ST/TCD/5

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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. 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.

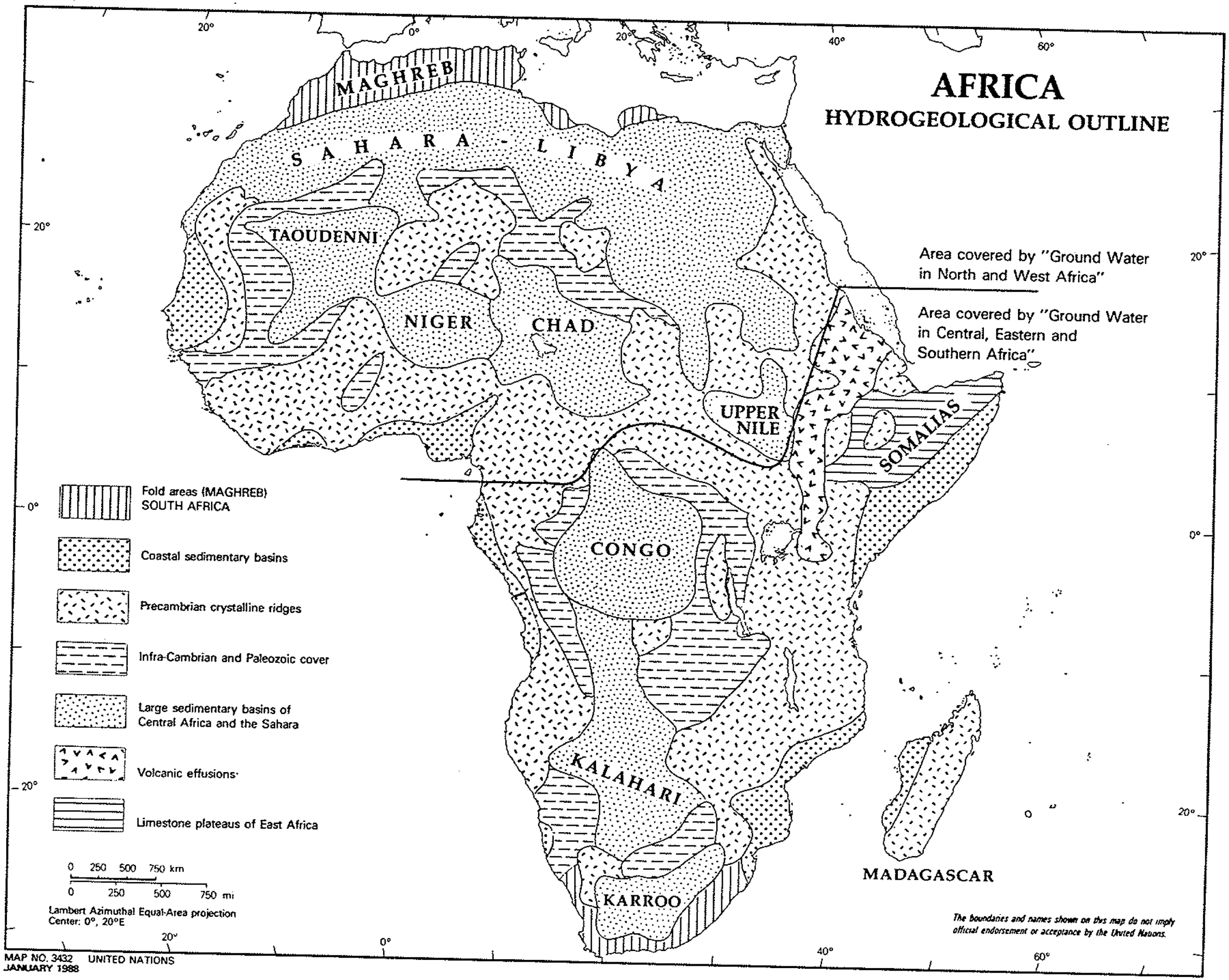
Use of a hyphen (-) between dates representing years, e.g., 1975-1978, signifies the full period involved, including the beginning and end years.

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
Area covered by "Ground Water in North and West Africa"
Area covered by "Ground Water in Central, Eastern and Southern Africa"
MAGHREB
SAHARA - LIBYA
TAOUDENNI
NIGER
CHAD
UPPER NILE
SOMALIAS
CONGO
KALAHARI
KARROO
MADAGASCAR
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.

