

Department of Technical Co-operation for Development
and Economic Commission for Africa

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**GROUND WATER
IN
NORTH AND WEST AFRICA**



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NOTE

Symbols of United Nations documents are composed of capital letters combined with figures. Mention of such a symbol indicates a reference to a United Nations document.

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FOREWORD

The Economic and Social Council, by 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 (now the Water Resources Branch of the Division of Natural Resources and Energy, Department of Technical Co-operation for Development).

The Advisory Committee on the Application of Science and Technology to Development, in its World Plan of Action, 2/ gave priority to ground-water exploration and development. In fact, in the course of the First and Second United Nations Development Decades, more than 100 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 prospecting, assessment or pilot development. (A list of ground-water projects in the Eastern Mediterranean and Western Asia sponsored by UNDP is contained in the annex to the present report.)

While such operational activities were developing, the need for a comprehensive review of the results of the projects and for a dissemination of relevant information became more evident. As a result, the Economic and Social Council, by resolution 1761 B (LIV) of 18 May 1973, requested the Secretary-General to take the necessary measures, within the budgetary limitations, to improve and strengthen the existing United Nations services for the analysis, evaluation and dissemination of world-wide data on natural resources, including water resources.

With respect to ground water, a first comprehensive review of the African continent was published in 1972 and 1973 under the title Ground Water in Africa 3/ as a synthesis of material available in the records and files of the United Nations. The material of the second volume in this series, Ground Water in the Western Hemisphere, 4/ was drawn from country papers which were prepared by hydrogeologists and by ground-water engineers, specialists of the countries concerned. This was also done for the third volume, entitled Ground Water in the Eastern Mediterranean and Western Asia, 5/ for the

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- 1/ United Nations publication, Sales No. 60.II.B.3
 - 2/ United Nations publication, Sales No. E.71.II.A.18.
 - 3/ United Nations publication, Sales No. E.71.II.A.16.
 - 4/ United Nations publication, Sales No. E.76.II.A.5.
 - 5/ United Nations publication, Sales No. E.82.II.A.8.

fourth, entitled Ground Water in the Pacific Region, 6/ for the fifth, entitled, Ground Water in Continental Asia, 7/ and for the present volume, the sixth in the series, which is to be followed by a seventh on ground water in central, eastern and southern Africa and an eighth on ground water in Europe. This will complete the presentation of (a) a necessarily brief but full overview of the world's ground-water resources, (b) the state of knowledge about them and their potential, and (c) information about their exploitation and the problems involved.

The present work indicates the progress made since the publication of the first volume on ground water in Africa. A point to note is the large number of African specialists who have taken part in the drafting of the text. There is now hardly a single African country which does not have among its nationals university graduates or engineers specializing in hydrogeology or ground water.

It is to be hoped that this volume, which deals with a number of arid countries, in particular the "Sahelian" countries affected by long periods of severe drought since 1973, will contribute to the development of ground water which is so vital in this part of the world.

The United Nations wishes to thank for their valuable assistance the governmental organizations and the consultants and experts from Africa and other countries who have collaborated in the preparation of this work, in particular the Department of Water and Energy of Mali, the Office of Water Research and Planning of the Department of Water of the Kingdom of Morocco, the Mataria Desert Research Institute (Arab Republic of Egypt), the National Service for the Installation of Water Points of the Republic of Guinea, and the Office of Geological and Mining Research (Orleans, France), as well as A.M. Abdoul, N.B. Ayibotele, I. Barry, R.M. Blamdandi, A. Cavaco, P. Chaperot, Checkh Becaye Gaye, N.C. D'Almeida, E. De Boer, A. Diallo, M.A. Diallo, S.M. Dossou, J. Dubus, M. Faloci, D. Fernandopulle, R. Friedmen, J.A. Hanidu, M. Haupt, W. Iskander, M.T. Jones, L. Kossakowski, J.C. Lachaud, J. Margat, T. Mba Mpondo, L. Moullard, E. Njié, Saad Ali Sabet, O.M. Salem, M. Simonot, W.G. Strupczewski, D.Z. Sua, P.S. Zahir, E.H. Zander and H. Zebidi.

The simplified hydrogeological map of Africa appended to this volume was kindly supplied by Mr. J. Marget. He is warmly thanked for that. The Division of Natural Resources of the United Nations Economic Commission for Africa (ECA, Addis Ababa) helped with the collection of information on some countries for this publication, for which ECA is jointly responsible with the United Nations Secretariat in New York.

6/ United Nations Publication, Sales No. E.83.II.A.12.

7/ United Nations Publication, Sales No. E.86.II.A.2.

Explanatory notes

The following symbols have been used in the tables throughout the report:

A dash (-) indicates that data are not available or are not separately reported.

A blank indicates that the item is not applicable.

A full stop (.) is used to indicate decimals.

A slash (/) indicates a crop year or financial year, e.g., 1976-77.

Use of a hyphen (-) between dates representing years, e.g., 1975-1978, signifies the full period involved, including the beginning and end years.

Reference to "dollars" (\$) indicates United States dollars.

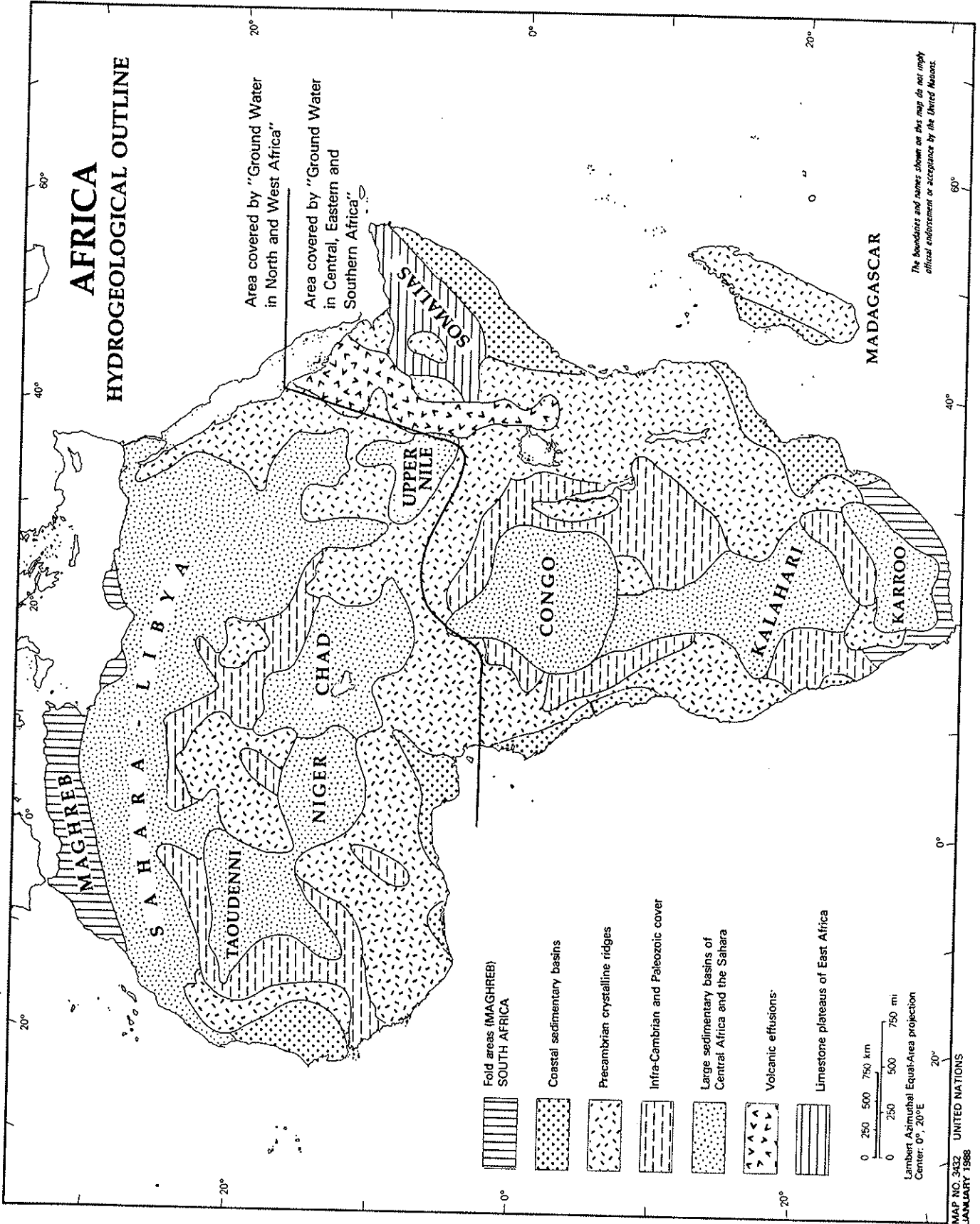
Details and percentages in tables do not necessarily add to totals because of rounding. Some of the data series are not homogeneous; they have been taken from various reviews and publications; the differences or divergencies may be due to typing errors.

