. The highest point is in the east, in the Loma Mountains (1,948 m).

The country is crossed by numerous coastal rivers with broad estuaries, sometimes ending in coastal lagoons; the rainy season lasts from May to September. Rainfall is heavy: 3 to 5 m per year on the coast, 2.5 m over the country as a whole, 1.5 to 2 m near the northern frontiers.

Geology

The entire country consists of Pre-Cambrian basement formations: granite gneisses and schists cut by pegmatites (Lower Pre-Cambrian); schists and quartzites (Middle Pre-Cambrian); and conglomerates, feldspathic sandstones and dolerites (Upper Pre-Cambrian and Infra-Cambrian).

9/ Communauté financière africaine.

These formations are often altered and covered with lateritic deposits.

A sedimentary basin about 40 km wide, in which Eocene clays have been identified under the Quaternary estuarine deposits (gravels, sands and clays), extends all along the coast. It is possible that, as in the Ivory Coast, these Eocene clays overlie Cretaceous sediments.

Ground water

No regional ground-water surveys have been conducted in Sierra Leone. Many localities in the interior obtain their water supply from bore-holes and wells in the basement formations. Water for the capital city of Freetown, situated on a mountainous peninsula, is supplied from reservoirs behind a number of small dams.

The important diamond-mining installations in the eastern part of the country, mainly in the area of Yengema and Sefadu, use both ground water and water from reservoirs formed by small dams.

SOMALIA

Area: 638,000 km^2; population: 2,700,000; north-eastern Africa.

General

Somalia's coastline, extending along the Gulf of Aden in the north and the Indian Ocean in the east, is longer than that of any other African country.

The country as a whole forms a kind of plateau sloping down towards the Indian Ocean in a NW-SE direction. The altitude along the southern frontiers ranges from 300 to 500 m. An arc of mountains (the Ouagai and Medjourtine Mountains) borders the Gulf of Aden, with peaks between 1,700 m and 2,200 m.

Two major rivers, the Scebeli and the Giuba, rising in the Harar plateau of Ethiopia, cross the southern part of Somalia; their course disappears in a sort of inland delta, an elongated playa not far from the coast (5 to 40 km).

The climate is of the arid type, particularly along the coasts, with rainfall less than 250 mm per year in the north, down to the fifth parallel, and reaching 400 mm in the south and 700 mm in the south-west.

Geology

The basement formations - gneisses and schists with granodiorite intrusions - crop out in two regions: the mountain chain in the north and a zone between the two rivers in the south. The central part of the country is occupied by a syncline; the formations overlying the basement are generally Middle Jurassic (locally Triassic or Cretaceous). The "Horn of Africa" is an Eocene plateau.

The Jurassic began with the deposition of gypsiferous sandstones. This was followed by an oolitic series several hundred metres thick, mainly limestones, but including shaly limestones in some locations.

Sandstones comparable to the Nubian Sandstones were then deposited during the Lower Cretaceous, followed by Cretaceous marls and limestones of marine origin and, conformably with this, by an Eocene deposit which was also limestone.

The marly Oligocene occupies a discontinuous band along the Gulf of Aden and in the northern part of the Indian Ocean littoral. It is overlain by sandy Miocene formations.

Ground water

The ground-water resources are somewhat unevenly distributed among six large regions, as indicated below:

Southern coastal zone. Bounded on the west by the great Banta-Gialalassi fault. The principal aquifer consists of Tertiary lumachelles and sands. There are artesian potentialities; in some areas the artesian waters are brackish or salty;

Crystalline region of El Bur. In the depressions the weathered zone sometimes attains thicknesses of over 30 m. There is little ground water;

Southern inland region. The best aquifer is found in the Nubian Sandstones. The Karstified Jurassic limestones and Cretaceous limestones locally form aquifers which have not yet been carefully studied;

Plain of Mudugh. Almost nothing is known about the water resources here. The only aquifer used by the sparse population is the sandy alluvial fill in the beds of uebis or depressions. The possibility of finding artesian waters is not to be excluded. Some wells contain radio-active water;

Shol Plateau. This area, covered with Eocene sediments (marls and anhydrites), has never been explored; it may, however, contain artesian water at great depth; and

Northern mountain zone and neighbouring zones. This is a rugged, uneven area, with very little rainfall. The only water reserves are in the alluvial fills. There are some thermal springs in this region, in which very few bore-holes have been drilled.

It is possible that the Nubian Sandstones, under the Tertiary sediments of the Haud, contain artesian water.

Ground-water exploitation is the responsibility of the Ministry of Mines. The drilling section has a total of some 20 drilling rigs, not all of which are in use.

A limited amount of technical assistance in the ground-water field has been furnished, for limited periods, by FAO in connexion with the execution of an agricultural project, by the United States Agency for International Development (water supply of Mogadiscio, training of drilling technicians) and by a Soviet mission.

A United Nations project on mining and ground water has also included a ground-water phase, limited to the El Bur and Chisimaio areas. The second phase of this project, undertaken in late 1969, provides for the organizing of a hydrogeological section, the preparation of a hydrogeological map, a preliminary inventory of ground-water resources and detailed investigations in selected zones.

SOUTH AFRICA

Area: 1,221,000 km^2; population: 18,700,000; southern Africa.

General

The major portion of the country is occupied by a plateau, the height of which varies from 1,000 to 1,500 m. The 1,000 m contour is roughly parallel to the coast, at a distance from it of between 150 and 200 km in the south and 80 and 120 km in the east. It follows an arc of mountains formed by the Karroo (2,500 m) in the south and the Drakensberg (3,500 m) in the east.

The climate is Mediterranean in the Cape region, humid temperate in the western areas and hot with a dry winter in the interior. Rainfall does not exceed 400 mm per year in the western half of the country and decreases towards the north and west. Potential evaporation in these areas is high (approximately 1.80 m per year for a free water surface). The coastal regions and the escarpments which overlook them have higher rainfall, especially in the east (1.20 to 1.50 m in Natal Province).

A major river, the Orange, and its main tributary, the Vaal, cross the country from west to east. In the north, the Limpopo forms the border with Southern Rhodesia and Botswana.

Geology

More than 40 per cent of the country is covered by the continental formation of the Karroo, composed of Carboniferous-Triassic sandstones and argillaceous schists in mainly horizontal beds, with low permeability except in areas traversed by dikes and doleritic sills.

The formations of the Pre-Cambrian basement (granite-gneisses and schists) outcrop in the area of the lower reaches of the Orange downstream from Prieska and close to Swaziland.

Upper Pre-Cambrian rock is found in the north of the Orange Free State and particularly in the southern Transvaal, where it comprises sandstones, slates, and gold-bearing conglomerates in the synclinal Witwatersrand system (7,000 m thick).

In the Late Pre-Cambrian, there is a very extensive, 2,500 m thick series of "cherty dolomites" to the south and west of Pretoria and the north-west of Kimberley, between the Vaal and the Orange. These dolomites are overlain by the 3,000 m of shales and quartzites which constitute the Pretoria series.

On the coast, there is a number of small sedimentary basins of Cretaceous-Tertiary age.

Ground water

The main aquifers currently being exploited are:

The fractured dikes of the Karroo, and the metamorphic zones of the same system at their contact;

The weathered zones (30 to 150 m thick) in crystalline rocks, which cover 20 per cent of the country; such zones are detected by electrical geophysical prospecting. Fifty per cent of the country's bore-holes are found in these formations;

Fluviatile sands and alluvia;

The dolomite series in the Transvaal, which probably constitutes the country's largest aquifer. The proved capacity of two "compartments" in this series exceeds 500 million m^3 in each case.

These dolomites are the subject of intensive study. It has been discovered that they contain vast drainage areas corresponding to faults which have been widened by decomposition and filled with porous and permeable sediments.

Most of the hydrogeological studies made have concerned these dolomites, particularly in the Transvaal (Far West Rand), where several compartments bounded by syenitic dikes were studied separately, with particular regard to the assessment of reserves and recharge potential and the ground-water balance.

Ground water is the only water found in the arid region of South Africa. It accounts for 13 per cent of the total amount of water used in the country, which has 600,000 bore-holes, 300,000 of which have been drilled since 1950 (an average of 20,000 bore-holes is now being drilled each year). About half (300,000) of these bore-holes are equipped with pumps which draw out approximately 6,000 to 7,000 million m^3 per year. In all, approximately 250,000 wells equipped with wind- or motor-driven pumps are used to supply the population in rural areas, to water livestock (5,500,000 head of cattle and 26,000,000 head of smaller animals) and to irrigate more than 80,000 hectares; a further 50,000 wells supply urban and rural centres.