GUINEA-BISSAU

Area: 36,125 km^2

Population: 860,000 (United Nations estimate, 1983)

I. BACKGROUND

Guinea-Bissau is situated on the west coast of Africa between Guinea and Senegal. In addition to its mainland territory it has the Bijagos archipelago which lies just offshore. The archipelago consists of 40 islands of which only 20 are inhabited. The country has 160 km of coastline and 705 km of land frontier. Its maximum length is 330 km and its maximum width 193 km. Not counting the tidal mangrove zones, the permanent _terra firma_ is estimated at 28,000 km^2.

Natural regions

Most of the country is flat and low-lying with a wealth of marshes and mangrove swamps along the coast; the maximum altitude is 40 metres. To the south-east near the frontier with Guinea there are some small hills, a prolongation of the Fouta Djallon massif. Lateritic cuirasses and clay-sand formations cover much of the surface. From the morphological standpoint the country can be divided into five main zones: the Boe uplands, the Bafata plateau, the Gabu peneplain, the transition zones (Oio and Forrea) and the coastal plains.

The Boe uplands are flat-topped hills forming small plateaus separated by valleys which are mostly open and covered with ancient lateritic, ferralitic or aluminous cuirasses which produce disintegrated and conglomeratic laterites in the valleys. The escarpment of the Bafata plateau dominates the alluvial plains which are gouged by the meandering lower courses of the Geba and the Corubal.

The Gabu peneplain in the north-east has a slightly undulating relief with gentle slopes and a loose and poorly defined hydrographic system.

The coastal plains are broad in the west and south of the country; they correspond to a band of Mesozoic-Cenozoic formations. They are mostly very low but do have a large number of small elongated ridges.

The transition zones in the regions in which the tidal influence is very small or non-existent form a link between the coastal plains and the Boe uplands, the Bafata plateau and the Gabu peneplain.

Climate

Guinea-Bissau has a wet tropical climate with two distinct seasons: a rainy season from April to October and a dry season from November to March. The rainy season is caused by the moist Atlantic winds which blow from the south-west and west towards the Saharan and sub-Saharan zones. The dry season is caused by the dry winds blowing mostly from the mainland in the opposite direction.

The country can be divided into two climatic regions: one is of the tropical Sudanese type with very low rainfall, wide thermal ranges and high humidity in the rainy season and low humidity in the dry season; the other is of the sub-Guinean or coastal type with higher rainfall, smaller thermal ranges and high humidity throughout the year. The first region corresponds to the western part of the country, the second to the wide coastal band.

There is little vegetation but it is very varied: forest, rain forest in the wet areas, scrub savannah and mangroves.

Surface water

The country is crossed by large rivers which rise in Senegal or Guinea. It also has a number of coastal rivers; these are, from north to south, the Cacheu, Mansoa, Geba-Corubal, Grande de Buba, Tombali, Cumbija and Cacine. Even the smallest of these rivers have wide deep estuaries. They are navigable and provide means of communication with the interior of the country; the main urban areas are situated on their banks. They are tidal as far as 100 km inland. Even the Geba has a tidal wave.

There are 43 climatological stations and three stations measuring the flow rate: two on the Curubal and one on the Cumbija.

The mean annual flow rate on the Corubal over a nine-year period was 14,410 hm^3 (maximum 23,710 hm^3; minimum 6,110 hm^3).

In 1979/80 the minimum flow was 6 m^3/s and the maximum 1,100 m^3/s; these figures indicate the wide regional variation of flow rates in the dry and rainy seasons. The water quality is equally varied.

II. GEOLOGY

Guinea-Bissau lies between the Fouta Djallon massif, of uncertain Paleozoic age, and the Mesozoic-Cenozoic Senegal basin. It can be roughly divided into two geological units by a line starting in the north in the Pirada region and passing through Contuboel, Bambadinca and Buba before deviating towards Gadamel and the frontier with Guinea. Paleozoic formations predominate to the east of this line.

To the west of the line most of the terrain consists of Mesozoic-Cenozoic sedimentary formations. These are the most important formations from the hydrogeological stanpoint; all the deep boreholes are found in these formations.

The ancient formations have very few outcrops, for they lie below fairly thick surface formations and are not very fossiliferous. They have been dated by analogy with similar and better-known formations in neighbouring countries and from samples obtained during oil-prospecting drilling operations.

The same can be said of the Mesozoic sedimentary series, even though fewer data have been obtained from the oil-drilling sites.

