ST/TCD/5

Department of Technical Co-operation for Development
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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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CONTENTS

CONTENTS (continued)

Maps and figures

CONTENTS (continued)

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

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. Zahiri, 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.

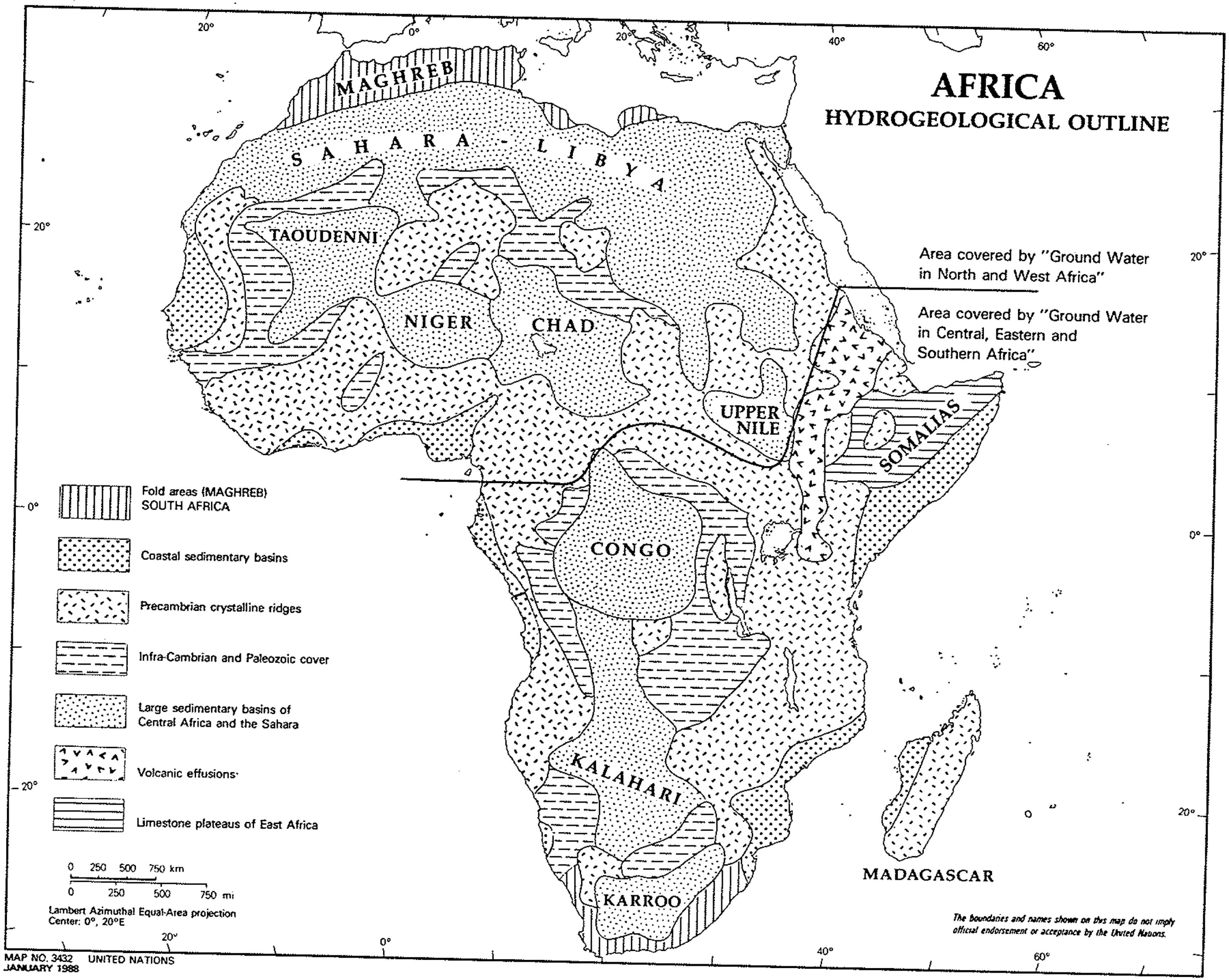
Use of a hyphen (-) between dates representing years, e.g., 1975-1978, signifies the full period involved, including the beginning and end years.