The daily pumping rate is approximately 3,000,000 m^3 (nearly 40 m^3/s).

The yield per well varies as follows: from 2 per cent of the total number of bore-holes, it is over 20 m^3/hr; from 18 per cent, between 5 and 20 m^3/hr; from 30 per cent, between 0.5 and 5 m^3/hr; and from 50 per cent, less than 0.5 m^3/hr (dry wells). The yield from 10 per cent of the bore-holes is considerably reduced during the dry season. Many of the wells are over-pumped. Increasing use is being made of hydrogeological and geophysical surveys to select sites for bore-holes.

SOUTHERN RHODESIA

Area: 389,000 km^2; population: 4,500,000; land-locked country in southern Africa.

General

The country consists of a plateau lying at an average height above sea level of 1,000 m. A succession of small chains of mountains in the east forms the frontier with Mozambique; the mountains are 2,600 m high in the north and 2,440 m high in the south. The high veld, a large rocky area, runs from south-west to north-west in the centre of the country.

Because of the altitude, the climate is generally temperate. Annual rainfall varies according to the region from 300 to 1,200 mm and occurs at an even rate from November to April (southern summer). The climate is generally very favourable to the production of a wide range of crops.

In some areas, surface water is very plentiful: there is the artificial lake formed by the Kariba dam, which is one of the largest in the world, and two rivers, the Sabi and the Zambezi, in the north of the country.

Geology

The central area, comprising two thirds of the entire country, consists of mainly granitized basement formations. These are cut from north to south by the Great Dyke, which is 500 km long and 5 km wide and stands out above the surrounding granites.

Infra-Cambrian schists, sandstones and quartzites outcrop to the west of Salisbury and near the frontiers. The shales and the more or less argillaceous sandstones of the Karroo are fairly widespread along the northern borders and in the centre of the country, with some outcrops in the south. There are remarkable formations of basaltic lavas of Triassic-Jurassic age in the north-west, at Victoria Falls, and in the south-east, between the Sabi and the Limpopo. A few scattered outcrops of thick Cretaceous conglomerates occur to the north of Mount Darwin and in the south-eastern corner of the country. Finally, Kalahari sands extensively cover the western areas and occur in thin layers at the surface in the central and eastern regions.

Ground water

In 1959, a mission from the United States Geological Survey visited Southern Rhodesia and made an inventory of the aquifers, a description of which is given below:

Kalahari sands: consolidated at depth. Geologists associate with them the alluvial filling in the beds of watercourses. They probably contain the country's largest reserves of ground water; in some places, bore-holes sunk into these sands yield more than 70 m^3/hr;

Cretaceous conglomerates (thickness: 700 m). They sometimes yield 2 to 7 m^3/hr, with 750 to 2,400 ppm of dissolved solids;

Jurassic lavas. They constitute a poor aquifer, except for the sandstone beds they contain or overlie, which may hold artesian water; one well yields 6 m^3/hr, with 1,200 ppm of dissolved solids. The deep bore-holes, however, have encountered only basalts and are sterile;

Upper Karroo (Triassic). The sandstones of this period are capable of yielding as much as 60 m^3/hr; the very fine-grained pelites, however, are dry;

Lower Karroo (Permian); represented by argillaceous shales and also by sandstones capable of yielding artesian water which is sometimes heavily mineralized;

Crystalline formations. These are generally overlain by an alluvial or weathered layer which may be as much as 50 m or more thick but which has been removed by erosion in many places. Water can be found in the basement fractures;

Umkondo crystalline system. This is a complex and little known group of arkoses, quartzites, limestones and basalts which occurs in most areas of the country and which is thought to contain large amounts of exploitable water;

Lomagundi system (dolomites and quartzites). With some exceptions (4 m^3/hr to the north of the Hunyani Range), it is less productive;

Intrusive granites. They constitute a poor aquifer extending over the whole of the country. The areas with dolerite dikes contain the most promising water bodies, which are identified by electrical methods of geophysical prospecting; and

Gold beds (Bulawayan system). They contain basalts, conglomerates and various metasediments. To the east of Salisbury, some wells yield 7 to 12 m^3/hr. The results from test bores have been used as the basis for a few regional studies of aquifers, such as that made by H. Lange in 1962.

Over much of the country ground water is the only kind of water permanently available. There is almost no area where the yield is less than 1/2 m^3/hr. Wells are sunk at a rate of 1.5 to 6 m/day by percussion rigs with 5-6 inch tubing. Sites are often selected on the basis of geophysical prospecting.

The traditional watering points of the type most often used are simply holes dug in the alluvium of watercourses. More than 30 thermal springs have been studied in Southern Rhodesia; they are linked with faults affecting the post-Karroo basalts.

SPANISH SAHARA

Area: 226,000 km^2; population: 30,000; includes the two districts of Saguia el Hamra and Rio de Oro; Spanish administration.

General

Spanish Sahara lies at the extreme western edge of the great deserts of northern Africa. It comprises a vast, low-lying platform, with a coastline 800 km long which includes several stretches of cliffs overlooking narrow beaches. The ground rises fairly steadily towards the interior, reaching 400 to 500 m near the frontier with Mauritania.

The platform is dotted with numerous depressions, whose flat bottoms are covered by argillaceous deposits which are often saline. Rainfall is very low: 10 to 50 mm per year on the coast and less in the interior. There is no perennial watercourse. Occasionally, however, storm showers cover the bottom of the Saguia el Hamra depression with rain water.

Geology

The crystalline and metamorphic (granite gneiss) formations of the Pre-Cambrian basement outcrop extensively in the south and along the eastern borders of the country, in large, fractured peneplains cut by numerous granitic and other eruptive bodies and veins of basic rocks. They support a layer of sediments which includes the following subdivisions:

Infra-Cambrian and Cambro-Ordovician: limestones, shales and shaly sandstones;

Gotlandian and Devonian: sandstones and soft black shales with intercalated strata of limestone;

Carboniferous: sands and clays with intercalated limestones;

Cretaceous deposits of continental and lagoonal type (saliferous and gypsiferous sandstones and clays) at the bottom and top; purely marine in the Middle Cretaceous (marly sandstones and limestones);

Neogene, marine facies: sands and limestones in the coastal region;

Quaternary: alluvial deposits, anchored and wandering dunes, shelly and sandy limestones.

Palaeozoic formations form a syncline in the north. The Cretaceous sediments transgress on the Palaeozoic formations in the centre and on the basement in the southern half of the country.

Ground water

Most of the ground water is extracted by means of shallow wells; it is generally drawn from the Quaternary or Neogene formations (consolidated dunes, alluvial beds and sandstones); occasionally it is found in fractures and veins in the basement, as in the Tiris-Tisla region. The degree of salinity of the water varies (from 1 to 5 g of dissolved solids per litre). A total of some 150 wells has been recorded. The Spanish military installations receive their fresh water supplies by tanker from the Canary Islands and also through brackish water desalination. There are a few springs at the foot of the cliffs and in the Saguia el Hamra valley; they usually have a low yield.

Deep wells were sunk in the El Aiaún area in 1962-1963 and are said to have yielded artesian water with a low mineral content. This information, which was widely disseminated in the press, does not seem to have been confirmed by any scientific publication. It is, none the less, true that the geology and the topography of the Saguia el Hamra seem very favourable to the formation of bodies of artesian water. On the other hand, what is known of the geological structure of the sedimentary basin leads one to think that water found at depth would normally be saline or brackish.

SUDAN

Area: 2,506,000 km^2; population: 14,300,000; eastern Africa.

General

The Sudan is the largest African country in area. It is an almost entirely land-locked State, with 550 km of Red Sea coast, extending from 18° to 22° North latitude.