The oldest formations are Cambrian and are found in the north-east. They lie on microgranites of the metamorphic complex, then the multi-coloured argilites of Pirada and Canquelifa overlain by the schist-sandstones of Cantari, which are themselves overlain by purplish feldspathic sandstones (Caium sandstones) of Upper Cambrian age. As a rule, the Cambrian formations constitute very poor aquifers. Small local aquifers can be found in the alteration zones and in particular in the more permeable sandstone zones. Drilling is difficult and the productivity low owing to the great lateral and vertical variations in permeability. The Cambrian formation is followed by the mainly sandstone Ordovician series (Gabu sandstone) identified at Canjufa, Sonaco, Gabu, Canjadude and Cabuca. Most of this series is thick and steeply inclined (up to 48°). At the base of the series the sandstone is white and coarse-grained with some feldspar and muscovite crystals. It is 170 m thick. These very compact sandstone strata are overlain by less compact and sandier strata of considerable thickness covered by fine-grained sandstone, quartzitic in places, which forms the top of the series, with thicknesses of 10 to 30 m.

Little is known about the ground water in this formation except for the wells in the Canjadude region, where the compactness of the sandstone makes drilling difficult and unproductive. In this region the thick alluviums of the Nharasse river give the best results, although the recharge is uneven and the yield intermittent.

The Silurian formation is represented by the Buba sandstones of Gothlandian age. It has been reached by boreholes at Buba, Guilege, Gadamael and Sangonha and by several oil drillings. It is found in the north-east in the same areas as the Ordovician formations and in the south-east as well. The drillings carried out in this area have penetrated very compact black or carbonaceous schists with fine sandstone intercalations at the top and some doloritic layers. At Có and Safim the formations are mostly metamorphic with micaceous sericitic and pyritic schists interbedded with dolorite. The Silurian formations in the north-east are of similar facies, with major or minor indications of metamorphism and with fine clay sandstones at the top forming a transition zone with the Lower Devonian formation. These formations are very poor aquifers. The positive results of the drilling at Buba and Sangonha are no doubt due to the collection of water in the sand-sandstone strata of the Maestrichtian base which overlie the Silurian sandstone in discontinuity.

The Devonian formation occupies a vast area in the east close to the frontier with Guinea. It forms a large north-west/south-east syncline. The base consists of a sandstone series (Cusselinta sandstone) of Lower Devonian age overlain by a thick schist series (Bafatá schist) of Middle-Upper Devonian age. The Cusselinta sandstone identified in outcrops in certain water courses (Geba, Curubal. etc.) is mostly compact feldspathic and micaceous with pink and brown tints. The Bafatá schists are argillaceous and pale or pink in colour with intercalations of fine-grained quartz sandstone. The Devonian sandstone has been reached at a depth of 20 m during water-prospecting drilling operations in the Nhabijocs plain (Bombadinca); it is much darker and more compact than the neighbouring altered rocks. The alteration zone in the schists has proved completely barren.

The post-Paleozoic series, i.e. the Mesozoic sediments of the Senegal subsidence basin, rests on the Paleozoic formation, whereas in Senegal it is also found above the metamorphic basement rock. Little is known in Guinea-Bissau about the "intercalated continental" of Senegal at the end of which the Mesozoic transgression occurred, but it has been identified at S. Domingos, Có and Safim. In the north-east it consists mainly of schists with some sandstone intercalations and limestone layers in places. In the centre of the country it occurs in clearly continental series which also consist of schists with intercalations of fine dandstone. The series is 120 m thick at Safim and 330 m at S. Domingos.

Nothing is known of the hydrogeology of these formations owing to their great depth (800-1,800 m). It is assumed that the sandstones are important aquifers, as they are in Senegal.

The Middle and Upper Cretaceous formation is of lagoonal or coastal facies, as in Senegal, and of great thickness (1,360 m at S. Domingos and 600 m at Safim). The base consists of schists with some limestone-dolomitic intercalations; it is overlain by dark shales streaked with sand and terminates in a thick sandy layer of Maestrichtian age.

The Maestrichtian formation is certainly an aquifer of major importance in Guinea-Bissau. At the edge of the Paleozoic formations it forms a wide band of sandstone outcrops with varied granulometry and containing layers of schist at the base with very fine argillaceous intercalations throughout the series. In the south, where it rests in discontinuity on the Silurian formation, the sandy layers lead to compact argillaceous sandstones of average or coarse granulometry. It is up to 490 m thick in the north-west (S. Domingos) and 540 m in the west (Cangongue).

