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Department of Technical Co-operation for Development

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GROUND WATER IN EASTERN, CENTRAL AND SOUTHERN 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 date 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 fourth, entitled Ground Water in the Pacific Region 6/ for the fifth, entitled Ground Water in Continental Asia 7/, for the sixth, entitled Ground Water in North and West Africa 8/, and for the present volume, the seventh in the series, which is to be followed by an eighth on ground water in Europe. This

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2/ United Nations publication, Sales No. E.71.II.A.180.

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.

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

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

8/ United Nations publication, Sales No. E.87.II.A.8.

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 university graduates or engineers specializing in hydrogeology or ground water.

It is to be hoped that this volume, which deals with several arid countries, in particular the countries of Eastern and Southern Africa affected by long periods of severe drought since 1983, 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 on Africa and other countries who have collaborated in the preparation of this work, in particular the Ministry of Mineral Resources and Water Affairs of the Republic of Botswana, the Department of Geology of the Republic of Burundi, the Ministry of Mines and Energy of the People's Republic of Congo, the Agricultural Engineering Service of the Republic of Djibouti, the Hydrogeology Department of the Ethiopian Institute of Geological Surveys, the Inter-African Committee for Hydraulic Studies at Ouagadougou, the Department of Land Valuation and Water of the Republic of Malawi, the Central Water Authority of Mauritius, the Public Utilities Corporation of the Republic of Seychelles, the National Water Well Association (USA), the Executive Secretariat of the National Action Committee for Water and Sanitation of the Republic of Zaire, the Ministry of Agriculture and Water Development of the Republic of Zambia, and the Office of Geological and Mining Research (BRGM-Orléans, France), as well as S. Bonfa, J.L.T. De Sommerville, D. Ferro, J.J. Imangue, S. Jacobi, J.H. Johnson, E.P. Kabunduh, F. Kolman, D. Labodo, C.L. Lekkerkerker, S. Makhoalibe, J.S. Makundi, J. Margat, A. Navarro, T. Nkanira, J. Nowacki, R. Pozzi, J.H. Rakotondrainibe, N.S. Robbins, G. Rogbeer, E.M. Siamachoka, L. Stieltjes, C. Uramutse and P. Wurzel.

The colour map of the ground-water resources of Africa, which will be found in the jacket, was kindly supplied by Mr. J. Margat, chief of the water mission of BRGM Orléans, France. 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.

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.