The central part of the country has the form of a depression at an elevation of 300 to 500 m, sloping downward towards the north. This depression, crossed by the Nile Valley, is bounded:

On the east, by the Ethiopian massif, which has a northward extension into Sudanese territory in the form of a mountain massif along the Red Sea, with its highest points at Jebel Hamoyet (2,780 m) in the south, Jebel Oda (2,260 m) at the centre, and Jebel Obkeik (1,860 m) in the north;

On the west, by a vast assemblage of plateaux and reliefs, with altitudes ranging from 500 to 1,000 m, which separate the Chad and Nile basins. In the west-central portion, near the Chad frontier, lies the vast Darfur massif, which reaches 3,087 m at Jebel Marra. Further east, in the central part of the country, lies the Kordofan plateau (400 m), with the Nile flowing around its base.

The Nile crosses the country from south to north. First, under the name of the White Nile, it waters the vast Upper Nile plain, where an important tributary, the Bahr el Ghazal, joins it on its left bank. The Nile valley then becomes narrower. At Khartoum, the capital, at about the sixteenth parallel, the Blue Nile, rising at Lake Tana in Ethiopia, flows into the river on its right bank; starting from Khartoum the river is known as the Nile.

As in Egypt, a large part of the population is concentrated in the Nile valley, but the population density is lower (50 to 100 inhabitants/km^2, locally 100 to 200). However, about 7 million inhabitants live away from watercourses. The climate is continental, except along the Red Sea. The regions with the most favourable conditions are those of Kassala and Tokar, the Gezira plain (gum-tree forests) and the Kordofan, which is grazing country.

The isohyetal lines cross the country in a WSW-ENE direction, with humidity increasing towards the south. The 20-mm isohvet intersects the Nile at about the nineteenth parallel, the 100-mm at about the seventeenth parallel, the 250-mm at about Khartoum and the 500-mm at about the thirteenth parallel.

Geology

There Pre-Cambrian basement crops out in the Sudan over a very wide area and includes the following series:

The Lower Pre-Cambrian or Primitive System: granite gneisses, mica schists, and granitic and doleritic schists;

The Middle Pre-Cambrian or Nafirdeib series: quartzites, cipolins, schists and green andesite flows, the entire series being traversed by intrusions of granites and gabbros; and

The Upper Pre-Cambrian or Awat series (1,600 m of lavas and argillites), intruded by granites.

The basement formations are overlain by very extensive sediments in the northern and north-eastern zones, of various ages (from the Palaeozoic to the Eocene). These formations include:

The Ennedi-Erdi sandstones and conglomerates towards the west;

The Uweinat series (north and west);

The Nawa series (locally in the central region);

Nubian Sandstones, mainly Cretaceous, widely represented in most of the regions (cross-bedded sandstones and conglomerates), with thicknesses of several hundred metres; and

The Umm Ruwaba series (Neogene and Pleistocene) in the southern and central regions. These last two units are very thick; they have few outcrops, being overlain almost everywhere by more recent formations: plains clays or Kordofan sands.

After the Oligocene, lacustrine régimes became established at various epochs in various regions of the country, particularly in the north-east, resulting in complex deposits usually consisting of fine elements: argillaceous (black clays), chalky, siliceous oozes and ferruginous crusts.

Volcanic eruptions took place during the Miocene, Pliocene and Pleistocene epochs; they are manifested today in basalt flows (Jebel Marra).

The alluvial formations overlying the basement may reach thicknesses of 250 m; they have been detected by drilling. Much of the country is covered by sands, especially in the north-west (in the Libyan desert) and also further south (Kordofan sands).

Ground water

A great deal of progress has been made in water borings in the Sudan. However, no comprehensive survey has yet been made of ground-water reservoirs, their occurrence, their recharge and their potentialities, except in some sectors of the western part of the country.

The regions regarded as priority areas for exploration are those of the Kordofan, the Darfur, the Blue Nile and Kassala (on the Red Sea).

The principal aquifer assemblages are the following:

(a) The fracture or weathered zones of the Pre-Cambrian basement.

(b) The Tertiary (and Quaternary) series of Umm Rawaba, which fill wide troughs in the central and southern Sudan. They contain water, under a small head, which is sometimes so brackish that it cannot be used for irrigation.

(c) The Nubian Sandstones, which have been drilled and exploited at many points. They contain non-flowing artesian water which is usually of better quality than the waters mentioned above. The recharge of these reservoirs is thought to come, in the west, from the flanks of the Ennedi and Darfur massifs and, in the east, by infiltration of water from the Nile, whose bed lies above the water table in some areas, particularly near Khartoum. The central plain is clayey and has no infiltration; it is arid during the dry season and becomes swampy after the rains. From Bor to Khartoum there is no drainage of the Nile.

In some places the Nubian Sandstones form extended lenses isolated in the midst of vast expanses of crystalline formations, such as the nearly circular En Nahud-Khuwei-Sa'ata outcrop, which covers some 10,000 km^2. The sediments are about 150 m thick at the centre of the lens, which is fed by infiltration from the dunes and underlying sediments as far as the clay beds; the water then flows laterally. In desert areas such resources are of great potential importance. However, the water lies at considerable depths (60 to 120 m). In the south, the "Continental terminal" lies directly over the Nubian Sandstones, with ground-water flow from south to north.

(d) The surface weathering zones of the above assemblage, the Kordofan sands and other Neogene and Quaternary material, such as rubble, coarse valley deposits, alluvial fills and lacustrine deposits. These aquifers are sometimes of small dimensions and form small basins; in other cases, they may have a compartmentalized structure which does not show at the surface because it is due to changes of facies at lower levels or to uplifts of the impermeable substratum.

The Kordofan sands form an aeolian cover over the basement formation; they sometimes include intercalations of Nubian sands in the En Nahud-Sa'ata-El Fula basin.

The upper horizons of the Umm Rawaba (Mublad Ghabeish) trough contain water of good quality in:

Coarse alluvial materials of fossil stream beds; when these beds cut into the basement, the basement contains substantial water resources; and

Lacustrine intercalations, which are coarse at the base, fine at the top and generally sterile.

The existence of ground water is linked with the presence of inselbergs which receive rain water, as at Jebel Kubja.

The Kordofan sands contain important water reservoirs if they overlie the substratum. If they overlie Nubian Sandstones or Umm Rawaba formations, they do not contain any reservoirs of water.

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Certain special hydrogeological studies in the Sudan are supervised by the Hydrogeology Section of the Geological Survey. However, most of the ground-water prospecting and development operations come under the Rural Water and Development Corporation, a State agency responsible for the development of rural areas away from the Nile and its principal tributaries.

In recent years the Sudan has undertaken, as part of its annual campaigns to relieve water shortages, an extensive programme of rural drilled-well construction. Most of these wells are drilled in Nubian Sandstones. The equipment includes a pumping station, with a diesel engine and a piston pump capable of drawing about 5 m^3/hr. A total of 82 wells were drilled in 1966-1967, 950 from 1967 to 1969, and 516 in 1969-1970. The figures for pumping stations are about 500 for 1967-1969 and 256 for 1969-1970.

According to present plans, 6,000 pumping stations will be constructed during the next five years. The water is sold to users at a moderate price. Most exploration is carried out in the Savanna belt (humid areas) with the assistance of teams from Italy, Czechoslovakia, the United Arab Republic, the United Kingdom and Yugoslavia. About 20 hydrogeologists are employed by the Rural Water and Development Corporation (4 by the Geological Survey). Some local hydrogeological studies have been or will be carried out as part of UNDP-FAO projects for the Kordofan, Jebel Marra and the savanna belt.

A United Nations technical co-operation mission is participating, together with the Government, in water-drilling operations and the training of drilling technicians. The drilling unit of the Rural Water and Development Corporation has a total of 32 rigs.

In the Kassala region, where ground water is intensively exploited for the irrigation of cash crops (bananas), the level of the ground-water reservoirs has been considerably lowered over the past few years, and attempts to recharge them artificially are being planned.

Operations in search of water in the Umm Rawaba formations and the crystalline basement are still very limited; very little exploration is being done and the results obtained, if any, are mediocre both in quantity and in quality.

SWAZILAND

Area: 17,400 km^2; population: 400,000; southern Africa.

General

Swaziland is a mountainous country, an enclave in the Republic of South Africa except in the East, where it is bounded by Mozambique.

The country is divided into four regions, according to altitude: the High Veld (1,000 to 1,800 m), the Middle Veld (1,000 m), the Low Veld (300 m) and the Lebombo plateau, which overlooks the territory of Mozambique.