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, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

The term "country" as used in the text of this report also refers, as appropriate, to territories or areas.

AFRICA

HYDROGEOLOGICAL OUTLINE



PART ONE

OVERVIEW

This volume deals with ground water from the standpoint of the physical conditions of the accumulation of this natural resource, the state of knowledge about its potential, its exploitation and the uses to which it is put. It deals with all the African countries north of the Equator, except for Ethiopia and Somalia which belong geographically to East Africa, to be covered in a second volume on all the countries of central-equatorial and southern Africa, including Madagascar and the neighbouring island countries and territories.

I. LARGE AQUIFER SYSTEMS

This vast territory of 17.2 million km² with 300 million inhabitants can be subdivided on the basis of geological, morphological and climatic considerations into a number of large aquifer systems in which the ground-water resources can be reasonably well distinguished from the standpoint of their accumulation, their fossil or renewable state and their accessibility.

i) To the north-west, the mountains and plateaus of the Atlas and the Rif and the Mediterranean and Atlantic coasts in the north and west. This is the "Maghreb" of Morocco, Algeria and Tunisia, north of the Sahara. From the geological standpoint these are mainly sedimentary formations strongly affected by Alpine orogeny. The region has contrasting landscapes: it has different climates ranging from the Mediterranean or subhumid type to the semi-arid or even arid type: Moroccan plains north of the Atlas, Algerian high plateaus; here the ground water is intensely exploited to an average extent of 80 or 90 per cent of the renewable resources or even higher in some places, especially in the semi-arid and arid areas.

ii) In the north-east, the Mediterranean fringe constitutes a kind of extension of the Atlas but much more modest in its relief, extent and altitude. The mountains receive quantities of rain which can recharge the neighbouring aquifers, but the renewable resources are small and generally overexploited.

iii) To the south of these areas lies the Saharan region and the deserts which form its eastern extension - the Libyan and Nubian deserts; this is an enormous, generally flat, monotonous territory where the rainfall is infrequent, irregular and very meagre, except over some mountainous areas. It is made up of sedimentary basins mainly of continental origin but with some lagoonal and marine basins in which the beds generally lie in regular horizontal or subhorizontal strata. Two sandstone formations constitute large aquifers of the fossil and Mesozoic types: the "intercalated continental" in Algeria and Libya and the "Nubian sandstones" in Libya-Egypt-Sudan. To the west (western Algeria and Mauritania), the formations are of hard Paleozoic rocks with low permeability in which the ground-water resources are much smaller, except locally.

- iv) The crystalline Precambrian basement rock underlying these sedimentary basins emerges in great masses at the west-east axis of the Sahara: Tiris-Adrar, Yetti-Karet (Mauritania-Algeria). The Hoggar mountains which rise to almost 3,000 m in volcanic peaks (Algeria) flanked in the south by the ranges of Adrar des Iforas (Mali) and Air (Niger), Tibesti (Chad), Ouaddai (Chad), Darfour (Sudan) and the majority of the territory to the east of the Nile as far as the Red Sea. As far as ground water is concerned, this is a mainly barren region, with the exception of a number of alluvial deposits at the foot of the mountains. When present - a fairly rare occurrence - the ground water is far from abundant and in many cases heavily mineralized.
- v) To the south of this ancient backbone the general situation of the aquifers is fairly similar to the one found in the north; here too there are enormous sedimentary basins subject to a desert climate, with hard and unproductive Paleozoic strata in the west (Tagant, Mauritania), except for a number of limestone layers, and with sandstone strata in the east: intercalated continental (Azaouad in Mali), the Air sandstone in Niger and the Nubian sandstone further east, which contain fossil aquifers.
- vi) The Chad basin, occupied in its centre by the eponymous lake which is shallow and has declined in size over the last decade, is formed by a complex of sediments of various ages, mainly recent, Quaternary and Cenozoic, in which the ground-water resources are considerable: in places artesian, but with relatively low unit yields per well, for the clay strata are frequent and extensive.
- vii) The basement-rock areas of West Africa which cover the majority of the territory of Guinea, Sierra Leone, Liberia, Côte d'Ivoire, Ghana, Togo, Benin, Burkina Faso and Cameroon, as well as large areas of Mali and Nigeria. The rocks are exposed to Sudano-Sahelian climatic conditions and are water-bearing in their altered and fractured parts. At its northern edge the crystalline shield of western Africa is flanked by a sandstone rim of Precambrian or Paleozoic age which constitutes a major aquifer in Mali and Burkina Faso. The unit yields obtainable from the wells or boreholes are not large except in a few cases (Bobo Dioulasso sandstone) but they are usually sufficient for village and livestock needs. The sedimentary basins in the central part of Niger, along the axis of which run the River Niger and its main tributary the Benoue, which has its source in Cameroon, are made up mainly of gray argillaceous Cretaceous formations containing artesian aquifers.
- viii) The coastal sedimentary basins are very different in extent, the largest being the Senegalese-Mauritanian basin which runs southwards into Guinea-Bissau. Then come the bevel-shaped coastal basin of Nigeria which narrows towards the east (Cameroon) and towards the west (Benin, Togo, Ghana), and the very narrow but economically important coastal basins along the shoreline of Guinea, Sierra Leone, Liberia, Côte d'Ivoire and Ghana. These basins contain recent, Quaternary and Cenozoic sediments with very productive sandstone and limestone layers. They are intensely exploited - sometimes overexploited.

II. CLIMATIC CONDITIONS: EFFECTS ON THE RECHARGE OF THE AQUIFERS

The territory is subject to very varied climatic conditions in which latitude plays an essential role. From the anticyclone of the Azores, a high-pressure centre, the trade winds blow towards the Equator and are deflected westwards by the rotation of the earth. In January a cool dry wind - the Harmattan - blows from the Sahara towards the west coast of Africa from Mauritania to the Niger delta. At this period the whole of Africa south of the equator is subject to a low-pressure system (below 700 mm). In July, in contrast, a high-pressure system prevails over southern Africa and a cyclonic depression is centred over the plateaus of Iran. As a result, the winds tend to blow towards the east and a monsoon from the southwest brings heavy rains to the western coast.

As a general rule the winds blow from the sea to the land, bringing rain; but there are notable exceptions: the Harmattan and in mid-year some local winds from the Maghreb which blow towards the Mediterranean, and some regular winds which blow towards the north-east of Africa in the direction of the Arabian Peninsula. The mountains halt the wet winds.

In January, the regions to the south of the 20th parallel N (from Nouakchott to Port Sudan) have average temperatures below 20°C. In July, the whole of the continent north of the equator (except for the coastal zones) has temperatures above 30°C, sometimes 32°C.

The temperature ranges are very small in the equatorial regions (10°C) but increase in step with distance from the equator; they are from 20°C to 30°C in the Sahara.

The rainfall is irregular with wide variations from season to season and year to year.

In the extreme north of the continent the Maghreb and certain coastal parts of Libya and Egypt and, in the extreme south, the Cape region have rainfall of the Mediterranean type (winter rains).