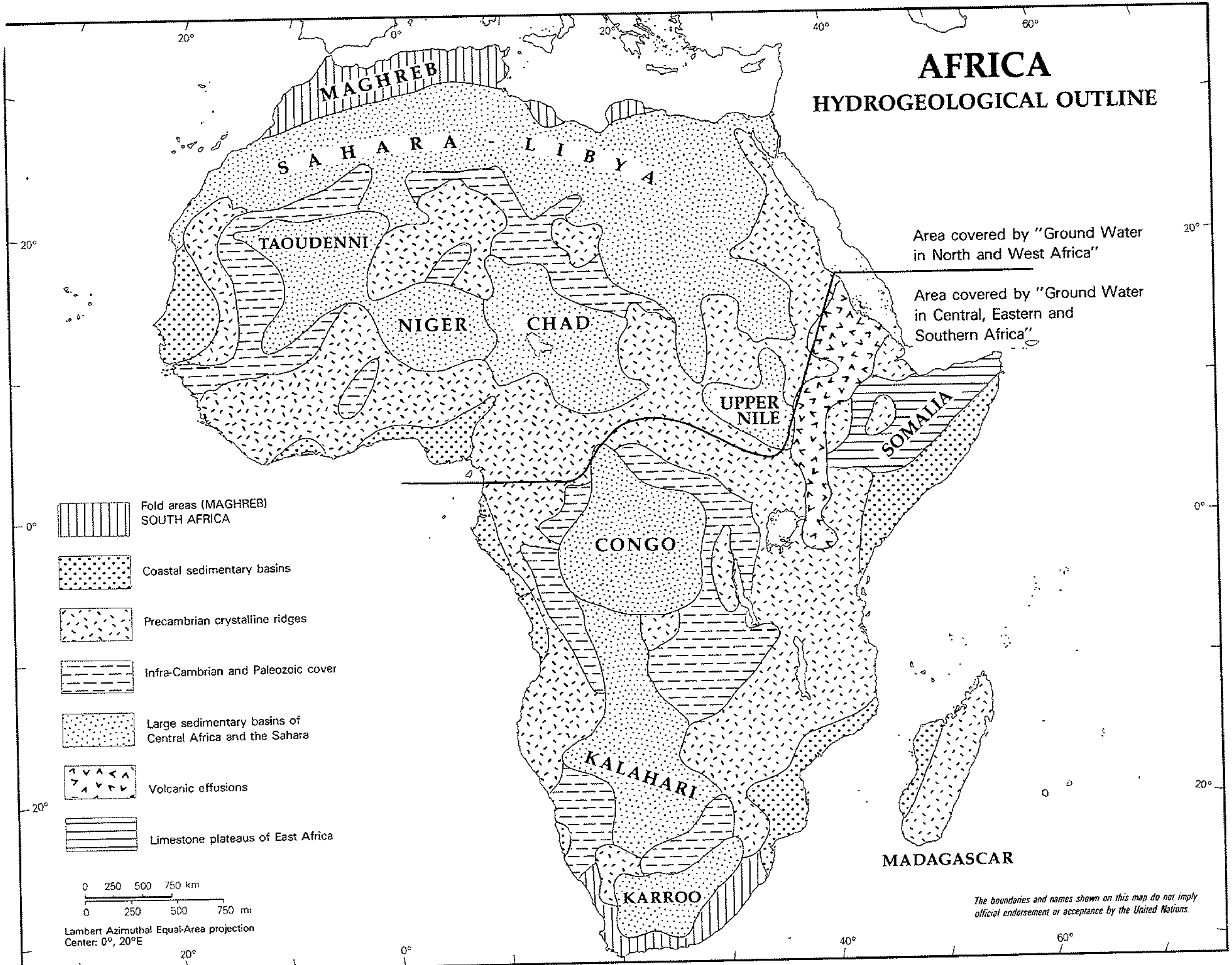
Use of a hyphen (-) between dates representing years, e.g. 1975-1978, signifies the full period involved, including the beginning and end years.

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

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 divergences may be due to typing errors.

The designations employed and the presentation of the materials 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.



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PART ONE - OVERVIEW

This volume deals with ground water in Eastern, Central and Southern Africa from the standpoint of the deposits 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 located entirely or partly in the southern hemisphere, with the addition of the Republic of Djibouti and Equatorial Guinea. The other African countries, i.e. those situated in North and West Africa are dealt with in a sister publication.

I. LARGE AQUIFER SYSTEMS

This vast territory of more than 13 million km^2 with 230 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) The Precambrian crystalline basement rock which forms the continental mass outcrops - or suboutcrops - in a band 100 to 300 km wide, inland from the Atlantic coast in Equatorial Guinea, Gabon, Congo, Zaire, Angola, Namibia and South Africa. The outcrops are much larger towards the east, for the crystalline formations are in places raised above the big Rift Valleys - major tectonic depressions, the floors of which are covered by a series of big lakes. Masses of outcropping or suboutcropping crystalline formations are found in almost all the countries considered here. In some countries such as Rwanda, Burundi, Tanzania, Kenya, Zimbabwe and Madagascar, they cover most of the land area.

(ii) The sedimentary formations which overlie the depressed crystalline basement in the axial part of the continent. This includes the basins of the Zaire, the Okavango, and the Kalahari. The Karroo basin is a fossil basin raised in a vast plateau. Mention must be made, at the edge of the basement rock, of the "stromatolithic" calcarodolomitic Lower Cambrian formations which are very extensive in Congo, Gabon, Zaire and in Angola, Namibia, Tanzania and Zambia.

The essentially Continental formations of the Karroo (Carboniferous and Triassic) consist of fairly coarse sandstones which are good aquifers. The sand and sandstone formations of the Kalahari (Neogene-Pleistocene), likewise continental, can also provide good aquifers.

(iii) The vast basalt effusions resulting from the tectonic movements which have affected the African continent at various periods since the end of the Triassic, especially in Ethiopia and in the Rift Valley zone, Kenya, Tanzania and Rwanda, and in South Africa, Botswana and Madagascar. These volcanic formations provide springs in accidented areas (Ethiopia). When they form vast tablelands, as in Kenya, they provide large aquifers exploited by borehole but the water layer can be fairly shallow.