The rainy season lasts from October to February. At the higher levels, which lie in the humid and subhumid zones, annual rainfall reaches 1 m to 1.75 m. The Low Veld has a semi-arid climate, with rainfall from 500 to 750 mm. The country is crossed by large streams, including in particular the Usutu, a tributary of the Vaal.

Geology

Most of the country consists of granite gneisses cut by dioritic dikes. The Low Veld includes sandstones, shales and basalts of the Ecca series (Karroo). The Lebombo consists of rhyolites and basalts.

Ground water

Surface water is abundant in most regions. Ground water is used only for the domestic needs of isolated farms and for a few schools and some small population centres. No urban centre obtains its supply from ground water.

The Geological Survey and Mines Department determines where wells are to be drilled. Electrical geophysical prospecting has been used since 1965. In 1969 magnetometric reconnaissance studies were carried out to locate the aquifers along the dikes of the Low Veld. The drilling is done by a private company which uses two percussion rigs and drills 30 to 40 bore-holes per year. Diamond-crown drilling rigs owned by the Geological Survey and Mines Department are used in some cases.

No regional hydrogeological survey has been conducted, and no hydrogeologist is stationed in the country. Geophysical field work is carried out by staff not assigned exclusively to ground-water exploration. It is known, however, that the principal aquifer formations and structures are:

The granito-gneissic (Pre-Cambrian) weathered zone in central Swaziland, between Manzini and Malkerns (30 m thick); yield per well: 2 m^3/hr on the average, up to 8 m^3/hr;

The faults and the fractured zones, particularly at the contact surface between the Karroo and the Pre-Cambrian, in the western part of the Low Veld (yield up to 8 m^3/hr; depth of water: 20 to 30 m). There are only a few wells in this area;

The weathered zones of the Stormberg basalts, or the zones of contact between hard basalts and conglomerated or softer basalts. Water is found between 30 and 90 m but the yields obtained below 50 m are usually low. Yields may range up to 4 m^3/hr, but it is difficult to determine locations for such high-yield wells;

The metamorphic contact zones of the dikes and sills cutting the Karroo. The water depth is between 20 and 30 m, and yields range as high as 2 m^3/hr; and

The rhyolitic breccias of the Lebombo Mountains. Yields are highly variable, ranging up to 2 m^3/hr. The water depth is between 10 and 20 m.

TOGO

Area: 56,000 km^2; population: 1,700,000; West Africa.

General

Togo occupies a narrow strip of territory extending 550 km from north to south, with a seacoast 80 km long on the Gulf of Guinea, between Ghana and Dahomey.

In the north the altitude is about 250 m. A mountainous fold, the Atacora range, occupies the west-central part of the country, with a branch extending eastward; the altitude reaches 700 to 950 m in some places.

The annual rainfall is over 1 m everywhere in the country and sometimes reaches 1.25 m; there is only one important river, the Mono, the lower course of which forms the frontier with Dahomey.

Geology

The Pre-Cambrian basin occupies the entire country, with the exception of the north-west, which is included in the Oti Cambrian sedimentary basin, and the coastal zone (Cretaceous-Tertiary sedimentary basin). The geological units are the following:

The Lower Pre-Cambrian (Dahomean): granites, gneisses and mica schists; this occupies the south-eastern and east-central parts of the country, as well as the north-western tip;

The Middle Pre-Cambrian (Atacorian): quartzites with schistose intercalations. The outcrop band crosses Togo from south-west to north-east. The quartzites form the skeleton of the Atacora range;

The Terminal Pre-Cambrian (Buem series), which forms a strip 30 km wide to the west of the Atacora quartzites; it includes basalts, dolerites, clay shales and feldspathic sandstones.

The sedimentary Cambrian (Oti series): feldspathic sandstones, shales, pelites, siliceous beds and limestone lenses; and

The Cretaceous and Eocene of the coast, with the following formations from top to bottom: the "Continental terminal" (about 100 m, with sandy layers resting on the Lama clays, the Lutetian, with phosphate horizons (mining activities), the Eocene (limestones and marls) and the argillaceous and sandy-sandstone Maestrichtian.

Ground water

As part of a UNDP Special Fund project executed by the United Nations, a study was conducted between 1965 and 1970 on the aquifer potentialities of all the geological formations listed above, by means of geophysical prospecting, wells and bore-holes, and pumping tests. In addition, an inventory of water points and an inventory of requirements were drawn up. The results are summarized in the following table:

Formation or location	Lithology	Water depth (m)		Yield (litre/s per well	Drawdown (m)
		Wet season	Dry season		
Dapango	Granite-gneisses	0 to 5	3 to 8	0.9 to 48	6 to 13
Oti basin	Sandstones, schists	2 to 15	12 to 15	0.1 to 2	5 to 7
Buem	Quartzites, sandstones, shales	3	(10 to 15 m^3/d)	1 to 6	
Kandé	Schists	0	5 to 11	Artesian, 0.2	10
Atacorian	Quartzites, mica schists	0 to 4	5 to 8	2	
Dahomean	Gneisses, granites, migmatites	0 to 5	5 to 20	0.1	

The dissolved-salts concentration is 200 to 400 ppm.

The sands of the "Continental terminal" are exploited for the water supply of Lomé. The wells have a yield of 210 m^3/hr with 3 metres of drawdown at Agouévé. This intensive exploitation is creating a danger of marine invasion from the littoral and from the brackish-water lagoon known as Lake Togo; this invasion is shown on the map of salt concentrations determined by the resistivity method. The river Sio offers some additional water-supply possibilities.

The Pre-Cambrian basin is deep along the coast, since it has a sharp drop as a result of a fault which has been detected by geophysical prospecting.

It is possible that the Maestrichtian sands and sandstones reach a thickness of several hundred metres at a depth of more than 400 to 500 m, which makes them expensive and difficult to exploit. No deep bore-holes have yet been tried in this coastal sedimentary basin.

A number of hydrogeological maps on scales of 1:500,000 and 1:200,000 have been compiled as part of the project.

A further project was begun in 1971; most of the operations will be concentrated in the coastal sedimentary basin, where the potentialities of the "Continental terminal" aquifer will be studied in detail.

TUNISIA

Area: 164,000 km^2; population: 4,500,000; North Africa.

General

In relation to its area, Tunisia has a very long coastline on the Mediterranean, with the result that most of the country, except for the extreme southern part, is less than 200 km from the sea.

In the north the relief is rugged owing to the great Dorsale - produced by the east-end junction of the Tell Atlas and the Saharan Atlas (high point 1,554 m) - and the High Tell on the northern flank of the Dorsale.

Along the Mediterranean to the north, the low massifs of the Kroumirie and the Mogods frequently have a very sharp relief.

East of the Dorsale, the relief goes steadily down towards the Mediterranean: first the High Steppes, then the Low Steppes and, lastly, the coastal Sahel. South of the thirty-fourth parallel the Saharan domain begins, starting from the vast depression occupied by the chotts of El-Djérid and El-Gharsa. The bottom of Chott El-Gharsa is 15 m below sea level.

The southern part of Tunisia, shaped like a wedge driven between Algeria and Libya, is occupied by a plateau, the Dahar, bounded on the east by the Ksour range (500 to 1,000 m). Most of Tunisia's territory, including the capital city of Tunis, is in the semi-arid and arid zones. The southern half of the country has less than 100 mm of rainfall. Only a narrow 100-km band along the Mediterranean, in the north, and part of the High Tell have more than 500 mm of rainfall.

Tunisia has only one river of any importance, the Medjerda, which ends in a marshy area along the coast, north of Tunis. Further south, on the southern slope of the Dorsale, the country is poorly drained, since the streams disappear in inland depressions.

Geology

The northern part of Tunisia consists of folded formations, mostly of Neogene and Cretaceous age, with some diapir outcrops of the Triassic. The tectonic structure is complex.

The southern part of the Dorsale and the so-called High Steppes region consist essentially of anticlinal domes and synclinal beds of Aptian and Senonian age.

The Dahar region consists of Cretaceous formations of marine origin, while Djebel Dahar consists of Jurassic limestones, with Triassic sandstones at its base.

The coastal plain of Jefara is occupied by a subsident Miocene syncline (sandstones, marls, clays). Much of the country, towards the south, is covered with limestone crusts.

Ground water

Among Africa's French-speaking or Arabic-French-speaking countries, Tunisia was the first to establish a specialized ground-water prospecting service, including, in particular, a water resources inventory unit.