The very wet equatorial regions to the south of 10° latitude N have two rainy seasons when the sun is high above the horizon, generally from March to June and from September to November. From the 10th to the 15th parallel N the tropical regions have only one rainy season, from May to October. Lastly, the subtropical desert region, i.e. the whole of the north of the continent with the exception of the Mediterranean zone, receives only occasional and irregular showers.

The annual rainfall is two to six metres along the coast of West Africa from Conakry to Abidjan and from the Niger delta to Libreville in Gabon; one to two metres in some mountainous regions of the Maghreb and south of the line from Dakar to Mogadishu; 500 to 1,000 mm in the High Atlas, in the coastal regions of Algeria and Tunisia and in a strip 300 to 500 km wide to the north of the line mentioned above; less than one metre to the

north of the line from Nouakchott to Port Sudan, with the exception of the Maghreb, the majority of this region receiving less than 20 mm.

Climatic zones

The climatic zones, characterized by very different vegetation types are as follows:

- Mediterranean zone with dry summers (hot season) northern Maghreb.
- Steppe zone with the following subdivisions:

Pre-Saharan regions south of the Maghreb with drier summers. This climate is sometimes described as "semi-arid Mediterranean". The rainfall is less abundant and the temperature range broader than in the Mediterranean zone.

Regions to the south of the Sahara with semi-arid tropical climate of the Senegalese or Sahelian type. They receive more abundant rainfall in the hot season from June to September.

- Wet savannah zone or zone of tropical Sudanese climate. The wet season grows longer the closer to the equator, but in some places the uninterrupted dry season can last from four to five months. The belt of wet savannah is 500 km wide on average.

- Desert zone with Saharan climate (Sahara).

- Equatorial forest zone with very wet climate and two rainy seasons or continual rain. It includes, over a width of 300 km, the region of the Gulf of Guinea from Freetown to Accra and from Lagos to Douala, southern Cameroon and the Congo basin as far as the rift valleys.

- Coastal fringe zone, a narrow coastal strip in which the climate is heavily influenced by the sometimes very powerful coastal currents. The Canaries current, flowing north to south from Tangiers to approximately the 20th parallel N, is cold; the Guinea current, flowing west to east from Dakar to the equator, is warm.

Aridity and evaporation

The climatic zones can also be classified according to the index of humidity or aridity (Thornthwaite), which takes into account both the temperature and rainfall and its distribution and which expresses a characteristic ratio between potential evapotranspiration and the amount of rainfall.

The surface aquifers (lakes) undergo large variations in level owing to the imbalance in some years between the headings "evaporation" and "recharge". This is particularly true of Lake Chad. It is also true of the unconfined ground-water aquifers when the piezometric surface is shallow in comparison with the soil. Evaporation produces - and can be

measured by - concentrations of salts in the aquifers. The question of the depth to which evaporation takes place is disputed. However, all authors agree that this effect operates for several metres (five metres on average and as deep as eight to ten metres). Some authors speak of much greater depths.

Conclusion

The amount of rainfall available to recharge the ground-water aquifers depends on three main climatic factors: the annual rainfall, its distribution in time or the "heaviness of the precipitation", and the value of the potential evapotranspiration, which is essentially a function of latitude, altitude and temperature.

In some cases each of these three factors singly can have a decisive influence.

In all the regions in which the rainfall exceeds roughly 1 to 1.2 metres a year, neither the heaviness of the rain nor the evapotranspiration value should be taken into account, for a large part of the rainfall is almost always available for infiltration, in some places after runoff. In this case the decisive factor is the amount of the rainfall.

In the case of rainfall below 250 mm, it is the heaviness of the precipitation which is important. It is interesting to note that in conditions of increasing aridity - decline in rainfall accompanied by an increase in the evaporation potential - the heaviness of the showers increases to the point where most of the annual precipitation sometimes falls in a few hours. Accordingly, in the Sahara some daily figures can produce a surplus - which can persist over several days - of rainfall over potential evapotranspiration; this gives the water time to infiltrate and thus recharge local aquifers in particular cases.

The following table compares some potential evapotranspiration values with the rainfall at a number of climatological stations in Africa.

	Annual rainfall (cm)	Potential evapotrans- piration (cm)	Quotient (percen- tages)
<u>Arid and hyper-arid zone</u>			
<u>(rainfall below 250 mm):</u>			
In Salah (Sahara)	0.5	140	0.3
Biskra (southern Algeria)	18	133	
Moudjeria (Mauritania)	17	187	3
<u>Coastal regions</u>			
Nouadhibou (Mauritania)	4	116	4
Tarfaya (Morocco)	11	85	13
<u>Zone with rainfall between</u>			
<u>250 and 1,000 mm:</u>			
Kayaes (Mali)	74	187	30
Algiers: wet Mediterranean climate	76	92	83

Thus in some regions a large or even overwhelming part of the rainfall is almost immediately lost through evaporation. The heading "evapotranspiration" in the water balances is often the largest. Some authors offer the following figures for the various regions of Africa: evapotranspiration, 40 to 98 per cent; infiltration, 2 to 40 per cent; runoff, 2 to 12 per cent.

In regions with rainfall between 250 mm and one metre (steppe and dry savannah) the potential evapotranspiration is the decisive factor, for the rainfall is spread out better in time. During the rainy season, which can vary widely from one year to the next, the potential evapotranspiration can still have a large value. However, a very variable remainder is almost always available for runoff and infiltration. In contrast, during the dry season which can last from three to six months, some regions of Africa have climatic conditions of the semi-arid or arid type while receiving more annual rainfall than some countries in the wet temperate zone of Europe. During the dry season, the evaporation effect can be considerable in surface and shallow aquifers.

Some recent studies on the treatment of rainfall data in the Sahelian countries tend to show that the rainfall falls into two distinct categories:

- A "monsoon" system with moderate rainfall fairly well distributed in time and little variation from year to year. To some extent this rainfall can help to maintain the vegetation but most of the water evaporates after having soaked the upper layers of the soil.

- A system of very heavy, brief and frequent showers which produces large amounts of surface runoff and deep infiltration. This type of rainfall is essential for the renewal of surface- and ground-water resources. It is the decline in the heaviness or frequency of these showers which causes "drought" when the main consequence is a drop in the level of water in the wells, which can even dry up completely. Lastly, a drop of 50 per cent in the amount of total annual rainfall as a result of less frequent showers can mean so surface runoff or recharging of the aquifers.

III. PRODUCTIVITY OF THE AQUIFERS

The values given below are by way of example. Additional data will be found in the country papers (see Part Two).

Extensive sand formations

In Africa sand dunes cover large areas north of the 14th parallel. Little is known about their role as aquifers in the Sahara. But it is known that the sands themselves, despite their great permeability, cannot provide a large reservoir in many cases since they quickly lose, through runoff or evaporation, the rainwater which they absorb.

Country	Location	Geology	Flow rate per installation
Mauritania	Plain of Kaffa	Sand dunes	5 to 10
	Plain of Assaba	Sand dunes	5 to 10
Senegal	Malika	Sand with clay	26
Cape Verde	Tiaroye	Sand dunes	50

Alluvial fill, deltas, chott deposits, Quaternary formations of the Chad basin and coastal sedimentary basins

Country	Location	Geology	Flow rate per installation (m ³ /h) <u>a/</u>	Drawdown (m)
<u>Fluvial alluviums.</u> These aquifers are among the most important and serve large populations.				
Algeria	Wadi Biskra	Sands-gravels	-	-
Morocco	Doukkala	Sands-gravels	10 to 1,000 m ³ /day	-
	Tafilalet	Gravelly alluviums	-	-
	Sous	Gravelly alluviums	Up to 360	1
Mauritania	Wadi Seguelil	Gravelly alluviums	10	-
Egypt	Nile	Coarse Pliocene-Pleistocene gravels	1000	3
<u>Coastal or continental alluviums</u>				
Côte d'Ivoire	Treichville lagoon	Coarse sands	210	-
Guinea	River Nunez	Alluviums	20 to 50 (subartesian boreholes: 7)	-
Togo	Coastal zones	Argillaceous sands	3 to 5	-
Cameroon	Flats	Fill formations	10 to 80	-
<u>Coastal sedimentary basins</u>				
Cote d'Ivoire	Abidjan	Paleocretaceous sands and limestones	18	80
Benin-Togo	Coastal region	Cretaceous sands	1 to 35 m ³ /h/m; (average: 8 to 15)	-
Togo	Afagnagan	Cretaceous sands	18	10
Libya	Syrte	Miocene limestones and sands	25	42
Morocco	Agadir	Pliocene limestones and sandstones	5 to 20 m ³ /h/m	-
	Plains of Doukkala and Berrechid	-	10 to 100	-
Senegal	Basin (total)	Maestrichtian sandstone	15 to 120 (artesian)	-
Tunisia	Zarzis-Djerba	Upper Miocene	50 (artesian)	-

a/ In the column "Flow rate per installation", the underlined values indicate a specific yield.