(iv) The sedimentary coastal basins, which differ very greatly in size: the Gabon basin, the narrow basin which covers the whole of the west coast from Angola to the Cape, the vast basin of variable width of Somalia-Kenya Tanzania-Mozambique, and the basin of the west coast of Madagascar. These basins consist of Recent, Quaternary and Cenozoic sediments, in which the sandstone-sand and limestone strata form large aquifers, artesian in some cases.

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

This vast territory is subject to very varied climatic conditions in which latitude plays an essential role. From the anticyclones of the South Atlantic and the southern Indian Ocean, which are high-pressure centres, the trade winds blow towards the Equator and are deflected westwards by the rotation of the earth. As a general rule, the winds blow from the oceans to the land, bringing rain as the high ground checks the wet winds. Some depressed areas such as the Rift Valleys receive little rainfall. Eastern, Central and Southern Africa has maximum average temperatures of over 20 °C, with 30 °C in the Ogaden and 35 °C in the Kalahari, and average minimum temperatures generally below 20 °C; these minimum temperatures decline from the equatorial zone to the Cape. The world's highest average temperatures have been recorded in southern Somalia.

The temperature ranges are very small in the equatorial regions (1 °C) but increase in step with distance from the equator: they reach 02 °C to 30 °C in the Kalahari.

The Sahara

The precipitation is irregular in the Sahara, with large seasonal variations from year to year.

The extreme south of the continent, the Cape region, has a rainfall pattern of the Mediterranean type (winter rains).

The very wet equatorial regions have two rainy seasons at the solar zenith - i.e. when the sun is high above the horizon - usually from March to June and from September to November. From 10 to 15 degrees of latitude the tropical regions have only one rainy season - from May to October. Lastly, the subtropical desert zone, in particular the Kalahari-Namib and Somalia, receives only occasional and irregular showers.

The annual rainfall is 2 to 6 m in Gabon, in the loop of the River Zaire, to the west of the Great Lakes, and on the east coast of Madagascar; it is 1 to 2 m on the Ethiopian plateau, to the north of a line between Mossamedes and Dar Es Salaam, on the east coast of Southern Africa, and over most of Madagascar; it is 500 to 1,000 mm to the south of the Mossamedes-Dar Es Salaam line, with less than 500 mm in Somalia, in some parts of Uganda, Kenya and Tanzania, and in the Kalahari and the south-west part of Madagascar.

Climatic zones

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

- Mediterranean zone with dry summers (hot season): Cape region.

- Steppe zone with a semi-arid tropical climate, i.e. with rainy summers (cool season). The precipitation is less abundant and the temperature ranges are larger than in the Mediterranean zone: this includes the whole of Eastern Africa with the exception of the coastal areas and the highest plateaus, and the central part of South Africa. The dry savannah zone (tall grasses) forms the transition between the steppe - with short grasses - and the wet savannah.

- Wet savannah zone or zone of wet tropical climate. Here 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 (Kalahari-Namib and Somalia).

- Equatorial forest zone with very wet climate and two rainy seasons, or continual rain: it includes 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 current of Benguela flowing south-north from Cap to the equator, is a cold current. The warm currents are those flowing north to south from the Mozambique channel towards the Cape, and the monsoon current flowing south to north from Mozambique to Somalia, with surges of cold water in the area of Cape Ghardafui.

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 the rainfall and its distribution and which expresses a characteristic ratio between potential evapotranspiration and the amount of rainfall.

Some evapotranspiration values are given below and compared with the rainfall values at a number of African weather stations:

Weather station	Annual precipitation (cm)	Potential evapotranspiration (cm)	Quotient %
Arid coastal regions			
Walvis Bay (Namibia)	1	78	17
Area of rainfall between 250 and 1,000 mm			
Lug Ferrandi (Somalia)	36	206	17
Garissa (Kenya)	31	187	17
Luanda (Angola)	33	134	25
Dodoma (Tanzania)	59	111	50
Catuane (Mozambique)	67	130	50

Thus, in some regions a large or very large proportion of the rainfall is lost almost immediately through evaporation. The heading "evapotranspiration" often has the highest values in the water tables. Some authors put forward the following figures for the various regions of Africa: evapotranspiration - 40 to 98 %; infiltration - 2 to 40 %; runoff - 2 to 12 %.