In the very strongly folded zones north of the Medjerda valley there are no aquifer formations of any significant extent. No intensive hydrogeological surveys have been conducted in these areas.

In the mountainous parts of the country the principal aquifers are generally limestone formations, as follows:

Karstified and Liassic Upper Jurassic limestones, such as Jebel Zaghouan, which provides part of the water supply of the city of Tunis;

Reef limestones of the Lower Cretaceous, of limited extent, in anticlinal position;

Limestones of the Lower Cretaceous (100 m) included in a marly series (western part, near the Algerian frontier);

Eocene limestones (100 to 120 m) included in a marly series in which many large springs are found; and

Oligocene sandstones in synclinal position.

In the valleys and the plains the principal aquifers are the following:

Fill formations in subsident blocks, including thicknesses up to several hundred metres of sands, gravels and pebbles, more or less consolidated and sometimes containing artesian reservoirs;

Alluvial fills in the valleys; and

The Pliocene sands of Cape Bon and aeolian sands.

In the anticlinal domes of the High Steppes the best aquifers are Jurassic or Cretaceous limestones (Aptian, Turonian or Senonian), which are of local importance.

The plains of central Tunisia are made up of Miocene sediments which are sometimes very thick (2,000 m) and contain coarse sandstone formations. These formations made good aquifers, especially along the faults delimiting collapsed zones, where there are large springs, such as the Kasserine spring (300 litres/s).

Subsidence troughs, such as the Kairouan trough, contain permeable Plio-Quaternary continental sediments, in which there is sometimes ground water under some head.

Southern Tunisia is a region of oases concentrated along the coast and also south and north of the Chotts. These oases are irrigated with water from springs and drilled wells fed by two important ground-water reservoirs: the "Continental terminal" (Miocene) reservoir and, especially, the "Continental intercalaire" reservoir (Upper Jurassic and Infra-Cenomanian), whose outcrops cover the entire Dahar region and extend over a wide area in Algeria.

This last reservoir, which is the very life-source of southern Tunisia, makes it possible to obtain discharges of more than 100 litres/s by artesian drilling; its natural outlet is the zone of intense evaporation constituted by Chott El-Djerid.

There has been considerable advancement in hydrogeological studies in Tunisia, resulting in the preparation of many hydrogeological maps, at 1:500,000 for half of the country and at 1:200,000 for one quarter. Out of a total of 88 identified aquifers (54 near the water table and 34 in deep aquifers), complete studies have been conducted on 39 and preliminary studies on 14.

It is estimated that the annual recharge of ground-water reservoirs amounts to 700 million m^3/year, about two thirds of which goes to the deep aquifers.

The Office of Water Resources Inventories (Bureau de l'inventaire des ressources hydrauliques) attached to the Sub-Administration of Water Resources (Sous-Direction des ressources hydrauliques), has 10 hydrogeologists and 4 hydrologists on its staff. The Water Borings Service (Service de sondages d'eau), subordinate to the same agency, has 18 reconnaissance drilling rigs and 25 exploitation drilling rigs, operated by about 40 drillers and 3 drilling engineers; some of these rigs are old.

At present, most of the surface water runs off to the sea during the flood periods, before it can be put to use. A major programme for the construction of surface-water retaining dams, designed to supplement existing installations, is now being studied and carried out. In addition, the Tunisian Government has decided to conduct experiments, with the co-operation of the United Nations, on different methods of artificially recharging ground-water reservoirs in the northern and central parts of the country. In the future this kind of recharging will be co-ordinated with the overdraft that occurs during low-water months. The result, it is hoped, will be a substantial improvement in the water balance of certain reservoirs and hence a fuller use of the country's water resources.

UGANDA

Area: 236,000 km^2; population: 8,050,000; East Africa.

General

Uganda borders on Lake Victoria and extends northward to Sudan. The country lies on a plateau, almost all parts of which are more than 1,000 m above sea level and which contains many lakes.

Rainfall over most of the country exceeds 1 m and even 1.5 m per year. The Karamoja district in the north-east is arid, having less than 250 mm of rain per year.

Uganda has very substantial water resources. The White Nile flows out of Lake Victoria and through Lake Albert. Yet despite the widespread occurrence of surface water, there are areas of the country other than the Karamoja district which do not have adequate local water resources; most of these areas lie in the centre, the north and the west.

Geology

Virtually the whole of the country consists of formations of the basement complex, with granite gneisses at the lower levels and conglomerates, schists and volcanics above them. The Infra-Cambrian is represented mainly by limestones with stromatolites.

In the east of the country, running from north to south, there is a chain of volcanoes formed of Miocene and Pliocene lavas. The highest of these is Mt. Elgon (4,320 m). Tertiary and Quaternary formations are most frequent in the lake regions.

Ground water

There are no very extensive bodies of ground water in Uganda. Many rural centres receive their water supply from wells drilled in fracture zones of the basement complex.

The Government's Geological Survey has drilled some 4,500 bore-holes, most of which are productive. The water-table usually lies at a depth ranging between 30 and 100 m. Yields are of the order of 5 to 40 m^3/day.

Intensive studies have been made of ground-water resources in the Karamoja district, an arid area inhabited by herdsmen who are still to some extent nomadic, as part of a UNDP Special Fund project executed by the United Nations between 1965 and 1968. This was a large-scale project, involving 4 hydrogeologists, 1 hydrologist, 2 geophysics teams and 6 drilling rigs run by experienced engineers. It represented the largest integrated ground-water survey operation ever undertaken in East Africa.

From 1932 to 1965, approximately 490 bore-holes were sunk in the Karamoja district, 256 of which are still in operation (209 of these have hand pumps and 47 motorized pumps). The minimum usable yield has been set at 0.5 m^3/hr for hand-operated pumps and 4 m^3/hr for motor-driven pumps. Annual recharge of the ground-water bodies is thought to be of the order of 30 million m^3.

In general, the water has a salt content of between 300 and 900 ppm.

Drilling operations under the Special Fund project involved the sinking of 92 exploratory bore-holes, with a total depth of approximately 10,000 m. Sixty-nine of these wells are productive and 36 of them can be fitted with motor pumps. The average yield obtained during the project was 8 m^3/hr, with a maximum of 70 m^3/hr. The highest yields were obtained from wells 45 to 90 m deep (below 100 m, yields are small) and in the flat bottoms of valleys lying between steep hills.

The survey located sufficient water to meet the needs of the population and its livestock, but, with some exceptions, the water is not suitable for irrigation purposes because of its cost and the low utilizable yield per well.

Over the rest of the country drilling for water is carried out by the water drilling section of the Geological Survey, which has 18 percussion rigs. No hydrogeologists have been serving in the country on a permanent basis since the departure of the United Nations experts.

UNITED ARAB REPUBLIC

Area: 1,000,000 km^2; population: 30,200,000; north-east Africa.

General

Egypt opens onto both the Mediterranean and the Red Sea. The country as a whole is flat and is generally less than 500 m above sea level. In the north, the bottoms of certain depressions (such as those of Qattara and the Siwa oasis) are below sea level. In the south-western corner, the ground rises to almost 2,000 m in the Jebel Uweinat, which forms a sort of natural boundary marker at the juncture of Egypt, the Sudan and Libya. The ground also rises to the east, reaching 1,800 to 2,000 m in the mountains of the Arabian Desert which overlook the Gulf of Suez and the Red Sea.

With the exception of the Nile Valley and some oases, 97 per cent of the country is desert. Rainfall reaches its peak (approximately 250 mm) over a narrow belt of land on the Mediterranean coast.

Geology

The Pre-Cambrian basement (granite gneisses, schists, quartzites, cipolins and gabbros) outcrops in the east in the Arabian Desert chain. It is overlain by Nubian Sandstones, continental deposits of Carboniferous-Cretaceous age which have also been found to contain intercalated marine formations. The total thickness of the Nubian Sandstones increases from the south-west (50 m at Aswan) to the north-east (500 m in the Sinai Desert). Most of these Nubian Sandstones are of Lower Cretaceous age. The Upper Cretaceous seas extended deep into the south, depositing mostly limestones. The Eocene seas also deposited limestones, as at Thebes, where there are 400 m of limestone of Lower Eocene age.

The Upper Eocene contains many argillaceous intercalations. The Oligocene is represented by the fluviolacustrine Faiyûm series; these series, of sandstones and limestones, are 250 m thick.