Terminal continental sandstones and conglomerates (Late or Post-Cretaceous)

Terminal continental

Burkina Faso	Bobo Dioulasso	-	90
Mali	Gondo	-	50 to 100
Mauritania	Trarza	Sandy intercalations	(up to 300/day) 1 to 4
		Bennichab	Sandy intercalations
	Nouakchott	Sandy intercalations	15
Senegal	Casamance	Argillaceous sand-sandstone	6 m ³ /h/m
Togo	Lomé-Agouévé	Variegated sandstone	5 to 40 m ³ /h/m

Intercalated continental, Nubian sandstone and other continental Precretaceous or Cretaceous continental sandstone

Algeria	Charadaia	Intercalated continental argillaceous sandstone	variable
Cameroon	Bénoué-Garoua	Cretaceous sandstone	10 to 20, up to 50
Nigeria	Sokoto	Consolidated Eocene sands	heavy flows (variable)
Egypt	Casis de Kharga	-	3,000 to 4,000 per day (artesian)

Limestone tableland of the hammadas of northern Africa (Pliocene-Pleistocene)

The hammadas cover vast areas south of the Atlas; their surface is generally made up of a subhorizontal plate of hard Pliocene-Villafranchian lacustrine limestones with varying degrees of sandiness, often overlying softer sand-clay formations. The scant rainfall which infiltrates in the hammadas quickly circulates through a karstic system, flows towards peripheral or central depressions and is rapidly lost through evaporation. The few wells found in the hammadas are fed from dune or alluvial formations. Water-drilling operations have generally not produced positive results.

Karstified limestone aquifers of the Jurassic, Cretaceous (North African Cenomanian-Turonian plate) and Eocene periods

Country	Location	Geology	Flow rate per installation (m ³ /h)	Drawdown (m)
Algeria-Morocco	High plateaus	Jurassic limestones	150 (artesian)	
Morocco	-	Liassic limestones	Up to 500 (artesian)	
	Doukkala	Upper-Jurassic marly limestones	10 to 100	
	Bahira	Dolomitic limestones	150 to 200	
	Sous	Cenomanian-Turonian limestones	Up to 1,200	
		Cretaceous sandy-marly limestones	1 to 10	
Mauritania	Trarza	Eocene limestones	0.1 to 1	
Senegal	Pout-Ndiass	Paleocene limestones	Up to 4	
Tunisia	Djebel Zaghouan	Liassic limestones	2,000 (in 6 springs)	

These few examples show that the karstified limestones of North-West Africa can yield rates of flow often in excess of 50 m³ per hour, sometimes as high as 100 and even several hundred in certain cases.

Tectonized zones of northern Africa with complex structures of marl-sandstone, marl-limestone, flysch, etc., of the Jurassic and Cretaceous periods.

The ground-water resources are very local; they are found mainly in fractured zones with thin limestone or sandstone seams alternating with schists, marl-limestones, clays, etc. The available yields are very variable.

Dolomitic-limestone massifs and plateaus of the Upper Precambrian and Cambrian periods

The dolomitic-limestone sedimentary formation (of Upper Precambrian and Cambrian age) is often very thick and constitutes a major ground-water reservoir:

Dolomitic limestones of Tin Hrassan (Burkina Faso) in arid zones. Transmissivity: $5 \times 10^{-4} \text{ m}^2/\text{s}$. Flow: $4 \text{ m}^3/\text{h}$, with a drawdown of 10 m. Storage coefficient: 1.8×10^{-3} ;

Fissured dolomitic limestones of Atar (Mauritania). Flow: $70 \text{ m}^3/\text{h}$, with a drawdown of 4 m. Such a flow is exceptional for an arid area; it is produced by a river bed infiltrated by flood waters;

Precambrian and Cambrian limestones of the Anti Atlas (Morocco). A number of overflow springs have flows of 20 to $40 \text{ m}^3/\text{h}$ and up to $250 \text{ m}^3/\text{h}$;

Mention must also be made of the dolomites of Tiara (Burkina Faso) and Gondo with its karstic sink-holes (Mali), for which no figures are available.

Precambrian and Paleozoic hard sandstones, schist-sandstones and quartzites

Country	Location	Geology	Flow rate per installation (m ³ /h)
Mauritania	Hodh	Cambrian pelitic sandstones Brazer sandstone	Up to 0.2 to 0.5 2 (maximum)
	Ayoun el Atrous	Precambrian sandstones	0.2 to 0.3
Togo	Bombouaka	Sandstone	0.3 to 7
	Dapango	Sandstone	3 to 7 (maximum)
Togo-Benin	-	Atakora quartzites	2 to 3, up to 7

Schists (mainly Precambrian and Paleozoic) and clays

When they are not totally impermeable these formations do contain some meagre water resources, mainly in fracture zones. Some examples of available yields per installation are given below:

Country	Location	Geology	Flow rate per installation (m ³ /h)
Ghana	-	Volta schists	Very low
Guinea	-	Black Gothlandian slates	Very low in fractures and seams
Burkina Faso	Banfora	Schist-sandstone	12 (exceptional)
Mali	Nara	Cambrian schists	Very low
	Azaoud-Timbuktu	Metamorphized Pre-Cambrian schists	0.5
Mauritania	Atar	Schists under alluvium	20
Togo	Sansanne-Mango	Schists	<u>0.3 to 1 per day</u>
	Buen	Marly-sandy schists	<u>0.5 to 10 per day</u>

Examples of available yields per well and borehole in crystalline zones

Country	Location	Geology	Flow rate per installation (m ³ /h)	Drawdown (m)
Cote d'Ivoire	Yamoussoukro	Fractured granites	6	-
	Daloa	Granitogneiss	2 to 4 (up to 12)	12
Benin	Parakou	Fractured granites in tectonic depressions	7 to 8	-
Benin-Togo	-	Birimian schists, quartz seams	3 to 7 (exceptional)	-
Ghana	-	Granites and granodiorites with quartz seams	5 to 20 m ³ /day	-
Burkina Faso	Various	Mica schists	less than 1 m ³ /day	-
	Various	Granitogneiss	1 to 4	10 to 20
Mauritania	Fort Detrick	Mica schists and gneiss with pegmatitic seams	20 m ³ /day	-
	South-east	Diorites	0.5	-
Chad	Ouaddai	Granitic sands	2	-
Togo	Elavagnon	Mica schists and graniteogneiss	2 to 5	6 to 20
	Kande	Chlorite schists quartz seams	7 to 12	9 to 15
	Dapango	Alkaline granite-gneiss	1 to 5 m ³ /day	-
	Palime	Granites and granodiorites with amphibolites and quartz	5 to 20 m ³ /day	-

In summary, a flow rate of 5 m³/h is a good one for granites and granitogneiss; a rate of 1 m³/h is considerable for mica schists and metamorphic schists. Better yields are obtained in the quartz zones.

Crystalline and metamorphic rocks (basement formations, granites and gneiss)

Since they have virtually no porosity, the crystalline rocks are impermeable except in faulty, fractured or altered zones. The best yields are usually obtained when a relatively thick altered stratum overlies a fault zone.

The nature and structure of the altered stratum vary according to the parent rock. This stratum can be almost entirely argillaceous and therefore barren.