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
MAGHREB
SAHARA - LIBYA
TAOUDENNI
NIGER
CHAD
UPPER NILE
SOMALIAS
CONGO
KALAHARI
KARROO
MADAGASCAR
Area covered by "Ground Water in North and West Africa"
Area covered by "Ground Water in Central, Eastern and Southern Africa"
Fold areas (MAGHREB) SOUTH AFRICA
Coastal sedimentary basins
Precambrian crystalline ridges
Infra-Cambrian and Paleozoic cover
Large sedimentary basins of Central Africa and the Sahara
Volcanic effusions
Limestone plateaus of East Africa
0 250 500 750 km
0 250 500 750 mi
Lambert Azimuthal Equal-Area projection Center: 0°, 20°E
The boundaries and names shown on this map do not imply official endorsement or acceptance by the United Nations.
MAP NO. 3432 UNITED NATIONS
JANUARY 1988

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 km^2 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 crystaline 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 Aïr (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 Aïr 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 south-west 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 (1°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 evapotranspiration (cm)	Quotient (percentages)
Arid and hyper-arid zone (rainfall below 250 mm):			
In Salah (Sahara)	0.5	140	0.3
Biskra (southern Algeria)	18	133	
Moudjeria (Mauritania)	17	187	3
Coastal regions			
Nouadhibou (Mauritania)	4	116	4
Tarfaya (Morocco)	11	85	13
Zone with rainfall between 250 and 1,000 mm:			
Kayes (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 supper layers of the soil.

- A system of very heavy, brief and frequent shows 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) a/	Drawdown (m)
	Fluvial alluviums. 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
	Coastal or continental alluviums			
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	-
	Coastal sedimentary basins			
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-Cretacean

Terminal continental

Burkina Faso	Bobo Dioulasso	-	90
Mali	Gondo	-	50 to 100 (up to 300/day)
Mauritania	Trarza	Sandy intercalations	1 to 4
	Bennichab	Sandy intercalations	30
	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	Chardaia	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 m^3 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: 5×10^{-4} m^2/s. Flow: 4 m^3/h, with a downdraw of 10 m. Storage coefficient: 1.8×10^{-3};

Fissured dolomitic limestones of Atar (Mauritania). Flow: 70 m^3/h, with a downdraw 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 m^3/h and up to 250 m^3/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	Up to 0.2 to 0.5
		Brazer sandstone	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	0.3 to 1 per day
	Buen	Marly-sandy schists	0.5 to 10 per day

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	-	Birrimian 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 m^3/h is a good one for granites and granitogneiss; a rate of 1 m^3/h is considerable for mica schists and metamorphic schists. Better yields are obtained in the quartzy 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 overlays 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 seperate category; a few examples are given below:

Fissured dolerites in arid zones - Ayoun el Atrous (Mauritania): less than 0.1 m^3/h; non-fractured: 0.2 to 0.3 m^3/h;

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

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

Green rocks of Kongolikan (Burkina Faso), fractured: 3 m^3/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, rhettaras. 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.

SIERRA LEONE

Area; 71,740 km^2

Population: 3.47 million (United Nations estimate, 1983)

I. BACKGROUND

On the basis of the interpretation of aerial photography, Sierra Leone has been divided into 44 natural units, grouped in four main regions, each subdivided into a number of subregions.

Natural regions

Two-thirds of the country are occupied by plains and plateaus deeply incised by the hydrographic network, from which rise a number of hills and mountain chains and massifs. The plains and plateaus correspond to areas of ancient erosion and their characteristics are similar to those of the higher parts of the country. A feature of this landscape is the large number of narrow valleys covered with alluvial and colluvial deposits which are transformed into swamps by flooding in the west season. The coastal area has swamps and escarpments flanked by marine terraces.

The coastal plain covers 15 per cent of the country. It can be divided into four subregions.

1. The marine terraces (about 50 per cent of the coastal plain) line between 2 and 40 m above sea level and consist of unconsolidated material incised in all directions by small watercourses. There are also some higher terraces bordering the mountains of the peninsula close to Freetown, the capital. They are about 70 m high and are overlain by a lateritic crust and eroded by the beds of swift-flowing rivers.

2. The estuarial swamps lie at the foot of the marine terraces. They were formed by the deposition of silt and clay along the main rivers. Areas of mangroves are common in this region.