The surface water (lakes) is subject to wide variations in level owing to the imbalance in some years between the headings "evaporation" and "recharge". This is particularly true of Lake Victoria. It is also true of unconfined ground water when the water table is close to the surface (delta of the Okavango in Botswana). Evaporation determines - and can be measured by - the concentration of salts in the ground water. The question of the depth to which evaporation takes place is disputed. All authors agree that this effect operates for several metres (5 m on average and as deep as 8 to 10 m). 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, 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.

In regions with rainfall between 250 mm and 1 m (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 temperature 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 date in the savannah 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" and one of its main consequences: a drop in the level of water in the wells, which can even dry up completely. Lastly, a drop of 50 % in the amount of total annual rainfall as a result of less frequent showers can mean no 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.

Coefficients: S = storage
K = permeability
T = transmissivity

1. "Porous" aquifers

Alluvial fill, deltas, Quaternary formations of the Congo basin, sedimentary coastal basins

Country	Location	Geology	Flow rate per installation (m^3/h) a/	Drawdown (m)	S %	K (m/d)	T (m^2/d)
			Fluvial alluviums				
These aquifers are among the most important and serve large populations.							
Congo (both Republics)	Congo (river)	Sands-gravels	(1 to 100 100 m^3/h/m)	-	-	-	-
Madagascar	Tananarive	Alluviums with clays	(15 to 40)	-	-	-	-
Zimbabwe	Sabi (river)	Non-argillaceous alluviums	60	-	-	-	-

a/ In the column "Flow rate per installation", the values in brackets indicate a specific discharge.

Country	Location	Geology	Flow rate per installation (m^3/h) a/	Drawdown (m)	S %	K (m/d)	T (m^2/d)
			Extensive alluvial fill				
Burundi	Graben	Fill formation	10 to 60	-	-	-	-
Congo	Basin apart from river	Fill formation	(1 $m^3/h/m$)	-	-	-	-
			Coastal sedimentary basins				
Madagascar	-	Cretaceous sandstones	60	-	-	-	-
			Kalahari sands				
Angola	-	Argillaceous-calcareous sandstones	2.5 to 4.5	-	-	-	-
Malawi	-	Non-argillaceous sands	1 to 5	-	-	-	-
	-	Argillaceous sands	0.5 to 3	-	-	-	-
Zimbabwe	-	Sands	Up to 70	-	-	-	-
Zambia	Barotseland	-	4 to 8 maximum	-	-	-	-
			Karroo sandstones and other Precretaceous or Cretaceous continental sandstones				
Madagascar		Isalo argillaceous sandstones	15 to 40	-	-	-	-
Namibia	Botswana frontier	Ecca sandstones (Karroo)	(40 to 4,000 per day, artesian)	-	8 to 15	-	-
Zimbabwe	-	Upper Karroo sandstone	3 to 6 (up to 50)	-	-	-	-
Swaziland	-	-	-	-	-	-	-

Country	Location	Geology	Flow rate per installation (m^3/h) a/	Drawdown (m)	S %	K (m/d)	T (m^2/d)
Zambia	-	Lower Karroo sandstone	Low	-	-	-	-
		Sandstone of Grit escarpment	7 to 10 (up to 60)	-	-	-	-
		Beaufort formations	20	-	3 to 10	-	-
Zimbabwe	-	Cretaceous conglomerates	2 to 7	-	-	-	-

2. Fractured aquifers

Karstified limestone strata

Country	Location	Geology	Flow rate per installation (m^3/h) a/	Drawdown (m)	S %	K (m/d)	T (m^2/d)
Madagascar	West coast	Eocene limestones	40 to 300, artesian (160 to 200 m^3/h/m pumped)	-	-	-	-

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

The dolomitic-limestone sedimentary system (Upper Precambrian and Cambrian) is often very thick and constitutes one of the most important ground-water reservoirs in Africa. This is borne out by the few examples given below:

Dolomites of the middle Katanga (Zambia): 4 to 10 m^3/h (40 m^3/h in the Mazabuka fault). The town of Lusaka draws 2,000 m^3/d from 10-inch boreholes;

Dolomites of Lubumbashi (People's Republic of Congo): specific yield - up to 100 m^3/h/m;

Dolomitic limestones of the Transvaal - Far West Rand (South Africa). Useful porosity: in the order of 10 % at 60 m, 2 to 3 % at 100 m, and 1 to 2 % at 150 m. The Suurbekom pumping stations supply 30,000 m^3/d to Johannesburg. A yield 30 times greater is available. The main purpose of the pumping in this region is to exhaust the limestone stratum which overlies the gold-bearing conglomerates, with a view to their exploitation. Over 15 years, 10^9 m^3 have been pumped.