The Eocene-Paleocene formation of more marine facies is represented by sandier marl-limestone formations with dolomitic intercalations. It forms a central strip running north to south, bounded in the south by the right bank of the Geba. There are occasional outcrops close to Bissau and the formation has been penetrated by a number of boreholes for groundwater reconnaissance and exploitation. It is an important aquifer and is exploited by deep boreholes.

The continental terminal formation is clearly lagoonal at the base and continental at the top; it includes the post-Eocene and Quaternary series. The lower formations of Oligocene age consist, from bottom to top, of fine-grained sand-sandstone layers, mostly argillaceous with clays at the top. Above this is found a small limestone-marl bank, sandy in places, of marine Miocene age, which is covered by more recent clays and argillaceous sands.

The main aquifers in this series are provided by the Oligocene sand and Miocene limestone strata.

The most recent series are represented by alluviums, clays, agrillaceous sands, coastal dunes and cars, lateritic formations, etc.

Tectonics

The topography is unvaried, and the thickness and regularity of the sedimentary formations indicate little tectonic activity. Series of folds running east/west and fault systems running north-north-east/south-south-west have been identified on the north slope of the Bafatã syncline which runs mainly north-west/south/east and occupies a large part of the east of the province. On the southern slope, however, the tectonics is much less marked.

III. MAINLAND HYDROGEOLOGY

As is the case in neighbouring countries and as the situation outlined above indicates, the mainland territory contains only a small number of geological formations providing constant and fairly extensive productive aquifers with relatively uniform hydrogeological characteristics. Such aquifers are usually found in soft sandstones and sandy or fissured limestones. Continuous aquifers are rarely found in other formations. The granitic and quartzitic rocks are very compact and contain only low-yield intermittent and local aquifers of very variable permeability in the alteration layers. The schists are usually clogged with clay deposits. In these formations water is found only in the porous lateritic cuirasses which may overlie the rock. The physical and chemical quality of the water is better at depth and close to the recharge zones.

Recharge is effected by infiltration of water migrating from the higher Paleozoic zones in the Mesozoic formations at their edge. Most of the tapped water is thought to be of fossil origin. The present recharge compensates for the natural drainage of the aquifer systems.

The isohyet map shows that the coastal zone receives the highest rainfall, owing to the proximity of the ocean. Along this zone the rainfall increases from north to south (2,600 mm/year) with the maximum at Catió-Cacine-Bedanda. In the interior the rainfall declines to 1,500 mm/year.

The distribution of the annual rainfall also varies according to place. Rain falls on 130 days in the north, on 150-160 days at the coast in the west, and on 170 days in the south. The average annual temperatures are fairly high, in the order of 26-27°C; the thermal ranges are highest in the interior: 13°C (maximum 32.8°C; minimum 19.7°C); they are lower on the coast: Bissau 9.8°C (maximum 31.6°C;). At Catió in the Bijagos archipelago the figures are even lower: Bubaque 7.7°C (maximum 30°C; minimum 22.2°C).

The evapotranspiration is very high and prevents any great infiltration of rainwater to recharge the aquifers. The transpiration is higher than the evaporation in the coastal zones where the rainfall is heavy and the forest and rain forest are found. The opposite is the case in the interior where savannah type vegetation predominates.

The infiltration potential in the coastal zone is not really very great.

The empirical formula of L. Turc, which gives a calculated value for real evapotranspiration (Re) in terms of rainfall (R) and temperature (T), has been applied to five stations and gives the following values (mm):

	R	Re	Rainfall infiltration
Nova Lamego	1,500	1,400	100
Catió (south)	2,600	1,600	1,000

In the country's interior, where most of the formations have low permeability and the aquifers are small and discontinuous, the actual stocks are smaller than those indicated in the table above. Other factors come into play, such as the drainage of the aquifers towards the low-lying areas and the intense exploitation in the dry season. In fact, the Gabu plain is the part of the country least well provided with ground water. In contrast, in the southern part of the coastal zones the effective infiltration can reach levels which offset the decline in the stocks of the surface aquifers in the dry season. However, this infiltration is probably smaller than the calculated value.

Furthermore, the sunshine rate is very high (62 per cent), which indicates that the evaporation potential of the atmosphere is independent of the relative humidity; it is therefore very high.

In conclusion, the recharge of aquifers in Guinea-Bissau is favoured by the rainfall pattern but impeded by the topographical and geological conditions (stratigraphy and lithology) and the amount of evapotranspiration. The recharge is generally insufficient.