Volcanic rocks

Lavas, especially basalts, dolerites and certain basal rocks which sometimes give high yields can be put in a separate category; a few examples are given below:

Fissured dolerites in arid zones - Ayoun el Atrous (Mauritania): less than $0,1 \text{ m}^3/\text{h}$; non-fractured: $0,2$ to $0,3 \text{ m}^3/\text{h}$;

Basal rocks of Akjoujt (Mauritania): 30 to $45 \text{ m}^3/\text{h}$, with a drawdown of 13 m ;

Basal rocks of Conakry (Guinea): 13 to $72 \text{ m}^3/\text{h}$ (very rainy tropical climate), with a drawdown of 20 to 50 m ;

Green rocks of Kongolikan (Burkina Faso), fractured: $3 \text{ m}^3/\text{h}$.

Conclusion

There is almost nowhere in Africa where ground water is not found at one depth or another. The highest flows are provided by clay-free alluviums, continental or marine Cretaceous sandstones and karstic limestones.

Most of the ground water is acceptable for human consumption and therefore for livestock as well.

In arid zones the ground water is usually of calcium/magnesium bicarbonate facies at the higher level, i.e. near the regions where the surface runoff infiltrates. It then acquires a higher sulphate content and finally increased amounts of chlorine and sodium at the end of the course in the regions where the evaporation effect is high and operates directly on shallow aquifers. This is particularly the case in pre-Saharan North Africa for the sabkhas (continental depressions).

Some geological formations, especially of Permian-Triassic or Cretaceous age and lagoonal origin, contain mineral salts which pass in solution into the ground water. This is particularly the case in North Africa.

In the coastal sedimentary basins, often made up of permeable formations, pumping causes sea-water intrusion which tends to contaminate the fresh water aquifers.

In the Precambrian basement rock in tropical rain country the water is usually not very mineralized or aggressive.

Mineral-water and thermo-mineral springs abound in the African continent in the fracture zones. They constitute a major potential resource which has been explored and exploited in only a few places.

IV. EXPLOITATION OF THE GROUND WATER

In Africa as in the rest of the ancient world ancient, densely populated civilizations with advanced social organization and a sophisticated way of life were associated with the big rivers. These rivers furnished abundant water, rich soil, and fish and game in their valleys and deltas, as well as means of transport and places of refuge.

Away from the big rivers the surface-water resources are scanty especially in the dry season. In tropical Africa they are limited to water-holes. In the northern Africa the ancient inhabitants, the Berbers, usually established themselves in the mountainous regions near the sources of permanent rivers. It was the Arabs, the occupiers of the plains and Saharan oases, who developed the use of ground water through the construction of wells and infiltration galleries, employing the original techniques of Central Asia and the Middle East. Various methods of dewatering were also imported from those regions.

However, until recent times and with the exception of Arabized Africa, ground water was drawn off only from shallow holes dug in alluvial beds devoid of surface water in the dry season. These crude wells are in general use in the pre-Saharan regions. They are rarely more than a metre deep and provide temporary water points still frequented by nomads; they usually last only a short time, for flood water in any amount destroys them.

Traditional wells and drains

The digging of wells and construction of traditional drains - underground galleries linking aligned wells - was practised mainly in arid countries under Arab or Turkish influence in northern Africa, including the oases of the Sahara, Libya and Nubia and some of the Southern fringes of these deserts.

The wells were excavated with simple digging tools in soft earth of good consistency. Sometimes the walls or vaults were reinforced in places with timbering or brickwork, either dry-stone or with lime mortar. Some of these wells, especially in arid piedmont areas, attain considerable depths, sometimes 100 metres and more.

The well systems described in the Bible and very numerous in Iran, where they are called kanats, are widespread in northern Africa where the total length of the galleries amounts to several thousand kilometres. In Egypt and the Sahara they are called foggaras; in Morocco, rhattaras. This system makes it possible to obtain the ground water from the soil without

using dewatering methods. The galleries are first built as trenches which climb underground until they intersect over a certain length the saturated formations to be drained. The length of the galleries is limited by the maximum depth of the "head well", which depends on the techniques used and the nature of the terrain.

These drains can only be built in formations of suitable consistency where the digging is easy: lacustrine formations, soft sandstone, tuff, consolidated alluvium, etc. The aquifer must also be relatively shallow and lie under land which slopes sufficiently for the galleries to discharge in the open air; but the slope must not be too steep, for the head wells must be of a reasonable depth. These foggaras are found in the beds of certain wadis and their environs: middle or adjacent beds on the flanks of gently sloping valleys and at the foot of dejection cones spreading from piedmonts. Some drains penetrate rock formations and reach aquifers whose flow is blocked downstream by natural obstacles.

The construction, cleaning and maintenance of these drains - arduous and dangerous work - is now very difficult. Many of the installations are deteriorating and collapsing for lack of maintenance. In small aquifers with irregular recharge the drains can cause a permanent discharge - often unused - which quickly leads to total depletion: this is particularly the case in the plain of Haouz (Marrakesh) and the plain of Sous (Morocco).

The traditional means of raising the water from the wells vary according to region, raw materials, depths and uses. For shallow irrigation wells (norias) bucket wheels operated by animal traction are widely used. For greater depths a simpler procedure is often employed; it involves a treadmill worked by an animal (cow or camel) which hauls up a leather water-bucket by means of a system of ropes and pulleys. This method raises hardly more than a few cubic metres a day.

The deepest wells are drawn by hand, for they are used only to supply the population and livestock. Beam wells are a traditional feature of the landscape in the Nile Valley. They are also found in Sudan and in all the sub-Saharan countries from Chad to Mauritania.

Wells drilled and dug by modern methods

In the deserts the discovery of ground water by deep drilling is essential for oil exploration works, especially for the mixing of drilling mud and the raising of oil by injecting water under pressure. The general geological studies and the geophysical studies carried out for this purpose have led to the identification of deep confined aquifers which have then been exploited by means of artesian boreholes. Thus, even before the proclamation of their independence the African territories under British administration benefitted from the experience acquired in oil exploration in the Middle East during the second quarter of the twentieth century and from the progress made in the same period by British and Swedish manufacturers of drilling equipment for the exploitation of ground water. In French Africa drilling for water also underwent a great expansion, especially from the time

when oil exploration activities were started in the Sahara, i.e. from the 1950s.

The ground water was first exploited by borehole in the arid zones of northern Africa: Algeria, Morocco, Tunisia, Egypt and northern Nigeria where there are vast stocks of ground water. This ground water sometimes has natural outlets in topographically low-lying areas such as the chotts, where it is subject to direct evaporation; in other cases these depressions offer favourable conditions for the drilling of artesian wells. Artesian wells have been dug in chotts in Tunisia from the end of the 19th century using big augers operated by groups of workers. Mention must also be made of the many artesian bore-holes drilled in the 1940s and 1950s in the New Valley, i.e. in the depressions of El Kharga and El Dakhla in Egypt's Western Desert.

Many small boreholes have also been drilled in all the countries of the semi-arid or arid zone in order to supply from shallow aquifers the administrative or economic urban and rural centres and modern agricultural enterprises. These works were first carried out in northern Africa; they were then extended to the wetter areas and as far as the equator, for the wet tropical countries also need ground water to supply their towns and villages.

The number of water-drilling rigs in Africa has increased rapidly over the past decade, especially in the arid countries. These rigs are used by a number of African and foreign companies and by State services such as departments of water development, or equipment, etc.

In most cases the boreholes are not equipped with motorized pumps. In rural areas many types of hand-operated or animal-traction pumps have been tried out. Some of these pumps are particularly simple and tough, for example the India Mark II developed with the help of UNICEF, which is now manufactured in Africa, in particular in Mali.

In addition to drilled wells, there are many wells dug by hand on the initiative of the administration in areas where they could not be constructed by the methods traditionally used by the local people (shovels and picks). In areas of hard rock, particularly Paleozoic schists and sandstones, compressed air tools and explosives are used to excavate the wells. These operations are usually costly.