3. The alluvial plains lie at an altitude of up to 15 m above sea level in the area of fresh water which follows the courses of the little Scarcies and the Sewa. Here the grassy plains can be very large in extent.

4. The coastal zones lies along the edge of mountain chains of various ages and it can be up to 20 km wide, in Turner's Peninsula for example. In places these coastal chains have deflected the courses of large rivers such as the Wanji and Sewa, which converge in their lower courses and flow as a single stream for 50 km along the coast.

The lower plains cover some 43 per cent of the country and form its largest geographical region. The plains rise steadily from west (40 m) to east (up to 200 m). They are divided into two main subregions.

1. The "undulating plains" in the west, gently sloping terrain covered with a thick compact layer of lateritic and pyrolytic gravel which has a high iron content. The swampy areas are less common and narrower than in

the plains in the east. In their central part these plains are formed of hard sediments of the Rokel group. The swampy areas spread out into depressions called "bolis".

The eastern plains lie on a complex of granitic rocks. The slopes are gentle and the swamps narrow; isolated hills are found throughout the region. In the north near the escarpment the terrain is more broken with many low rocky hills.

2. The "Bolilands" extend for 50 km at their widest point. These are depressions and low terraces along the Rokel and the Mabole resting on Rokel sediments. The extensive floods of the rainy season are due to the lack of development of the hydrographic network, which causes the rivers and streams to overflow.

The plateaus lie on granitic rocks at an altitude of 300 to 700 m and cover 22 per cent of the country in the north-east and south-east. The variations in relief and the heavy erosion lend variety to the landscape. There are two main subregions.

1. The high rolling plains in the east. They resemble the interior plains and are dotted with low isolated hills.

2. The plains and hills of the western and southern parts of the plateaus. Narrow alluvial plains are found here adjacent to the courses of the main rivers. Altered granite suboutcrops in the north; this area has many rocky outcrops. The southern hills are covered with a thick layer of ferrous and lateritic gravel.

The hills and mountains form two subregions:

1. The hills of basic and ultrabasic rocks resistant to erosion. These chains of hills are generally quite high. The high iron and alluminium content of the rocks has produced crusts of laterite and compact ferralitic gravel. Chains of hills formed of these gravels are common at altitudes of 470 to 800 m in the Freetown peninsula and along the escarpment. The isolated mountains or mountain chains are covered with laterites and rise above the plateau and the interior plains.

2. The hills of acid granitic rocks, which rise to 1,000 m along the perimeter of the plateau. In the escarpment area the hills are eroded by the water courses.

Mt. Bintumani rises to 1,945 m in the Loma mountains; it consists of "young" granites and is capped with dolorites.

Climate

The climate is generally of the wet tropical type with six separate seasons: three dry and three wet.

First dry season: end-November/mid-December, with temperatures of 21°C to 32°C, west winds and high humidity: storms sometimes occur at night and a dense wet mist in the morning.

Cool dry season: mid-December/mid-February, with hot days (32°C) and cool nights (below 7°C in the north). In the afternoon the air is very dry, sometimes with a relative humidity of only 10 per cent. An east wind, the harmattan, blows constantly from the late morning until the afternoon. This wind can be strong, especially in the north and north-east of the country. In the coastal areas the nights are never cool. The minimum temperature rarely falls below 18°C and the harmattan rarely blows hard.

Dry hot season: mid-February to early April in the south-east and to mid-May in the north and some coastal areas, until the first storms come. The days and nights are hot and increasingly humid. The winds blow from the west. The springs dry up.

Early squalls: April-July, characterized by sudden storms from the east with strong winds, heavy rain, thunder and lightning. The squalls occur in the early evening in the south-east and increasingly later in the centre and west. The days are not and the nights cool after the squalls have passed.

Main rainy season: July-September, cloudy, humid and fairly cool. There is frequent heavy rainfall but little thunder; the sky is usually overcast. The winds blow from the west. This is the season of food crops.

Late squalls: mid-September/mid-November, similar to the season of early squalls, with gradually diminishing rainfall.

The coast has the heaviest rainfall (3,000 mm or more). There is another zone of heavy rainfall in the centre of the country. In the north the rainfall declines to 200 m or even less. December-January and March-April tend to be the coolest and hottest months respectively, with annual temperatures ranging from 24°C to 28°C. The seasonal variations are less marked on the coast than in the interior. Temperature ranges of 5°C to 7°C are common along the coast, while in the interior they can reach 15°C in the harmattan season.