However, there are enormous stocks of fossil water in the Mesozoic-Cenozoic formations of the Senegal basin which would not be affected in the short term by intense exploitation.

In contrast, excessive exploitation of the small resources of the surface aquifers could lead to their complete exhaustion in the short term.

Description of the aquifers

The continuity of the Mesozoic-Cenozoic aquifers means that the results obtained at a few sites can generally be extrapolated to the full extent of these formations. Where ground-water resources are concerned, the country can be divided into two zones separated by the eastern limit of the Mesozoic-Cenozoic Senegal basin. Continuous and extensive aquifers are found in the western sedimentary zone. The eastern zone, with its Paleozoic and Ancient series, has only local aquifers of relatively small extent and yield. It includes the highest areas with least rainfall and greatest evaporation. Accordingly, the surface aquifers dry up in the dry season. Boreholes must be drilled with great care and preceded by geophysical prospecting; otherwise the risk of failure becomes very large. The fault system which had seemed promising, especially in the north of the Bafatá syncline, proved barren. These faults appear, in fact, to constitute an impermeable barrier. The water has a moderate or low mineral content.

The Mesozoic-Cenozoic strata slope north-west and west and increase in thickness in those directions, acquiring an increasingly marked marine facies. The main aquifers are found in the Maestrichtian sands, the sandy-marly limestones of Eocene-Paleocene age, and the fine Oligocene sands which contain some strata with permeable horizons - limestones, argillaceous sand, laterite - in Miocene and recent formations.

Three main aquifers have been identified, from bottom to top: Maestrichtian aquifer (mainly sands); intermediate Oligocene-Paleocene aquifer (sand in the Oligocene formation and limestone in the Eocene-Paleocene); and "surface" aquifer(s) (argillaceous sand and laterite), usually unconfined.

The Maestrichtian formations have been explored and exploited most intensively and at the shallowest depth close to the elongated zone where they outcrop (central and southern regions of the country) and at the sites of a number of deeper wells installed to obtain large yields at Bissau and Farim. The maximum tapping depths of 195-260 m have been achieved on the island of Bissau.

The map annexed to this paper indicates the location of the boreholes and the specific yields (l/s/m of downdraw) and the available yields, which are fairly high. The productivity declines in the direction of the Silurian formations owing to their lesser depth and the transition from sand to compact sandstone.

The attached diagrammatic map shows the isobaths of the top of the Maestrichtian formation and gives an idea of the depths to be drilled if this formation is to be exploited. This top layer deepens regularly and continuously towards the north-west and west. Towards the north-west it cannot be reached at less than 500 m below zero. In contrast, to the east of the 550 m contour line running north-north-west and passing through Quinhamel, Binar, Binta and Dungal, it can be reached at less than 200 m.

<u>The Maestrichtian aquifer</u> is for the most part confined, except at rare points where it outcrops. This artesian effect produces water spouts (of less than a metre) at only two points - Farim and Mansoa - with static water levels of +6m and +7m.

Water levels above ground level are found at the majority of the other installations in the centre and west of the country. However, the water level is below ground level in the southern part of the coastal zone, probably owing to the lower vertical permeability of the formations and their consequent smaller recharge. The highest levels are found at installations located roughly on the Farim-Mansaba-Mansoa line, and this might indicate the proximity of a more favourable recharge zone in the fairly thick shallow-lying Paleocene limestone resting on Maestrichtian sands.

The aquifer's main direction of flow would seem to be towards the north-west and west; this is confirmed by the chemical composition of the water.

The Maestrichtian water has a low mineral content (less than 500 ppm of dry residue) in the centre of the country. In the south (Bolama) the water contains 1,500 ppm, the maximum allowable under WHO drinking-water standards. The low salinity of the Maestrichtian aquifer even close to the coast indicates that the influence of sea water is practically non-existent, except at some points such as Bedanda (4,000 ppm of chlorides). However, the concentrations are low at Catió and Cufar, which have dry residues of 235 and 370 ppm respectively.

Lastly, the Maestrichtian water of mainly bicarbonate and calcium sulphate facies can be classified as very soft to soft, except in some coastal areas. The sulphate content is low, except at a few points (Bolama and Sul regions).

Some test pumping has been carried out in the Maestrichtian aquifer, with observation of the downdraw and recovery, in single wells or in coupled wells, with one serving as piezometer.

The levels are affected by the tide close to the estuaries or ocean. The water must therefore be exploited with care.