3. Compact-rock aquifers

Formations with little or no porosity, except locally in suitable altered or fissured zones

Precambrian and Primary hard sandstones, schist-sandstones and quartzites

Example: Angola (southern)

Lower-Cambrian quartzites and conglomerates: Yield, 0.5 to 3 m^3/h.

Schists (mainly Lower-Cambrian, Paleozoic and Karroo) and clays

When they are not totally impermeable, these formations contain very few water resources, mainly in the fracture zones.

Example: Zambia - phyllades, biotitic schists, Katanga schists, yield per well from 1 to (exceptionally) 4 m^3/h.

Examples of available yields per well and borehole in crystalline formations

Country	Location	Geology	Flow rate per installation (m^3/h)
Angola	South	Metamorphic rocks	0.6 (fractured)
	Catuiti	Tectonized and alterated granites	3 to 30 (up to 80)
Congo	-	Granitogneiss in alterations and fractures	(1 to 10 m^3/h/m)
Madagascar	Various	Altered gneiss	0.4 to 1.2
Malawi	Various	Gneiss with graphited biotite	2 to 5
Mozambique	Various	Rhyolites	Springs: 0.1 to 0.5 (wells 1 m^3/d)
	Various	Granites paragneiss orthogneiss	4 to 8
	Porto Amelia, Villa Perry	Granites paragneiss orthogneiss	12 to 20 (up to 25)
Namibia	Namaqualand	Gneiss and quartzites	1 to 20 (artesian)
Uganda	Karamoja	Acid gneiss	5 to 50
Zambia	Kaloma Choma	Quartz veins	8 to 12

In fact, a flow rate of 5 m^3/h is a good yield for the granites and granitogneiss; a flow of 1 m^3/h is considerable for the micaschists and metamorphic schists. Better yields are obtained in the quartz zones.

4. Volcanic rocks

The lavas, especially the basalts, the dolerites and certain basic rocks which sometimes afford large yields can be classified in a separate category; some examples are given below:

Jurassic basalts (Zimbabwe) - artesian waters: 8 m^3/h;

Bulawayo lavas, tufas, etc. (Zimbabwe) metamorphized into green rocks: 8 to 15 m^3/h (exceptionally 70); certain lavas have a low yield of under 1 m^3/h;

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

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

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

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

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

The volcanic rocks, and especially the basalts, also give large yields, in particular from big springs, in other countries (Ethiopia).

Conclusion

There is almost nowhere in Africa where ground water is not found at one depth or another. The biggest yields 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 very general terms it can be said that, with respect to its quality, which depends on the geology, climate and geographical situation:

- In arid zones the ground water is usually of calcium/magnesium bicarbonate facies at the upstream 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;

- 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 Mozambique;

- 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 thermomineral springs abound in the African continent in the fractured zones. There is a large potential for geothermal energy in the Rift Valleys which is currently being exploited, especially in Kenya.

IV. EXPLOITATION OF THE GROUND WATER

Up to recent times in this part of the world, ground water was drawn off from crude wells - shallow holes dug in the alluvial beds of water courses devoid of surface water in the dry season. These wells are in general use in arid regions such as northern Uganda.

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.

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 20th century and from the progress made in the same period by British and Swedish manufacturers of drilling equipment for the exploitation of ground water.

Ground water was first exploited by borehole in the arid zones of Southern Africa.

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 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.

The boreholes are not usually 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, and the Volanta of Netherlands'conception, which is now manufactured in Africa.

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 methods are usually costly and are going out of use.

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 services 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, 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 subtropical zones.

Ground water is extensively used to supply urban and industrial areas, especially in arid regions and coastal zones. This is particularly true of Djibouti, Berbera, Mogadishu, Mombasa, Zanzibar, Gaberones, Pretoria, Windhoek, Lusaka and several towns in Zaire.

The exploitation of ground water in Africa is intended mainly to meet the water needs of the towns, villages and pastoral areas and also 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 zones of semi-arid and Mediterranean climate in Southern Africa, the areas irrigated by ground water are still very small. However, the creation of small market-garden centres is envisaged in the vicinity of the motorized or hand pumps installed in the villages, with a view to diversifying the people's diet.