Evapotranspiration

There is little reliable data on evapotranspiration. FAO has calculated the potential evapotranspiration figures by computer on the basis of data for season, latitude, rainfall, number of hours of sunshine a day and wind strength. The figures vary with latitude from 1,300 to 1,400 mm a year. They are higher in the dry seasons than in the rainy season. The heavy evapotranspiration and negligible rainfall in the dry seasons have a serious effect on the moisture content of the soil, particularly in the north. The soil has a moisture deficit from mid-January to the end of April in the north and from February to mid-March in the south. Crops cannot be grown during these periods unless the land is irrigated, and crops grown on bushes suffer from lack of water.

Surface water

The size, flow and annual discharge of the main river basin 1/ are given in the following table.

Basin	Area (km^2)	Flow Min	(m^3/s) Max	Annual discharge (mm)	Station	Year
Little Scarcies	12,870	5.1	1,801	1,787	Mange	1971
Seli/Rokel	10,620	1.7	416	782	Bumbuna	1971
		2.2	784	1,112	Bumbuna	1972
Pampana/Jong	7,511	3.1	389	1,275	Magburaka	1972
Sewn	14,140	12.4	771	1,028	Jaiama	1972
		418	601	860	Jaiama	1973
Moa	9,220	34.5	978	511	Kenema	1971

The river basins are fairly small. However, owing to the heavy rainfall the flows are very large, as is the discharge coefficient, which represents 20 to 40 per cent of the total annual rainfall.

The main rivers continue to flow during the dry season and overflow their banks in the rainy season.

Most of the watercourses have a "young" profile in their upper courses where they erode the basement rock. Accordingly, with the exception of the Upper Mongo, it is only in their lower reaches that alluvial plains of any size are found, the most important being those of the Scarcies and the Sewa. However, the flood waters in the rainy season are an obstacle to agricultural development in these plains. A striking feature of the country's river network is the large number of swampy areas in the upstream valleys. They are the result of regional orogenic movemen ts which blocked the valleys and allowed alluvial and colluvial material to accumulate. The resulting narrow flat-bottomed valleys are drained only by temporary slow-flowing watercourses which usually become swamps for six months of the year. These watercourses tend to flow more quickly in their lower reaches in the better drained alluvial valleys.

Another important feature is the "Bolilands" area described above. This complex of seasonal swamps seems to have resulted from the formation by silt deposits in early times of a common delta of the Mabole, Rokel and Pampana, which flowed into the ocean north of their present estuaries during a period when the level of the sea was higher. The hydrographic network draining the Bolilands is very caried, and the extent and depth of the floods in this region are a major obstacle to agricultural development.

Geology

Introduction

Most of the country lies on series of ancient folded crystalline rocks of varied lithology dating from the Archean epoch, a subdivision of the Precambrian

1/ Except for the Little Scarcies, the data concern only part of the basin.

period, which occurred more than 2,100 million years ago. They are overlain in discontinuity by the Rokel and Saionia Scarp groups, which vary in age from Upper Precambrian to Upper Ordovician, and by the much later sediments of the Bullom group of Tertiary to Recent age. Intense igneous activity occurred in the Mesozoic period before the deposition of the sediments of the Bullom group, giving birth to the Freetown gabbros and the associated silts and minor dykes.

Archean rocks

The Archean formation can be divided into two main units in Sierra Leone. The Liberian complex of granites and green rocks which runs north-south and the Kasila group which runs north-west/south-east.

The first unit includes a series of rocks with high iron and magnesium content of metamorphized to amphibolitic facies (Sula group) resting on a basement of quartzitic granite.

The degree of metamorphism in the basement rock tends to increase towards the edges of the Sula group, producing local zones of granulite (Mano-Moa formation). Younger granites penetrated the series after the period of most intense deformation which occurred about 2.7 million years ago at the edges of the Sula group.

The Kasila group consists of a series of granulites flanked by amphibolites which developed in an area of intense deformation and came to form the south-west edge of the Archean basement rock. In the early stages of the formation of the Kasila group a section split off eastwards, producing the schists of the Marampa group.