In many African countries in the wet tropical zone the formations usually contain very loose clay seams which make it impossible to dig wells by hand, for the walls collapse even before the digger reaches the water-bearing strata underlying the clays. In such cases an appropriate lining must be used; this is always tricky and sometimes expensive or difficult, which means that the wells must be drilled.

The construction of wells is also very difficult in areas of sand-clay sediments where the installation of a prefabricated reinforced-concrete lining is always essential.

The installation of motorized pumps is justified only when the water requirement is large, and account must be taken of economic and social factors, the chemical quality of the water and the height of the lift. The communities or bodies concerned must also have the technical and financial means to maintain and repair the installations.

During the last 15 years the digging and drilling of wells has undergone spectacular development in the region, partly as a result of the International Drinking Water Supply and Sanitation Decade and partly because of the periods of exceptional drought (1973-1975 and 1983-1985) which affected the arid and Sahelian zones north and south of the Sahara.

Thus, for a Sahelian country in which about 20 wells a year were dug in 1965/66 the number of wells drilled had increased to four or five hundred in 1985.

Ground water is intensively used to supply urban and industrial areas, especially in arid regions and coastal zones. This is particularly true of Tangiers, Fez, Meknes, Marrakesh, Agadir, Constantine, Tripoli, Benghazi, Port Sudan, Ibadan, Cotonou, Lomé, Bobo Dioulasso, Abidjan, Bissau, Banjul, Dakar and Nouakchott.

The exploitation of ground water in Africa is intended mainly to meet the water needs of the towns, villages and pastoral areas and those of industrial and mining enterprises. In contrast, irrigation with ground water is limited either by its cost and the expenditure of convertible currency involved in the purchase of pumps, motors and fuel, or by the exhaustion of the aquifers in arid regions. Apart from the countries of North Africa - from Morocco to Egypt - the areas irrigated by ground water are still very small. However, small market-garden centres have been spontaneously created around the hand pumps installed in villages and this kind of small-scale operation is tending to increase (Mali).

CONCLUSION

The sharp increase in the use of ground water in Africa goes hand in hand with the continent's rapid entry into the modern world. This use is important for all sectors of the economy but was first concentrated in the towns, the mining centres and some priority farming regions. It is now tending to be extended to the small centres in the most isolated tropical and desert regions. A considerable effort to this end is being made both by Governments and by international and bilateral technical co-operation bodies. This sharp increase in the use of ground water is almost always one of the fundamental conditions for economic and social development, for it is an essential factor in the life or survival of many existing centres of population and a fundamental condition for the establishment of new centres.

However the development of ground water is beset with many difficulties. Firstly, the areas with the best aquifers from the standpoint of the capacity

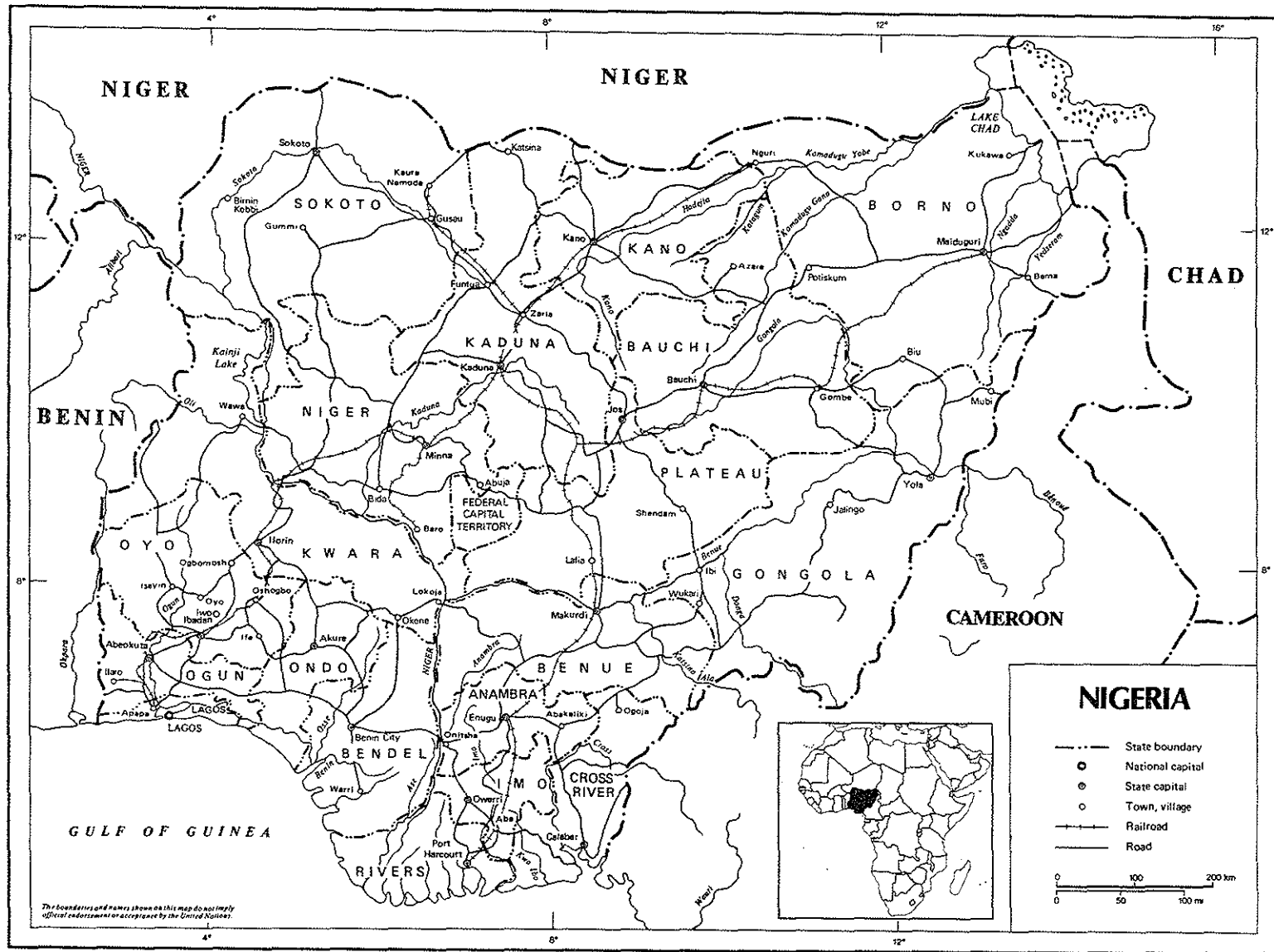
of the rocks to absorb, hold and discharge large quantities of water are the desert zones where there is little or no recharge from rainfall and the coastal zones subject to deep intrusion of sea water in the direction of the wells. In contrast, the rainy tropical areas have rocks which are poorly suited to the absorption and storage of water supplied by rainfall and surface runoff.

Furthermore, ground-water prospecting and the drilling and digging of wells are usually difficult and expensive operations owing to the weakness of the infrastructures, the unfavourable natural conditions, the remoteness of the zones to be reached and the wide dispersal of the villages, as well as the lack of equipment, qualified personnel, project-uptake facilities, and investment and maintenance funds.

Lastly, and this is not the least problem, African villagers do not always have the motivation, the basic technical capacity and the material resources required for the satisfactory operation, maintenance and repair of the manual pumps supplied to them. Substantial progress has nevertheless been made in recent years in several fields: training of technical personnel at various levels, including management and decision-making; rational planning of drilling operations; introduction of appropriate technologies for the construction and restoration of wells and for the movement of the water; introduction of relatively cheap and effective methods of prospecting (particularly remote-sensing and geophysical techniques); computerization of data and inventories; manufacture of equipment - especially hand pumps - in Africa itself; grassroots animation and education of villagers and creation of African water-drilling enterprises.

However, much remains to be done to ensure that the ground-water resources of North Africa are managed to best effect, i.e. without wastage or long-term threat to the existence of these resources in terms of both quantity and quality. This comment applies equally to the intensely exploited coastal zones, especially at Nouakchott, Dakar and Lomé.