On the basis of lithological information and the permeability data obtained, a diagrammatic map has been prepared in which the country is divided into three areas fairly suitable for drilling operations:

- Extreme south with K below 10^{-6} m/s in argillaceous sandstone with low specific yields (0.2 to 0.3 l/s/m), and high mineral content owing to the slow flow rate of the ground water;

- Centre south with K of about 10^{-4} m/s. A more favourable elongated zone has been identified in this region: Buba-Empada-Catió. This formation consists of fine to coarse sands. This zone is favoured by the aquifer's direction of flow;

- To the north of this area with K of about 10^{-5} m/s. The aquifer is less favourable owing to the presence of layers of clay and fine sand.

The Oligocene-Eocene-Paleocene aquifer is found in white sand-sandstones, usually of very fine granulometry, at the base of the Oligocene formation and in the Eocene-Paleocene limestone-sandstone formations, which are not separated by any sizeable impermeable layers. Accordingly, the whole unit behaves as a single aquifer; this is confirmed by the static water levels and the chemistry of the water.

In the north-east of the country the present installations penetrate no further than the shallowest Oligocene strata, which are sufficiently thick and productive. Elsewhere in the country they generally reach and tap the limestone series. The aquifer is 316 m thick at S. Domingos and 274 m at Cagongue, with its top at a depth of 177 m. It ought therefore to be possible to exploit the Oligocene-Paleocene aquifer west of a line running through Cumere-Mansoa-Mansaba-Caujambari and terminating at Cuntima. To the east of this area the series is either of insufficient thickness or does not occur. Unlike the Maestrichtian aquifer, the intermediate aquifer has a low yield. Only the sand-sandstone Oligocene formations, when they are sufficiently thick, can furnish high specific and available yields; this is easily explained by the irregularity of the facies of the limestone series both vertically and laterally in comparison with the high permeability of the Oligocene sands. Lastly, the yields of the boreholes in the Oligocene-Eocene-Paleocene aquifer are sufficient for the country's needs in most of the regions. The aquifer is mostly continuous, of vast extent and confined.

The aquifer's piezometric level is deeper than that of the Maestrichtian aquifer, confirming that there is no communication between the two; the great differences in permeability at various points in the limestone are matched by very marked differences between the aquifers' water levels and yields.

The highest mineral content (1,000 ppm) and the highest chloride content are found in the north-west coastal zone. These levels increase from south-east to north-west but they do not reach the maximums set by WHO. The sulphate content is higher than in the Maestrichtian aquifer, as is the hardness of the water.

In conclusion, although the intermediate aquifer is extensive and continuous, its stocks are much smaller than those of the Maestrichtian aquifer and it has less favourable hydrological characteristics and water of much poorer quality.

The upper shallow aquifer has fairly small stocks and is subject to very marked annual fluctuations which are directly linked to rainfall and evapotranspiration. Owing to its accessibility, it is intensely exploited throughout the country by innumerable wells of various depths - usually shallow, but deeper in the north-west and west where the series is thickest. This upper aquifer is the equivalent of the "continental terminal" aquifer of West Africa: it behaves in a similar manner.

Recent sand-clay formations, usually of lateritic littoral facies and with small banks of Miocene limestone, are found over most of the country's central and western regions. The north of the country has permeable sand-clay series attributed to the continental Miocene-Pliocene era. Their yield is usually quite low and varies from place to place and season to season. The water is subject to pollution and is often heavily mineralized with a high iron content; it is very aggressive.

IV. AQUIFER OF BISSAU ISLAND

Bissau island, where the capital is located, is the part of the country for which the largest amount of ground-water data is available - a consequence of the large and rapidly growing requirements of the densely populated metropolitan zone. The deep aquifers must be tapped, for the shallow-lying surface water is of only average or poor quality. An organized study must therefore be made of the depths to be reached and of the possible yields. In the past a large percentage of the boreholes proved barren or gave inadequate yields.

The island is fairly flat. The coasts are low, as is most of the land, which has many swampy areas. There is an abundance of recent alluviums consisting mainly of fine elements (silt and mud) called "bolanhas" where rice is grown in the traditional manner.

The land below 10 m in altitude ("terras baixas") is flat with alluvial layers situated between two and five metres above sea level. Only the highest areas, which are never above 40 m in altitude (with an average of 20 to 25 m), are inhabitated. The climate is wet with two distinct seasons.