Rokel and Saionia Scarp groups

A long time elapsed between the deformation of the Archean basement rock and the formation of the River Rokel trench very late in the Precambrian period. Fossil-free sand-clay sediments were deposited in this trench (Rokel group), forming a band of rock thirty kilometres wide and 225 km long running south-south-east from the frontier with Guinea.

Volcanic episodes occurred from time to time in this epoch, producing lava and ash (Kasewe Hills formation).

The Saionia Scarp group rests in discontinuity on the Rokel group and includes a non-fossiliferous sequence of horizontal strata of sedimentary sandstones and schists, which are usually attributed to the Upper Ordovician period.

Igneous intrusions

Two periods of igneous activity occurred when the Gondwana continental mass divided into several units in the Upper Mesozoic period. The first period was contemporary with the first big fractures and was marked by the intrusion of the Freetown gabbros in the form of superimposed strata and series of silts, dolorites and dykes running parallel to the Atlantic coast.

The second period of igneous activity produced the intrusion of dykes and pipes of kimberlite about 90 million years ago. These intrusions are found mainly in the east of the country, particularly at Tongo and Yengema where they produced the diamond-bearing alluvial deposits of Sierra Leone.

Bullom Group

The band of Tertiary sediments running along the coastal zone can be up to 40 km wide. These formations rest in discontinuity on the Kasila group and the Freetown gabbros and include almost horizontal strata of gravel, sand and clay of marine, fluvial and estuarial origin. Laterites are found in places at the heart of relatively unconsolidated sediments, thus forming resistant outcrops, for example along the Bullom coastline north of Freetown.

Sediments of rivers and streams

Quaternary sands and gravels contemporary with the most recent Bullom deposits are found in all the country's valleys. They are themselves covered with recent alluvial and colluvial deposits in the valleys and along the estuaries of the coastal rivers. The alluvial deposits tend to be silty or argillaceous, while the colluvial deposits are mainly sandy. Both types helped to produce the relatively fertile formations which play an important role in the present and potential use of land in Sierra Leone.

II. GROUND-WATER RESOURCES

Government bodies

Freetown was the first town to be equipped with a water distribution network. Other towns followed. The Ministry of Public Works (Water Supply Division) was initially responsible for the planning (studies), construction, management and maintenance of these networks. This responsibility was subsequently transferred to the Ministry of Energy and Power established in 1984 with a Water Supply Division (WSD), to take charge of water supply and sanitation for towns (except Freetown) and rural areas. The WSD's Rural Water Supply Unit (RWSU) was organized with the help of the United Nations Development Programme in June 1980 to take charge of the monitoring and co-ordination of all water supply programmes in rural areas. Most of these programmes have been implemented at the local level through several integrated rural development projects carried out by the Ministry of Agriculture and Forestry with the assistance of the World Bank, the European Economic Community, the Government of the Federal Republic of Germany and the African Development Bank. In addition to assisting the RWSU, UNDP is helping with the implementation of a pilot construction programme as part of the programme in operation in the Koinadugu area, where new methods and materials are being tested and the supervisory and technical staff are receiving appropriate training. UNICEF is taking part in water quality monitoring operations and in health education activities under all the rural water supply programmes. The Division of Water and Land Resources of the Ministry of Agriculture has carried out very limited hydrogeological studies, but no systematic study of any size has been undertaken.

The World Bank is assisting with the institutional reorganization of the WSD. Initially the efforts will focus on the urban sector and will seek to reduce to a minimum the financial support required from the State budget by applying sales tariffs which will at least cover the operating and maintenance costs of the installations. Parliament is expected to produce appropriate legislation to give either the Ministry of Energy and Power or a new water distribution corporation (water authority) the legal powers to enforce with the necessary vigour the regulations and tariffs applicable to drinking water supplies and sanitation.

Background of ground-water research

As Sierra Leone has an abundance of surface water, ground water has so far received little attention. In March-April 1980 the UNDP/FAO project on the study of land resources sent a mission to train in the field a team consisting of a civil engineer, a geologist and an associate expert. They were taught to operate and maintain the electrical-resistivity geophysical prospecting equipment. The methods included electrical sounding and airborne prospecting; the measurements were interpreted with an eye to the identification and development of ground water.