V. 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 being 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 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 the 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 often arid or even desert zones with little or no recharge from rainfall and coastal zones subject to deep intrusion of sea water in the direction of the wells. In contrast, some rainy tropical zones have rocks which are poorly suited to the absorption and storage of water supplied by rainfall and surface runoff.

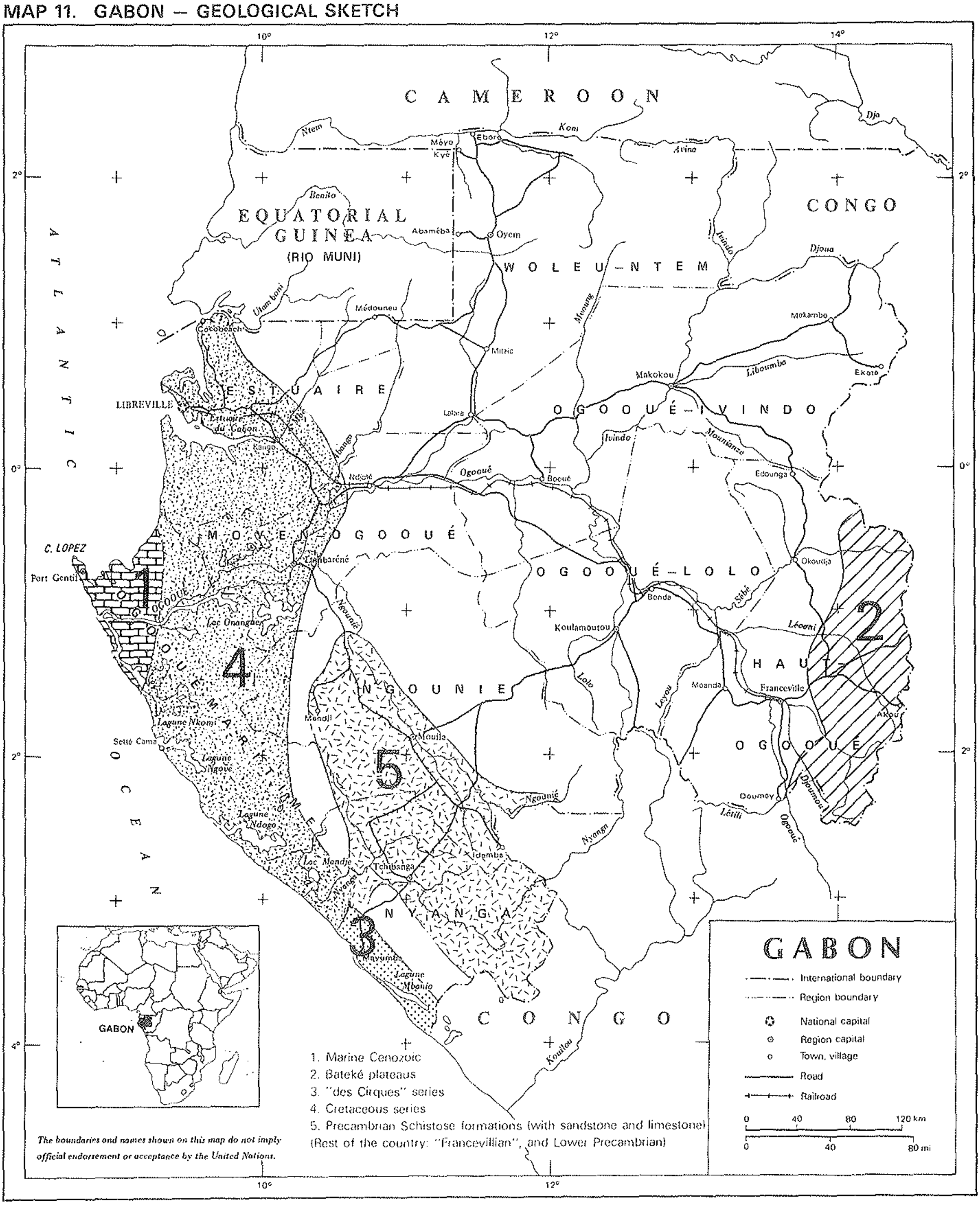
Furthermore, ground-water prospecting and the drilling and digging of wells are usually difficult and expensive operations owing to the weakness of the infrastructures, the unfavourable natural conditions, the remoteness of the zones to be reached and the wide dispersal of the villages, as well as the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

Lastly, and this is not the least problem, African villagers and herdsmen do not everywhere 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 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 (Tanzania); 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 arid Africa are managed to best effect, i.e. without wastage or medium and long-term threat to the quantity and quality of these resources. This comment applies equally to the intensively exploited coastal zone, especially at Mogadishu and in southern Madagascar.