Geology

The geology is known from deep-level oil and water drilling. The whole of the sedimentary series slopes to the north-west and west, more steeply as the geological age increases. The stratigraphic chart is as follows:

Quaternary: silt, mud, laterite formations (low land);

Miocene: (upland cover) mainly clays and fine argillaceous sands, with various amounts of laterite at the top of the series; marly and sandy limestone banks at the base; total thickness: 3 to 50 m;

Oligocene: clay in the upper part, fine sands and argillaceous or marly sandstone at the base; thickness: 40 to 50 m;

Eocene-Paleocene: sandy or compact limestones, with intercallations of sand and clay, and dolomitic and sandy intercalations in the lower part; thickness: 70 to 100 m;

Maestrichtian: less marked marine facies. The whole series consists of formations of fine or coarse sand with clay-marl intercalations in the upper part, and intercallations of schist in the lower part; thickness: 250 to 300 m;

Middle-Lower Cretaceous: thick schist and sand series with sandstone intercalations. Indications of metamorphism at the base; thickness: 400 m;

Paleozoic: the base of the sedimentary series includes sericitic metamorphic schists with sandstone-quartzitic intercalations and some doloritic banks of Silenian age.

Hydrogeology

The aquifer is located under the laterite zone; it is drained by the most permeable strata of the "terras baixas" at an altitude of about 10 m. Its lower limit is the marls and clays of the Miocene base and the clays of the top of the Oligocene formation. The aquifer is subject to major fluctuations due to rainfall and evapotranspiration. It can be reached at depths of 10 to 20 m in the "uplands".

These formations are very heterogeneous. It is not therefore possible to apply rigid criteria with respect to the drilling of boreholes - except in the vicinity of springs. The yield of the waterpoints exploited by hand pumps (portable) is usually below 5 m^3/h.

The Oligocene aquifer found in the sand-sandstones is mostly confined. It forms a single unit with the aquifer in the Eocene-Paleocene marly limestones.

This aquifer is very irregular in its yield, owing mainly to its lateral and vertical variations, the permeability of the formations, the thinness of the strata and the insufficient recharge.

Drilling operations are difficult owing to the very fine granulometry of the sands and sandstones and the aggressiveness of the water. The Oligocene aquifers cause blocking of the filters and rapid deterioration of the pumping equipment at most of the tapping sites on Bissau.

The intermediate aquifer on the island has a static water level of four to six metres below sea level. The available yields rarely exceed 15 m^3/h with large drawdowns and therefore very low specific yields. The top of the Oligocene formation can be reached at depths of between 30 and 60 m, and the most permeable layers lie at depths of 60 to 100 m. The Oligocene series lies above a limestone-sandstone and marl-limestone series (Eocene-Paleocene) in which permeable layers have been identified; they are irregularly distributed and more favourable and abundant in the middle and upper parts of the series, which are less marly.

As a rule the sandstones are very compact, but the limestones have a microfissure permeability; there are few fractures of any size. The marl-limestone series includes two distinct aquifer systems separated by very marly strata. The upper system corresponds to the Oligocene stratum, the lower is fed from the Maestrichtian stratum.

The intermediate aquifer in the Bissau region has a mineral content of 700-1,200 ppm. The water is neutral or slightly acid, ferrous or very hard (40^o to 70^o; it is of sulphate and calcium bicarbonate facies.

Both the increased salinity of the water and the low specific yields of most of the installations are due to the poor permeability of the formations.

The Bissau installations take almost all their water from the intermediate aquifer (Oligocene and part of the Eocene-Paleocene) and they discharged 10 to 40 m^3/h, with specific yields of around 0.1 to 0.6 l/s/m (an average of about 0.3 l/s/m).

Some deeper boreholes reach the base of the Paleocene formation and supply better quality water, part of which comes from the underlying Maestrichtian stratum. This water has a higher sodium content and is more neutral, with a hardness of only 2^o to 5^o.

The limestone aquifer is already overexploited by many uneconomical low-yield boreholes and it does not furnish sufficient water for Bissau. The underlying Maestrichtian sands must therefore be more intensively exploited. The first Maestrichtian boreholes confirm the hydrogeological importance of this series, which is well known in Senegal.

The Maestrichtian aquifer is totally confined, with its top located in the intermediate argillaceous-marly strata of the limestone series - thin and discontinuous layers which do not separate the aquifer. On Bissau the Maestrichtian aquifer is formed by sands of very varied granulometry and compactness. In the upper layers the clay intercalations are frequent and fine. The top of the series lies between 130 and 180 m below sea level. Boreholes which penetrate 50 m into the sands can discharge 50 to 150 m^3/h with a small drawdown and specific yields of five to seven l/s/m for a six-inch diameter hole. Larger yields could no doubt be obtained from deeper boreholes with larger diameters.