Three geological zones, each with its specific hydrogeological problems, were chosen for this research: the Bullom series in the coastal plain, the Bolilands in the Rokel area and the granitic series which covers more than half the country. The study was carried out in the middle of the dry season, so that the team would encounter the most difficult conductivity conditions. The best period for prospecting is October to December after the rainy season when the soil is wet and is a good conductor. A total of 12 electrical soundings were made, including seven deep ones (AB = 800 or 1,000 m) and four shallow ones (AB = 140 or 400 m); five geological units were identified:

- A thin layer of lateritic crust (resistivity 1,200 - 1700 ohm/m);

- A conductive layer of clay and sand (20 - 30 ohm/m);

- A resistant layer of clay (80 - 400 ohm/m);

- A conductive deep layer of clay (25 - 30 ohm/m);

- The Precambrian basement rock at a depth of 70 to 150 m (900 ohm/m and higher).

The E5 sounding in the lateritic crust identified a thick layer (30 m) with a resistivity of 800 ohm/m, corresponding perhaps to a water-bearing sand stratum.

The lateritic crust may be 38 m thick at the E52 sounding.

The electrical soundings have furnished new information about the Bullom series, the Bolilands and the fracturation of the granite formations. The Bullom series consists mainly of clay but it contains a sand aquifer 30 to 40 m thick in its eastern part. The Precambrian basement rock is 250 m deep at Waterloo. Two soundings in the Bolilands penetrated thick clay strata in the first 30 to 40 m. The electrical soundings made in granite areas seem to indicate that the fractured and altered rock may be 30 to 40 m thick along the main faults. Boreholes drilled along these faults would probably yield several litres a second.

Aquifers

The geological and hydrogelogical knowledge of the country is very limited. But it is possible to give the following description of the aquifers on the basis of the available data.

In some places the lateritic crust is fairly thick and forms a ground-water aquifer which could perhaps be used, but only to supply small villages.

The alluvial deposits are usually very permeable. In the biggest valleys they can be sufficiently large to provide an adequate water supply for small towns or small irrigated areas. However, it remains to be established whether in Sierra Leone, where permanent surface water is abundant, ground water can compete economically with surface water in meeting the requirements for irrigation.

The Bullom series of Pleistocene age, especially the sand and clay strata constitutes the country's main aquifer. Problems of sea-water invasion may arise near the coast and along the estuaries.

The Rokel series, which includes argillaceous sandstones and schists and covers a large area of the Bolilands, is probably water-bearing but to an as yet unknown extent. The metamorphic schists of Marampa might contain small aquifers in the fracture zones. The altered and fractured zones of the granite basement rock are water-bearing.

III. EXPLOITATION OF GROUND WATER

Government bodies

The Water Supply Division of the Ministry of Energy and Power is the Government body responsible for ground-water development. However, in 1983 it still had no hydrogeological or geophysical equipment. At the end of the 1960s it had a cable-tool drilling rig and a local drilling team which operated in only two towns. In 1968 two boreholes were drilled at Lungi with a depth of 22.5 m and a diameter of 150 m. In 1970 a third hole was drilled to a depth of 41 m by the Ministry of Public Works (at the milestone 91 miles from Freetown). Owing to the lack of spare parts the drilling rig was scrapped and the team broken up. There are no private drilling companies in the country.

The Ministry of Energy and Power is planning a hydrogeological study for the whole country and was seeking financing for it in 1983.

Urban water supplies

The towns listed below use ground water for their drinking water supplies. In most cases they take it from dug wells.

Two towns are supplied from boreholes equipped with submersible pumps.

Location	Maximum yield (m^3/h)	Water use	Type of Well	Comments
Lungi international airport	22.6	Domestic and commercial	Borehole	Insufficient yield
Milestone 91	4.0	Domestic	Borehole	Yield declines considerably in dry season
Bonthe	50	Domestic	Dug well	Yield varies slightly throughout the year
York	13.5	Domestic	Dug well	Insufficient yield
Newton	62.5	Domestic and agricultural	Dug well	No supply for two months a year in dry season
Songo	50	Domestic	Dug well	
Kamiendor	16.2	Domestic	Dug well	Water level declines considerably in dry season
Songo	50	Domestic	Dug well	
Kamiendor	16.2	Domestic	Dug well	Water level declines considerably in dry season
Gbinti	13.5	Domestic	Dug well	New station (1982)
Mambolo	50	Domestic	Ground-water spring	Supply sufficient for the population
Jimmi	50	Domestic	Ground-water spring	Supply sufficient for the population

Rural water supplies

The water supplied to the inhabitants of rural areas can be classified as follows:

1. Treated water supplied by the WSD through distribution networks. Seven towns receive these supplies: Makali, Batkanu and Mateboi in the north, Pendembu and Buedu in the east, and Serabu and Jimmi Bagbo in the south.