Nor are the objectives of the International Drinking Water Supply and Sanitation Decade about to be achieved for the villages. 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.

MAP 11. GABON — GEOLOGICAL SKETCH



MAP NO.3484.7 UNITED NATIONS
MARCH 1989

GABON

Area: 267,600 km^2
Population: 1.2 million (1983)

I. BACKGROUND

Gabon is crossed in its centre by the equator and has a coastline of about 800 km in the west on the Gulf of Guinea. The country is fairly flat and 85 % of its area is covered with the great equatorial forest. Seventy-five per cent of the country is comprised by the basin of the Ogooué River and it has the following geographic units:

- The plains and plateaus of the coastal basin with a few peaks rising to 240 m; this basin widens from the south (30 km) as far as the latitude of Port Gentil (250 km), and then narrows to the north (50 km at the level of Cocobeach);

- Inland, running NW-SE, the massifs of Mayombe (820), Chaillu (980 m) and Ndjoté (909 m) and the Cristal mountains (800 m);

- The crystalline plateaus of the north-east (450 to 650 m) dominated by Mt. Belinga and Mt. Boka Boka (1,000 m);

- In the south-east, the Batеké plateaus (550 to 800 m);

- The lower river plains of the Nyanga and the Ngounié;

- The Booué and Franceville basins (Haut-Ogooué).

Climate

The climate is of the equatorial wet tropical type, with annual rainfall declining from a maximum of 3,000 to 3,200 mm in the north-west (Libreville region) towards the east and the south-east in a number of depressions, the plains of the Ogooué and the Nyanga (1,400 to 1,600 mm).

The monthly maximums occur from September to mid-December and from mid-February to May. These two rainy seasons are separated by a long dry season (June-September) and a short dry season (December-February). There is an average of 130 to 140 rainy days a year, with a maximum of 225 days in the Cristal mountains and a minimum of 69 days at Booué. The relative humidity is usually above 80 % in all seasons. Evaporation measured in a pan averages 1,000 mm a year. Temperatures are high throughout the year, with averages of 20 °C to 28 °C, declining from the north towards the east and south. The annual thermal ranges are small: 2 °C to 4 °C.

Hydrography, hydrology and surface water

Gabon's hydrographic network has 77 units: 64 watercourses, 1 delta, 3 estuaries and bays, 5 lakes and 4 lagoons.

The main river, the Ogooué, drains 72 % of the country (as well as 22,000 km^2 in Cameroon and Congo). It is 1,000 km long. It rises in Congo at an altitude of 850 m in the Bateké plateaus. Its main tributaries are the Ivindo, which drains the north-east section of the country, and the Ngounié. The river is navigable below Ndjoté, which is 250 km above the delta.

The country's second river, the Nyanga, is 600 km long.

There are also several coastal rivers, including the Mbéi and the Komo, flowing into the vast estuary of the Gabon River which gave the country its name.

The rivers have numerous rapids in their upper courses. The country has a considerable hydroelectric potential.

Table 1

Annual rainfall (mm) at three pluviometric stations in Gabon

	Bitam: 24 years			Libreville: 21 years			Franceville: 24 years		
	Min.	Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.
January	0	116	58	76	523	250	54	315	184
February	7	152	79	132	411	271	99	316	207
March	57	336	196	203	670	436	58	466	262
April	46	353	200	207	545	376	98	326	212
May	99	460	280	9	510	260	69	336	202
June	46	240	143	0	125	10	0	122	(20)
July	0	122	(20)	0	4	2	0	77	(2)
August	3	122	(50)	0	41	(10)	0	59	(20)
September	43	444	243	3	244	123	7	195	101
October	105	431	268	92	649	370	118	444	281
November	84	386	235	247	799	523	149	368	258
December	17	136	74	84	643	364	103	323	(180)

The table shows the approximate average monthly rainfall for 21 or 24 years (1947-1950 to 1970-1971), illustrating the two rainy seasons, with maximums in spring and autumn, separated by the summer and winter dry seasons.

Rainfall varies in step with latitude; for the flow patterns of the watercourses this means a low-water season in winter in the north and in summer in the south.