Neogene deposits are confined to the Mediterranean coast; they reach a thickness of several hundreds of metres and include limestones, dolomites and gypsiferous marls.

The most complete Quaternary series are found in the Nile Valley and the lacustrine deposits of El Khârga and the Faiyûm area.

Ground water

There are two main categories of ground water: the fossil water, under a head, in the Nubian Sandstones, and the water in the aquifers of the Nile Valley, particularly the Delta, which are recharged when the Nile floods.

Approximately 200 artesian wells - and this number is increasing by 30 to 50 per year - have been sunk into the Nubian Sandstones in the Oases of Dakhla and El Khârga. The oases lie in a synclinal depression in the Western Desert, to the west of Luxor. This development scheme is called the New Valley programme. At El Khârga, the Nubian series contain approximately 30 per cent of sands and sandstones. Bore-holes reach depths of 200 to 800 m and a maximum of 2,500 m. Total yield is of the order of 300,000 m^3/day. Many surveys have been made in this area to determine the safe pumping limits and how long the available water will last. Various methods (laboratory research, pumping tests, geophysical investigations, analogue model studies) have been used during these surveys, in which experts from UNESCO, FAO, the (United States) Agency for International Development and Yugoslavia worked in collaboration with their Egyptian counterparts.

It seems that the aquifer is fed by water flowing in a north-easterly direction from the Tibesti-Erdi-Ennedi massifs. In addition to 300 shallow wells (200 m), more than 60 modern wells yield almost 200,000 m^3/day. The yield tends to decrease by 30 per cent during the first year of exploitation. Water temperature varies from 32 to 40°C and total dissolved salts from 190 to 620 ppm; the water becomes less heavily mineralized with increasing depth. None the less, many wells show signs of serious corrosion. The mechanism of the corrosion process has been very thoroughly studied.

A major study of water in the Nile Delta, involving drilling and pumping, is now in progress: it covers many areas where fresh delta water lies above saline water. Some 50 bore-holes 200 to 500 (and up to 1,000) m deep have been drilled; they are artesian or subartesian. Carbon 14 dating has shown that the water is of Quaternary age. Extraction of the water involves difficult problems, particularly that of protecting the fresh water against contamination with brine.

A study has also been undertaken of ground water in the areas on the Mediterranean and Red Sea coasts. It has shown that, along the Mediterranean coast, deep wells do not yield water from the Nubian Sandstones. The Neogene and Quaternary aquifers yield brackish water. In the Eastern Desert, ground water may contain as much as 3,000 ppm of dissolved solids. A deep discharge of salt water from the land into the sea has been observed along the Red Sea coast.

One of the major questions which will arise in the near future concerns ground-water recharge or pressurization of the water in the Nubian Sandstones owing to the enormous volume of water impounded in Lake Nasser behind the Aswan High Dam.

UNITED REPUBLIC OF TANZANIA

Area: 937,000 km^2; population: 12,200,000; East Africa.

General

The borders of Tanzania run through Lakes Malawi, Tanganyika and Victoria and the country has 700 km of shoreline on the Indian Ocean. Most of the country consists of a plateau from 1,000 to 1,500 m high, over which rise high volcanic peaks such as Mt. Uhuru (5,963 m) and, in the west, other smaller mountains (3,000 to 5,000 m).

A chain of mountains, with peaks approaching 2,000 m, crosses the country from SW to NE, from Lake Malawi to the hinterland of Dar es Salaam. In the south there are plateaux 700 to 1,000 m high which slope down regularly towards the Indian Ocean. The country has one major river, the Rufiji. In the north and south, there are extensive plateau-like areas which are poorly drained.

Most of the country has an average annual rainfall of between 750 and 1,000 mm; rainfall in the interior is less (500 mm).

Geology

The Pre-Cambrian basement outcrops over virtually the entire country. It comprises the following subdivisions:

Lower Pre-Cambrian: gneisses, mica schists and granite gneisses;

Middle Pre-Cambrian: granitized volcanic rocks and quartzites, conglomerates, slates and sandstones;

Upper Pre-Cambrian: slates and quartzites; and

Terminal Pre-Cambrian: sandstones and dolomitic limestones carrying stromatolites. These formations outcrop in the western part of the country, between the Malagarasi and Lake Victoria, and to the east of the Lake.

The Karro sediments (shales, sandstones, conglomerates and clays) are preserved in the tectonic troughs, particularly between Lake Malawi and the Rufiji. Along the coast there is a sedimentary basin of marine origin (Secondary-Nummulitic), which is as much as 150 km wide in places.

An extensive area, near the border with Kenya, is covered by effusive volcanic rocks of Miocene age (basalts, phonolites, trachytes and rhyolites), of considerable thickness.

Continental and lacustrine deposits of Plio-Pleistocene and Quaternary age ("Continental terminal") are found in scattered outcrops in the centre of the country.

Ground water

In terms of water resources, the country is divided into two distinct regions on either side of a line running from Mbeya (north of Lake Malawi) to Tanga (a port on the Indian Ocean near the Kenyan border). To the south-east of that line, i.e. over one third of the country, surface water is plentiful and can be used in large hydro-electric and agricultural schemes. Many potential dam sites have been identified and surveyed. To the north-west, on the other hand, over two thirds of the country (the centre, west and part of the north, particularly the Masai Steppe), the bioclimatic conditions are of the semi-arid type.

For this reason, the Department of Water Development and Irrigation of the Ministry of Land, Settlement and Water Development, which was established in 1945 and has its headquarters at Dodoma, is responsible inter alia for sinking bore-holes to supply the population and livestock with water.

Between 1953 and 1959, 196 bore-holes were sunk. The five-year plan for the period 1964-1969 called for 100 hand-dug wells from 7 to 20 m deep and 100 bore-holes producing 1 to 8 m^3/hr for new population centres; in addition, bore-holes are being sunk to water cattle on the Masai Steppe. Larger wells have been built to supply towns, including Dodoma and Tanga. The work is carried out both by private and public organizations.

In 1970, the Ministry of Water Development and Power (MAJI) was established with a large budget. A Swedish geologist, Mr. F. Coster, wrote a monograph on ground water in the United Republic of Tanzania after 25 years' work in the country on that subject. This very well documented report, published in 1960, does not, however, contain any quantitative information on ground-water resources. The drilling operations during the years 1931-1958, which provided the basic data used in the publication, involved only 860 wells, whereas a far larger number of wells is mentioned in the statistics for the period 1958-1971. It would seem, therefore, that the document needs to be updated.

UPPER VOLTA

Area: 274,000 km^2; population: 5 million; West Africa.

General

The whole of the Upper Volta is occupied by a peneplain with slight, gentle relief which slopes down towards the south and is generally between 250 and 350 m above sea level. There are some isolated areas of higher ground reaching 500 to 600 m in the south-east and 650 to 750 m in the south-west. The central and southern regions comprise the upper basin of the Volta River.

The country, the centre of which forms the boundary between the dry and humid savanna regions, has an annual rainfall of at least 400 mm in all areas, and 1 m in the west and south-east.

Geology

Pre-Cambrian basement formations occupy most of the country and include the following units: Dahomeyan (Lower Pre-Cambrian): granite gneisses and granitic batholiths, and Atacorian-Birrimian (Middle Pre-Cambrian): schists and quartzites.

There are relatively small Palaeozoic outcrops in the south-west (Black Volta area) and south-east; they contain sandstones, conglomerates, shales and dolomitic limestones which are thought to be of Cambrian age.

There is a narrow strip of formations from the "Continental terminal" along the north-western border. It marks the edge of the Gondo plain, most of which lies within the borders of Mali.

Ground water

In crystalline areas, the weathered zone and the over-lying residual or alluvial material, together with the fracture zones, constitute the only possible sources of ground water.

The wells are capable of yielding 5 to 50 m^3/day in the dry season and exceptionally as much as 70 m^3/day in the wet season.

The first hydrogeological surveys were not made until 1954. They involved mainly the recording of water sources and the supervision of reconnaissance operations.

Some 700 wells were sunk between 1952 and 1961. Subsequently, regional surveys were undertaken, in particular with the assistance of a United Nations expert.

In the Bobo Dioulasso sandstones, a deep bore-hole used to supply the town yields 90 m^3/hr with a 55 m drawdown.