In contrast to the intermediate aquifer, the hydrostatic levels of the Maestrichtian aquifer are found at positive altitudes (+2m to +3m), which seems to indicate that the two aquifers are not in contact. The water is alkaline with a very low hardness (below 5^{o} in the Bissau region) and a low mineral content of about 300 mg/1, which is very uniform for all the wells. The main recharge zone appears to lie south-east of Bissau where the series is close to ground level.

All the data on the Maestrichtian aquifer seems to indicate that its stocks of water are considerable. However, the exploitation must be controlled and efficiently managed from both the technical and the economic standpoint.

The water levels are subject to periodic variations due to the movement of the tides. However, the chloride content of the water does not vary, indicating that the Maestrichtian formation is totally separated from the overlying series. This movement weakens and becomes more irregular towards the interior of the island.

Lastly, the behaviour and characteristics of the Bissau aquifer are similar to those found throughout the sedimentary basin in Guinea-Bissau.

Practical hydrogeological regional divisions

(Potential of aquifers)

Hydro-geolo-gical zone	Hydrogeological region (Corresponding administrative region)	Description of exploitable aquifer: Stage	Lithology	Aquifer area	Drilling (m)	Dynamic water level (m)	Available unit flow (rarely) (l/s)	Total mineral content (g/l)	Degree of knowledge (number of test holes)	Possible uses
Zone I	I-1-western	N_2-Q	sand	± cont.	25-35	15-20	1-2(5)	0.1	fairly good (17)	village water supply
	Cacheu, except east of Bigene and bula sector	N_1	limestone	cont.	50-100 (E>W)	25-35	1-2(5)	<0.5 south >0.5 north	good(16)	village water supply (if N_2-Q absent)
		P_3	sand	cont.	100-150 (E+W)	15-25	5-10 (20)	<1 S and N >1 centre	insuff.(11)	fairly big consumption esp. irrigation.
		P_1-2	limestone	cont.	150	about 20	up to 20	1	poor (1)	occasional (if P_3 insuff.)
West	I-2-central	N_2-Q	sand	discont.	25-35	15-20	0.5-2 (5)	0.1-0.2	insuff.(10)	village water supply
	Oio, except extreme east; east Cacheu; Biombo and Bissau	N_1	limestone	SW	30-50	25-30	0.5-2 (5)	0.2-1	fairly good (16)	village water supply (if N_2-Q absent)
		P_3	sand	cont.	50-100 (E>W)	15-25	1.5(15)	0.1-1 (E>W)	very good (60)	village water supply and big consumption
		P_1-2	limestone	cont.	50-150 (E>W)	20-35	1.5(10)	0.1-1 (E-W)	very good (65)	village water supply (if upper aquifer absent) and fairly big consumption
		K_2m	limestone sand sandstone	cont.	100-200 (E>W)	20-35	15-25(40)	0.2-1 (E>W)	good, esp. south(36)	towns, indust., agri. very big consumption)
	I-3-eastern	N_2-Q	sand	discont.	25-35	15-20	0.5-1	0.1	poor(6)	village water supply
	(East Oio, west Bafatá)	K_2m	sand	cont.	50-100 (E>W)	10.25	10.20( ) (E>W)	0.2	W good (17) E poor	big consump., esp. irrigation
	I-4-southern	N_2-Q	sand	± cont.	20-30	15-20	0.5-1	<0.1	fairly good (60)	village water supply
	(Quinara, Tombali, extreme east of Bolama	K_2m	sand sandstone	cont.	50-100 (E-W)	15-30	2.5(15)	<1 north >1 south	insuff.(12)	fairly big consumption
	I-5 Bijagos (Bolama)	N_2-Q	sand	discont.	20-35	15-20	1	<0.1	poor(3)	village water supply
Zone II	II-1-north	c.t.	sand alterite	±cont.	25-35	15-20	0.5-1(3)	<0.2	fairly good (80)	village or livestock water supply
	(Gabu, except Boé sector; Bafatá - far NE part)	Pz. Pc	sandstone schist	discont.	40-50	15-20	0.2-0.5 (4)	0.1-0.5	insuff.(40)	village or livestock water supply
East	II-2-south (South Gabu, south-east Bafatá, east Quinara, north east Tombali	c.t.	sand alterite	discont.	25-35	15-20	0.2-0.5	<0.5	poor(4)	village or livestock water supply

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