Nor are the objectives of the International Drinking Water Supply and Sanitation Decade about to be achieved for the villages of the countries of Western and Central Africa south of the Sahara. However, it can be hoped that towards the end of the century the necessary infrastructures - wells and boreholes - and the corresponding elementary superstructures will be in place in all the villages and that the maintenance of the pumps, if not their replacement when they are worn out, will be undertaken mainly by the villagers themselves. The organizations of the United Nations system - as can be seen from the list of projects in the annex - will have contributed to this vast undertaking in a very considerable and in many cases decisive manner.



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NIGERIA

Area: 923,770 km²

Population: 89.02 million (United Nations estimate, 1983)

I. BACKGROUND

Nigeria has the biggest population in Africa, with about a fifth of the continent's people. In 1984 it occupied eleventh place among the petroleum producing countries, twelfth place for reserves and seventh for exports.

This West African country is shaped like a trapezium, with its short base formed by the 800 km of coastline on the Gulf of Guinea, half of which is occupied by the Niger delta. The long base of about 1,000 km touches Lake Chad in the north. The trapezium's highest side, i.e. at the country's eastern end, is about 800 km long.

The heart of the country is crossed by the valleys of the Niger and its main tributary, the Benoué. These rivers form a capital Y. The Niger is one of the longest rivers of Africa. Its basin affects nine countries.

In Nigeria the land rises steadily from the coast northwards up to a maximum altitude of 400 m. The east is occupied by the Cameroon plateaus, which are 800 to 1,400 m high on average, and up to 2,400 m in places.

In the central part the mass of the Jos plateau, which rises to 1,781 m, dominates the vast surrounding plains. The southern part receives 1,000 to 1,500 mm of rainfall a year; the south-east receives more, but in the drier regions in the north the rainfall is below 500 mm.

Hydrographic system

Nigeria has 11 river basins which together are shaped roughly like a tree. The country is divided into eight zones for the purpose of hydrological observations and exploitation of water:

1. Northern Niger (Sokoto-Rima basin);
2. Central Niger (Kaduna basin);
3. Upper Bénoué (Gongola and Tomba basin);
4. Lower Bénoué;
5. Southern Niger;
6. Western littoral zone (Ogun, Osse);
7. Eastern littoral zone (Cross basin).

The heaviest flows are from June to October, with the crests in August-September. The flows are usually regular, but with occasional rapids when the water flows directly over the crystalline basement formations without any alluvial cover.

As they cross the margin of the crystalline basement rock and the sedimentary basin the water courses lose force and spread out in vast flood plains known in the north as "fadamas".

In the north the high evapotranspiration rates reduce still further the downstream flows, but this phenomenon is offset by the draining of ground water towards the surface which maintains a permanent minimum flow. Some typical data are given in the table annexed to this paper.

In the southern part of the country, i.e. in the low-lying sedimentary areas of the eastern and western littoral zones, the climate is of the south-tropical type with:

- A long wet season from March to July;
- A short dry season from mid-July to mid-August;
- A short wet season in September-October;
- A long dry season, when the harmattan blows, from November to February.

The country's hydrographic network consists mainly of the Niger-Bénoué system and its many tributaries; the Niger discharges about 220 billion cubic metres of water a year through its delta. There is also a dense network of rivers and smaller watercourses, most of them permanent, with a total combined annual flow of 200 billion cubic metres.

Geology

The country consists of Precambrian formations of the "base complex" which outcrop over half of the territory. These are zones of gneiss, mica-schists schists and amphibolites, extensively penetrated by ancient granitic batholites - hard, mostly tectonized sequences forming the Goura and Kagoro mountains of the Jos plateau - and by younger granitic batholites.

In the centre, in the basin of the Niger and the Bénoué, the ancient basement rock is covered by marls, sandstones and clays, saliferous in places, of the intercalated continental (500 m), overlain by the marine Upper Cretaceous formation, which consists of thin Cenomanian-Turonian limestones, clays and layers of carbon. The Cretaceous sediments increase in thickness towards the south in the direction of the vast coastal subsidence zone.

The Eocene period is represented in the southern sedimentary basin; it includes clay strata which can be up to 1,000 m thick. In the south-west and south-east the sediments are less thick (100 m) and include sandstone and phosphated sand layers.

The marine Eocene period has also been identified in the north (Sokoto province).

The continental terminal covers a large area in the north-east, i.e. in the Chad basin, with argillaceous sands, sandstones and diatomites to a depth of 700 m. In the south the continental terminal includes two series: the lignite group (sandstones and clays with lignites for 25 m), covered by the

"Benin" argillaceous sands of Pliocene-Pleistocene age (250 m).

Some areas of basaltic volcanism of uncertain age are found in the centre and east,

The main sedimentary series include the Sokoto basin, the Chad basin, the middle Niger, the Bénoué trench, the eastern and western low-lying land in the south, and the coastal plains, including the Niger delta,

II. GROUND-WATER RESOURCES

Ground-water bodies

The following bodies have overall responsibility for water resources:

- The Federal Department of Water Resources;
- The Water Boards and Water Corporations of each of the states of the Federal Republic of Nigeria;
- The National Electric Power Authority (NEPA) which manages the hydro-electric power stations;
- The Ministries of Agriculture of the Federal State and the federated states;
- The Federal Department of Meteorology;
- The local office of UNICEF.

Only the first three bodies are directly concerned with ground water exploration.

Background of hydrogeological research in Nigeria

The Mining Service of Southern Nigeria made the country's first geological studies from 1903 to 1913.

In 1938 geological and geophysical work was carried out by petroleum-research teams (Shell d'Arcy). At that time a number of geologists prepared maps of the sedimentary formations, notably du Preeze (1945) and Simpson (1947).

Of all the major geological and hydrogeological studies covering vast areas of the country, mention must be made of those by Anderson and Ogilbee (1973), Barber (1965) and White (1972), Dessauvague (1975), Deswardt and Casay (1963), du Preeze and Barber (1975), Hazell (1961), Jones and Hockey (1968), Kiser and A. Kingbelin (1966), Kiser (1968), Kogbe (1976), Kowal (1972), Miller and others (1968), Raeburn and Tatam (1930), Raeburn and Jones (1964) and Rayment (1965).

The training of new or experienced staff can easily be carried out in the field by assigning them to the study and operational companies working in the country. Some young people have been trained at the National Institute for Natural Resources at Kaduna. The Institute's Department of Ground-Water

Research was reorganized in 1985; it was to be strengthened so as to be able in the future to train all categories of staff in the field of ground water.

Prospecting methods

Various methods of geophysical prospecting are used in Nigeria for ground-water research, including:

- Airborne geophysical prospecting;
- Electro-resistivity, mostly using the Schlumberger apparatus;
- Seismic refraction;

Electrical resistivity methods are the most commonly used owing to their low cost and easy operation.

The geophysical prospecting has concentrated on the crystalline basement rock, in particular since the start-up of the national water-drilling programme in 1981.

Main aquifers

Nigeria's main aquifers are found in the sedimentary formations which cover 524,000 km² of the country and range in age from Upper Cretaceous to Recent. The various basins are described below.

1. Sokoto basin

This basin is in the north-west of the country and consists of an area of more than 146,000 km² covering most of Sokoto and some parts of the Kaduna states. It is a south-east extension of the great basin of the Tullerenden which covers vast areas of Mali, Niger and Algeria and part of Mauritania. The depth of the water table in the formation ranges from 15 to 75 m for the unconfined aquifers. Elsewhere, artesian conditions occur in the sediments of several formations. Artesian aquifers are found at depths of 75 to 100 m close to the eastern edge of the Sokoto basin; the depth increases towards the west to a maximum of 390 m near the frontier between Nigeria and Niger. The depth of the water below ground level ranges from 2 to 54 m.

2. Chad basin

This basin covers an area of about 130,000 km² in the north-east of Nigeria. It includes the whole of Borno State and part of Bauchi and Kano; it has 53,000 km² of artesian aquifers.