The Republic of Upper Volta has received assistance in seeking water from the European Development Fund and France's Fonds d'aide et de coopération, which have provided the services of experts and subsidized various operations, including drilling, geophysical work and well-digging, carried out by specialized firms. The (United States) Agency for International Development has provided a drilling rig.

A UNDP project (executed by the United Nations), the main purpose of which was to carry out geophysical prospecting and test borings in the granitic sands of a selected area (comprising 50 villages), was completed in June 1967. A detailed survey is being made of the north-east of the country in connexion with the projects for the area's economic development through exploitation of a deposit of manganese. The Infra-Cambrian dolomitic limestones of Tin-Hrassan represent the best aquifer in this area.

In recent years, the Government water services have had available on a permanent basis the services of one to three experts in hydrogeology (of whom one is from the United Nations, while the others are assigned to the country under a French bilateral aid programme).

Village water sources have so far been inventoried for approximately one third of the country.

ZAMBIA

Area: 753,000 km^2; population: 4 million; southern Africa.

General

Zambia is a land-locked State whose vast territory is almost cut in half in the middle by a sort of bottle-neck resulting from wedge-like projections of the Democratic Republic of the Congo in the north and Mozambique in the south.

The western part of the country is traversed by the Zambezi, which thereafter forms the frontier with Southern Rhodesia. Here the course of the Zambezi is cut by the Kariba Dam, behind which is one of the largest artificial lakes in the world, 250 km long and 40 km wide.

This western half consists of a sort of regular plateau at an altitude of 1,000 to 1,300 m, with a slightly upraised zone in the north attaining 1,600 m. The plateau is fairly well drained by important tributaries of the Zambezi, including the Kafue.

The eastern part is more varied; it is bisected by the Muchinga Mountains, running in a line from north-east to south-west. In the north lies a plateau 1,200 to 1,300 m high; its central portion, of lower elevation, is occupied by the swampy region of Lake Bangweulu. To the south the basin of the Luangwa, a tributary of the Zambezi, forms a large depression which extends between the Muchinga Mountains and the mountains of Malawi.

In the northern part of the country, annual rainfall is of the order of 1.2 to 1.5 m. In the south, i.e. in the bend of the Zambezi and in the Luangwa basin, it ranges between 0.5 and 1 m. There are two rainy seasons, October-November and March-April.

Geology

The Pre-Cambrian basement (schists and granites) has extensive outcrops in the north-eastern, eastern, central and southern parts of the country.

Towards the north it is overlain by the so-called Katanga group formations (Terminal Pre-Cambrian), with the following three subdivisions:

At the bottom lies the Roan system (1,000 to 2,000 m): conglomerates, dolomites, limestones, shales and sandstones;

Above this lies the Mwashya system (1,000 m): tillites, shales and large conglomerates; and

At the top lies the Kundelungu system (1,500 to 3,000 m): shales, sandstones, calcareous shales and stromatlitic limestones.

The Luangwa valley constitutes a basement collapse trough, overlain by Karroo formations (argillaceous shaly sandstones), which are also found in the valley of the Zambezi beyond Livingstone and in the Kasempa-Kabompo area.

The Quaternary formations of the Kalahari are very extensive, particularly in the Lake Bangweulu basin and in the bend of the Zambezi in the west.

Ground water

The Department of Water Affairs, established in 1943 now has three hydrogeologists/geophysicists on its staff. Drilling work totals 4,500 m per year; the drilled wells are 6 inches in diameter and have an average depth of 55 m. The Department of Water Affairs, which has six drilling rigs, does 40 per cent of the drilling work; the rest is distributed among four local enterprises, which drill 100 to 150 wells per year, using 18 rigs.

Ground-water conditions are better in Zambia than in the surrounding countries, from several points of view: the depth, the storage capacity, the available yields and the possibilities for exploration.

The limestones and dolomites of the very extensive Katanga system (Infra-Cambrian) form the best aquifers and, at the same time, produce the best soils. The most important reservoirs are formed by erosive action in the Miocene peneplain, incised by erosion during the Villafranchian stage.

The available data on Zambian ground waters are summarized in the following table:

Localities and districts	Formations	Comments
Southern Province:		
Livingstone	Basalts, Kalahari sands	Low yields, water sometimes salty
Kalomo-Choma	Weathered granite-gneiss zone, quartz veins and pegmatites	Depth of wells: 35 m; yield: 0.9 to 1.5 litres/s (for 6-inch boreholes); in the quartz veins the water is under a slight head (yield: up to 2-3 litres/s)
Mazabuka	Lower Katanga: sandstone and shale	Depth of wells: 35 m; yield: 1 litre/s (0.4 litre/s in phyllites)
"	Middle Katanga: limestones, dolomitic shaly limestones, argillites	Low yield in argillites, 1 to 3 litres/s in dolomites, 12 litres/s at the Mazabuka fault
"	Upper Katanga: calcareo-siliceous rocks	
Munali Pass	Biotite schists	0.3 litre/s
Kafue	Shaly sandstones	1 litre/s
"	Upper Karroo sandstone	1 to 2 litres/s (depth: 45 to 50 m)
Gwembe valley	Karroo in a rift valley: shales, sandstones	0.2 to 0.5 litres/s
"	Sandstones	1 litre/s (water sometimes contains fluorides)
Central province	Synclines of the Katanga system isolated in depressions of the basement:	

Localities and districts	Formations	Comments
	Dolomites	1 to 5 litres/s (at 45 m)
	Fractured dolomites at Lusaka a/	2,000 m^3/d through 10-inch tubes
	Quartzose veins in the basement schists	1 to 2 litres/s
	Granite gneisses north of Broken Hill	Negligible yields
Western Province (Copperbelt)	Katanga dolomites and limestones (pumping for the copper mines)	Large yields (see below)
	Basement schists	0.5 litre/s (35 to 45 m holes)
Northern and Luapula Provinces	Plateau sandstones (Karroo): water supply to towns (Karama, Abercorn); sometimes overlain by fairly thick shales	0.5 to 22 litres/s (average: 1 litre/s); low yields in the shales or where the sandstones are not thick
	Basement zone	Low yields
North-Western Province	Katanga system (limestones and dolomites with sterile argillaceous schists)	No holes drilled
Barotseland (South-West)	Kalahari sands often overlying the Karroo	Little is known about the region; a few isolated bore-holes in the exceptionally favourable areas (1 to 2 litres/s)
Eastern Province	Basement formations: granite gneisses and schists	Yields are sometimes substantial or adequate

a/ In 1968, yields of up to 20 litres/s per metre of drawdown were obtained for the drilled wells of Lusaka (diameter 8 inches).

Lusaka, the capital, is the only major city in any of the African Commonwealth countries which draws its water supply exclusively from drilled wells (55,000 m^3/day). These wells are all situated in a dolomitic zone. Over the years, they have been drilled with gradually decreasing diameters (27, 24 and 18 inches) and increasing depths. Two wells today have a total yield of 20,000 m^3/day (the demand exceeds 6 million m^3 in October-November). Six new small-diameter (10-inch) wells are capable of delivering 2,000 m^3/day each.

Most of the other towns (Broken Hill, Mazabuka, Ndola, a number of mining towns in the Copperbelt and many others) and most farms are also supplied by drilled wells.

Thus the economic and social development of Zambia depends heavily on the exploitation of the country's ground water. Three hundred and sixty wells were drilled in 1969. The drilling is carried out by percussion, using equipment furnished either by the Government (12 rigs) or by a private firm (15 rigs).

The inventories list a total of 3,000 water bore-holes. Hydrological characteristics are tested more often nowadays than in the past. Chemical analysis of the water is also carried out more systematically.

PART III

CONCLUSIONS AND RECOMMENDATIONS

I. CONCLUSIONS

The most conspicuous fact that can be seen from this incomplete but general study of Africa's ground waters is that, unlike surface waters, which are very unevenly distributed, potential ground-water resources are available almost everywhere on the continent, in sufficiently large quantities and good quality to meet the people's water requirements for domestic use and stock-watering, both for the present and for the near future.

We have seen that ground-water prospecting and exploitation are of recent origin - except in the Mediterranean regions and the arid expanses of northern Africa - and have advanced in recent years at a rapid rate, which seems to be slowing down somewhat in certain countries but speeding up in others.