2. Untreated water drawn from dug wells by diesel pumps. Installation with storage tank, main pipes and standpipes. Most of these installations are managed by the WSD, the others by the people themselves.

3. Untreated spring water in the high plateaus. Installations piping the water to villages three to five kilometres downhill. Distribution by standpipes, most of which are maintained by the local people. For example:

Town	District	Region
Jaima	Kono	East
Gbawandu	Kono	East
Tombudu	Kono	East
Kayima	Kono	East
Panguma	Kenema	East
Royeima	Bombali	North
Yiffin	Koinadugu	North
Mabonto	Tonkolili	North
Bimbuma	Tonkolili	North

4. Water drawn by bucket from protected wells. Pulleys are sometimes installed to facilitate the drawing of the water; most of the well-construction programmes are carried out under integrated rural development projects implemented by the Ministry of Agriculture and Forestry with the assistance of the World Bank, the European Economic Community and the African Development Bank. The intensification of farming activities resulting from the implementation of these projects might cause the contamination of ground water by chemical fertilizers and pesticides; hence the "drinking water supply" element in these projects. The well programmes are operating in the following areas:

Area	Organization	Financing	Number of wells
Koinadugu	UNDP and KIADP	UNDP and EEC	220
Kenema and Kono	EIADP	World Bank	300
Bombali/Tonkolili	NIADP and International Plan	International Plan	700
Moyamba	CARE/MIRDP	ADB/CARE	225
Kambia	ILO/Danida	UNDP	14
Magbosi	MIADP	IFAD	300

A lined hand-dug well costs about US$ 4,000; this amount covers staff costs, depreciation of equipment and vehicles, spare parts, fuel and lubricants, and the cost of the equipment.

5. Water taken from unprotected wells, pools and watercourses. Most of the population is still supplied in this way.

Problems

Some of the water-supply systems described above have particular problems connected with the area and the type of system. In the case of dug wells, the recharge rate is very low, below 2 m^3/h for the most part. This is particularly true in areas of clay aquifers which have a very slow recharge rate. There may be villages close to the coast where the dug wells are affected by sea-water intrusion. In the case of the old gravity systems, the main problems are the deterioration of the piping, inadequate supplies and lack of maintenance.

IV. CONCLUSION

Generally speaking, Sierra Leone has sufficient water resources to meet its needs in the immediate future. However, it does not have enough drinking water. Only two per cent of the rural population, which makes up 75 per cent of the total population, has access to water of acceptable quality; the rest of the rural population takes its water from rudimentary wells, watercourses and pools and is thus exposed to water-borne diseases with their familiar harmful social and economic consequences. It must nevertheless be stressed that in Sierra Leone the exploitation of water in rural areas is planned as part of integrated rural development programmes which involve the local people closely in environmental training activities. A water quality control programme is incorporated in the construction programme and great importance is attached to sanitation; sanitation construction works are undertaken with the participation of the local people. Lastly, a maintenance programme is established.

It is envisaged that these water-supply activities in rural areas will be developed further over the next five years, in particular with respect to ground-water research. A proposal has been prepared for this purpose; it includes deep ground-water research and the drilling of boreholes, 100 of which will be equipped with hand pumps.

In the case of urban water supplies, the World Bank has proposed the establishment of a single distribution corporation for Freetown and 75 urban centres. The Guma Valley Water Company is to be gradually strengthened over three or four years and will eventually become the Sierra Leone Water Company (SLWC); the following measures will first have to be taken:

- Improvement of water supply management methods and of sanitation throughout the country except for Freetown;

- Study of ways of improving the qualifications of the staff, followed by their redeployment;

- Identification of means of covering costs and establishing realistic tariffs with a view to creating a viable financial situation and releasing the Government from the need to make grants.

If this transformation is to be accomplished, foreign technical assistance will be needed in the following areas: organization of services, vocational training of staff, preparation of legislation and regulations, repair of networks, and supply of essential equipment, including vehicles.

V. REFERENCES

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