The Chad formation consists mainly of non-consolidated fluvial and lacustral sands, together with silts and clays which were probably deposited during the Pliocene-Pleistocene era. The sequence includes intercalations of large lenses of grey plastic clay which can put the aquifers under pressure, i.e. create artesian conditions in some parts of the basin. Three main aquifers have been identified to the east (Borno State): the "upper", the "middle" and the "lower".

a) "Upper" aquifer. This aquifer is located at 30 to 100 m below ground level at Maiduguri. The depth to ground water varies in this zone; it is close to zero in the Chad area and about 75 m near Maiduguri. It is generally less along the river and fossil valleys.

b) "Middle" aquifer. This aquifer of the Chad formation has been identified over an area of almost 30,000 km² in the eastern part of the Chad basin. This is the area which has been most intensively studied and exploited both for urban water supplies and for irrigation.

The depth from ground level to the top of the aquifer ranges from 230 m around Maiduguri in the north-east to 350 m near Lake Chad. The thickness of about 43 m increases rapidly towards the north. A thickness of 98 m has been recorded at some points.

The head ranges from zero at Maiduguri to 18.3 m below ground level near the lake; the free flow ranges from 1.2 m³/h for a head of 5.5 m to 12 m³/h for a head of 15 m.

c) "Lower" aquifer. This aquifer consists of 105 m of medium and coarse sands and clays at a depth of 425 to 530 m. It is intensively exploited in the Maiduguri region.

3. Bénoué valley

The Bénoué basin runs north-east/south-east from the Cameroon frontier to the confluence of the Bénoué with the Niger.

It consists mainly of Cretaceous sediments and covers a vast area in the states of Banchi, Borno, Gongola and the Plateau. The valley, which is commonly and appropriately known as the "Benoue trench", covers an area of 80,000 km³, including the valley of the Gongola. In comparison with other regions of the country there has so far been little ground-water exploration and exploitation in this region. The reason for this is that the aquifers, in particular in the Gongola basin, have only average yields and the potential for ground-water exploitation is very small. Most of the aquifers are unconfined. However, artesian conditions are found in the Cretaceous formation in the Yola-Numan area.

4. Middle basin of the Niger

This basin covers an area of 37,000 km²; the dominant feature in the east is the river Niger which crosses this part of the country from west to east. Cretaceous sediments of Nubian sandstones predominate here. There are many springs. Artesian conditions with low heads have been found near Pategi.

5. Low-lying sedimentary terrain in the western littoral area

This area is bounded in the south by the coastal alluviums and terminates in the north at the edge of the crystalline basement rock, covering an area of about 38,000 km²; it runs through Abeokuta and to the north of Ijebu Ode (Ogun State) and to the north of Ore (Ondo State) as far as the western banks of the Niger near Agenebode (Bendel State).

The area consists of Tertiary and Cretaceous sediments with vast alluvial deposits along the main watercourses, which run north to south. The thickness of the alluvial deposits is variable but it can be as much as 15 m. These deposits are up to 8-10 km wide in the flood plains.

The free aquifer is usually found at a depth of 0 to 20 m. A free aquifer is also found in the areas where the other sediments outcrop, but artesian conditions may occur towards the south in the direction of slope of the three formations (Ilaro, Abeokuta and Ewekoro). The Ilaro formation has the best and most heavily exploited aquifer. The Ewekoro formation consists mainly of argillaceous limestones and schists and its yield is small. The Abeokuta formation contains clays but also considerable amounts of sand and silt.

6. Low-lying sedimentary terrain in the eastern littoral area

This area is the eastern equivalent of the area described above; it has been combined with that area into a single "hydrogeological province" with an area of 65,000 km² running through the states of the rivers Imo and Cross. It consists mainly of sandy sediments, generally with high porosity. The ground water is found at a depth of 15 m or less to 30 m.

7. Anambra basin

This basin is shaped like a mushroom and lies east of the Niger, mainly in Anambra State between the east bank of the river and the meridian of Enugu and between the Idah-Ankpa plateau in Bēnouē State and roughly the latitude of Onitsha in the south. It consists mainly of Cretaceous sediments and the main aquifer is found in false-bedded sandstones; the aquifers are unconfined in the north and become steadily artesian towards the south. The depth of the static water level ranges from 60 to 150 m.

III. EXPLOITATION OF GROUND WATER

The bodies mentioned above are responsible for the exploitation of ground water. The Federal Department of Water Resources in particular has a very comprehensive training programme for its staff.

Local water-drilling companies and branches of foreign companies operating in Nigeria are more numerous than elsewhere in Africa, and some of them have a very large range of equipment. The most commonly used drilling rigs are of United States (Ingersoll-Rand) or Swedish (Atlas Copco) manufacture.

The ground-water requirements differ greatly, from those of urban and rural communities to those of the industries located mainly in urban centres such as Lagos, Warri, Port Harcourt, Maiduguri, Ilorin, Ondo, Kaduna, Bauchi and Sokoto. In the north ground water is widely used for irrigation to offset the decline in rainfall over the past ten years.

IV. PROBLEMS

The lack of control over the exploitation of ground water has serious consequences for the whole country. It has led to overexploitation of the resources in Borno State, where boreholes must now be drilled to great depths in order to reach the lower aquifer (described above under "Chad basin").

Another major problem is the increased salinity of the coastal aquifers caused by sea-water intrusion resulting from excessive and uncontrolled pumping. This phenomenon has been observed close to Lagos, at Mahin (Ondo State) and in some parts of the coastal zones of Bendel State and the River States.

Very serious consideration is now being given to the possibility of the artificial recharge of ground-water aquifers, especially in the areas affected by drought.

Like many other developing countries, Nigeria has very little hydrogeological information about vast areas of the country. Accordingly, test pumping in new boreholes cannot be used as a means of forecasting the long-term behaviour of the aquifer, even though it does indicate the safe yield for the moment. A yield which is abundant when the borehole is first tapped can decline if additional boreholes are brought into use without any control. The Chad basin in the area of Maiduguri is an example of this. Other regions of the country also have many exhausted and abandoned boreholes. This problem is connected with the problem of the operation and maintenance of the installations. Concerted efforts are being made to ensure that all activities affecting water resources, particularly ground water, are subject to uniform national legislation applicable in all the states. This will ensure, inter alia, that the exploitation of the country's water resources will be equitably distributed and rationally controlled.

V. CONCLUSION

The economic and social value of Nigeria's ground water is summed up in the following quotation from Peter Sutcliffe (1982): "Water constitutes a large part of the environment in which man lives and it has an enormous influence on the other elements of the environment. It is a heritage, a basic element of the planet on which we live, essential to life itself. Water must therefore be respected."

The economic and social importance of ground water in this part of the world is difficult to evaluate in general terms, for the cost of developing this resource varies according to lithology, depth, and type of equipment used. It should be given greater weight in the preparation of measures for the rational management of the country's water resources. The most important and urgent step is to adopt water legislation placing the exploitation of aquifers under strict control and ensuring uniform and proper management of water resources.

There are considerable possibilities for ground-water exploration and exploitation, in particular in the sedimentary zones which give high yields. Even in the places where the crystalline basement rock suboutcrops or lies at shallow depths studies are being made of the fracture zones of the bedrock or altered rock which can help to recharge the aquifers. Increased use is also being made of geophysical and remote-sensing methods in geological studies.

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NORTHERN REGION

Station	Basin	Area of catchment basin upstream of the station (km ²)	Flow (m ³ /s)			Storage Coefficient	Specific yield (m ³ /s/km ²)
			Maximum	Minimum	Mean		
Jebba	Niger	631,960	3,740	370	1,292	0.33	0.002
Wuya	Kaduna	65,527	4,738	3	523	0.13	0,009
Baro	Niger	730,380	6,822	332	1,947	0.29	0,003
Makurdi	Bénoué	304,325	14,627	200	2,982	0.20	0,010
Umu Aja	Bénoué	333,619	18,425	46	3,425	0.19	0,010
Lokoja	Niger	1,087,000	27,140	712	5,737	0.21	0,005
Shintaku	Niger	1,088,000	24,110	970	5,512	0.23	0,005
Idah	Niger	1,103,200	26,790	840	5,613	0.21	0,005