In the tropical regions, ground-water is the only water whose bacteriological quality is acceptable to begin with and can be easily and economically kept under scrutiny through monitoring; for this reason, it has come into increasing use as drinking water for human consumption. Indeed, since ground water constitutes the principal, if not the only, permanent water resource in arid and semi-arid zones and frequently the most economical water resource in semi-humid or humid tropical areas, it should always be considered as a potential water source - either primary or supplementary - in any water resources development project.

However, the staff and equipment available in Africa for ground-water exploration and exploitation are still relatively limited and can only partially satisfy the most immediate needs; until now the requirements have been met in large part by external aid, which is now tending to decrease. It is therefore important that Africans should become increasingly aware of the need for prospecting and development of the continent's ground-water resources, primarily with their own means.

At the regional level, the situation may be summed up as follows:

Sedimentary basins and coastal areas: the Mediterranean and western Africa

General surveys have been conducted for this region, whose ground-water resources are extensively exploited, and sometimes over-exploited. In future it would be desirable:

(a) To study the potential resources on which little information is available and which have not yet been utilized, such as aquifer sands, induced recharge of flood waters into wadi beds, deep aquifers, submarine springs along the coast and karstic aquifers;

(b) To monitor water quality in coastal areas threatened by salt-water contamination, as well as on the fringes of the Sahara;

(c) To exploit ground-water in a rational manner, selecting the types of wells or bore-holes, determining their optimum characteristics and spacing, and exploring the possibilities for artificial recharge; and

(d) To adapt the production and distribution of ground water as well as possible to the relative priorities of different needs.

Large continental sedimentary basins north of the Equator

These basins are generally found in desert areas. As a result of regional studies, already completed or now in progress, on the Nubian Sandstones, the Sahara and Chad, determination of the water-resources potential is well under way. Studies must still be conducted to determine the least costly means of exploiting these resources - which may not be renewable within the span of a human lifetime - with a view to meeting priority needs.

Basement outcrops of crystalline rocks in western Africa

Investigators today know the water yields of the various geological formations and the types of zones most favourable for ground-water development. Work must still be done to develop economical methods for locating these zones, digging or drilling the wells and extracting the water. In terms of the number of wells required, the needs of this area, inhabited by more than 40 million people, are immense, while the facilities available for drilling or digging the wells are severely limited. The underground reservoirs generally have a fairly small capacity but are readily recharged every year by the rains, although the mechanism of this recharging is still not clearly understood.

High plateaux of eastern Africa (region of the great lakes and southern Sudan)

In these areas, which, like those mentioned above, generally consist of crystalline and metamorphic formations, the exploitation of ground water is frequently more intensive than in western Africa. Nevertheless, water needs are still very great, especially in the lower areas, at some distance from the lakes, particularly in Malawi, as well as in the Sudan. The waters of the volcanic massifs are still very little known and will require some preliminary reconnaissance, which should concentrate on the hydrothermal springs. Further work will be needed to develop exploration methods, general inventories and hydrogeological mapping.

Central Africa and equatorial Africa

These are regions of very heavy rainfall. The coastal sedimentary basins (Gabon) or continental sedimentary basins (Democratic Republic of the Congo) and the crystalline regions (Adamawa) have very large ground-water reservoirs, but these have not been greatly exploited, since surface water is abundant. However, the surface water is either contaminated or treated at considerable cost. More attention should be given in these countries to the possibility of low-cost use of ground water.

On the periphery, the Infra-Cambrian and Cambrian dolomitic limestone formations form important acquifers in the immediate vicinity of large-scale mineral deposits. This combination is also found elsewhere in Africa (the Moroccan Anti-Atlas, the northern part of the Upper Volta, the Witwatersrand). It is essential to study the hydrogeology of these formations, both in order to drain them to allow for mining and in order to draw the water required in conjunction with mining (domestic use, ore-washing).

Coastal plains of eastern Africa: Kenya, Somalia

The ground waters of these sedimentary basins, which include local artesian reservoirs, are still very poorly known. A general reconnaissance would be desirable, in view of the relatively high population density and the large amount of livestock.

Islands

The few islands which surround Africa generally suffer from a shortage of water. Very thorough hydrogeological exploration is needed. In any case, ground-water use in the islands should be strictly regulated. In Madagascar, ground water represents a very important and thus far little explored natural resource, the exploitation of which, although very slight at present, will probably expand considerably.

* * *

Lastly, attention should be drawn to a domain about which little is known as yet: that of the thermal and mineral waters associated with the great fracture lines of the continent. This natural resource should be systematically prospected, since it can be exploited for many purposes: therapy, geothermal energy, hydrochemistry and the detection of metal deposits.

II. RECOMMENDATIONS

It is becoming a matter of pressing importance to assemble, synthesize and interpret the abundant data on African ground waters, which have been only very briefly surveyed in the present report. International co-operation - and, first and foremost, inter-African co-operation - should make it possible to establish "data banks" and to prepare the indispensable synthesis documents and analytical bibliographies. This implies, in particular, an improvement of the flow of information and movement of technicians between countries.

Future scientific and technical studies relating to ground-water prospecting, evaluation and exploitation should be based on the real needs of the people of each area and the means available for constructing the facilities for ground-water exploitation. Priority should be given to projects whose execution follows soon after the surveys and to regions in which ground water constitutes a particularly vital resource that is threatened by over-exploitation, salt-water invasion, pollution or other dangers.

In the past, some operations have been carried out by means which were not always adequate, either because the methods were too elementary or, on the contrary, too intricate, or because the equipment was ill-adapted to African conditions. It is time to learn the lesson of past experience and to follow more economical, effective and practical lines. An outline of the action that needs to be undertaken is given below.

Hydrogeological reconnaissance

Generalization of hydrogeological reconnaissance mapping by simplified methods (standards to be determined);

Identification of standard geomorphological criteria for detecting ground-water reservoirs, especially in crystalline-basement areas; and

Establishment of networks of wells for recording water-level fluctuations.

Inventory of ground-water resources

Preparation of an instruction manual for use by African prospectors on the recording of water-point data; and

Standardization, on an international scale, of presentation of data in water-point records and village records so that collected information can be processed by computer.

Geophysical prospecting

Reappraisal of the results of all geophysical explorations for ground water, as a part of an over-all comparative study, in order to determine the most economical and effective methods, equipment and materials for a given set of conditions.

Drilling for water; pumping stations

Preparation of a comprehensive study on the factors affecting drilling performance, carried out on a statistical basis, possibly by computer. Analogous study of pumping equipment.

Pumping tests

Preparation of a simple mannual for the execution and interpretation of pumping tests, geared to African conditions. The manual should give specific instructions covering different geological environments: fractured rocks of the crystalline basement and of the Palaeozoic cover (with necessary distinctions for limestone-dolomitic and sandstone-shale rocks), continental sandstones, alluvia and other acquifers.

Water analyses

Formulation of guidelines for establishing water chemistry laboratories. A general preliminary study of the chemical composition of African ground waters should be prepared.

Tracers, nuclear techniques, analogue and mathematical models

Determination of the conditions under which these modern methods may be advantageously substituted for the classical methods, to save both time and money.

Legislation

Establishment of ground-water laws or regulations in countries where these do not yet exist; and

Revision, where appropriate, of any existing laws or regulations which originated in the colonial period and are no longer suited to present conditions.

Economic questions

Collection of data on the cost of ground water in Africa, with a view to determining ways to reduce the cost price, both for prospecting and monitoring of water resources and for their exploitation.

Technical services

Strengthening, regrouping and reorganization of ground-water services in those countries where they already exist, and establishment of such services in other countries. This applies in particular to the planning and execution of well-drilling and well-digging operations.

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To sum up, Africa should make the best possible use of its limited but growing supply of specialists and equipment for ground-water development. To this end, existing data and past experience should be utilized to the fullest extent. Exploration methods should be adapted to the objectives sought, which are often modest (productive wells to provide water supplies for human populations and livestock) but always vital.

This task of simplifying and standardizing methods and techniques and adapting them to Africa should be regarded by the African countries concerned as a prerequisite to future ground-water investigations. It would be desirable to have the competent international agencies participate in this work.

It is greatly to be hoped that the necessary basic documents, prospecting technology and well-drilling and well-digging equipment will become available for the entire African continent in the near future. It is clear, however, that international co-operation and determination on the part of the Africans are equally essential for achieving this result, on which depends, in large measure, the improvement of living conditions for most of the peoples of Africa.