Taken as a whole, the flow patterns of the rivers are extremely regular if the mean interannual flow (Qm) - which is obtained by establishing successively the monthly mean of the daily values, the annual mean of the 12 monthly values, and the interannual mean of the annual values since the establishment of the measuring stations - with the mean annual peak flow (Qe), which is obtained from the annual peak flow, i.e. the highest daily value in the year, and the mean of all the annual peak flows available for a given station.

The results for Gabon's 24 stations are:

Qm < 2 Qe at 6 stations = 25 %)
2.01 < Qm < 4 Qe at 15 stations = 62.5 %) 87.5 %
4.01 < Qm <10 Qe at 3 stations = 12.5 %)

It is remarkable that the peak flow is less than 10 times the minimum flow at three-quarters of the stations, and less than 20 times at nine-tenths of them.

Gabon's hydrographic network is as a whole very well developed, with high permanent flows in all seasons. The navigable watercourses are used as a means of travel and transport of goods, in particular timber, and they have many sites suitable for the construction of dams for the production of hydroelectric power.

The following table gives some information about the main dams built and planned.

Characteristics of Gabon's main dams

Name of installation	River	Slope of dam	Collection capacity ($10^6 m^3$)	Operational flow (m^3/s)	Status
Tchimbelé	Mbéi	+ 539	220	35	Built
Kinguelé	Mbéi	At stream level		60	Built
Petit Poubara	Ogooué	+ 390	Low	108	Built
Grand Poubara	Ogooué	+ 432	2,080	198	Under construction
Fougamou	Ngounié	+ 86	4,800	645	Planned

In addition to the five installations described above, there are many sites which can be developed after further feasibility studies: nine sites on the Ogooué or its tributaries, from upstream to downstream: Abouka on the Mpassa, Lebombi on the Lebombi, Mafouta and Liboka on the Ogooué, Akieni and Angouma on the Lekoni, Lifouta and Souka on the Ogooué, and Booué on the Ogooué.

There are four possible sites on the Ivindo: Koungue, Mingouli, Kouata-Mango and Tsengue Leledi.

There are five closely-spaced sites exploitable from the Tchimbele dam.

II. GEOLOGY

Geological introduction

Gabon has three large geological systems:

- The crystalline and cristallophyllian basement rock which constitutes the North-Gabon massif, the Chaillu massif and the Mayombe range. The North-Gabon massif contains important iron deposits. The Mayombe range is 450 km long and

30 km wide. It contains migmatites, granitogneiss, quartzites, micaschists and complex metamorphic series;

- The Precambrian sedimentary cover with, from bottom to top:

  - The Francevillian system in the south-east, which includes five formations containing deposits of detritic uranium (conglomerates, sandstones, pelites, with jaspers and pyroclastic products); the Ogooué system in the centre contains volcano-sedimentary and metamorphic formations, and the Mayombian system in the south-west contains conglomerates, arkoses, quartzites and carbonated schists;

  - The middle series at the eastern edge of the Mayombe range also contains arkoses, quartzitic and carbonated rocks, schists and various detritic rocks; the upper series in the Nyanga synclinorium contains tillites, schists, sandstones, conglomerates of glacial origin, and schist-limestone and schist-sandstone series;

- The sedimentary cover with formations dating from the Paleozoic to the Neogene and Quaternary. It is divided into two systems:

  - The coastal sedimentary basin divided into two by the Lambaréné crystalline horst deposited in the Lower Cretaceous, i.e. the interior synclinal basin (area - 200 x 60 km; thickness - 3,500 m), with fluvio-lacustral and lagoonal continental formations: sand-sandstones, marls, clays, shales, conglomerates of Upper Paleozoic to Middle Cretaceous age, and the Atlantic or western basin (area - 500 x 15 to 200 km; thickness - 8,000 m), with marine deposits of Cretaceous to Quaternary age (carbonated sandstone, argillite and detritic deposits);

  - The Bateké plateaus in the south-east at the edge of the Congo Basin, consisting of Tertiary continental sandstones and sands resting in discontinuity on the Francevillian formations.

The Quaternary and Recent formations include *inter alia* coastal sand belts and fluviatile alluviums.

General description of the aquifers

The large geologic systems are distributed roughly as follows:

Atlantic coastal basin	50,000 km^2
Bateké plateaus	12,000 km^2
Upper Precambrian	29,000 km^2
Middle Precambrian	32,000 km^2
Lower Precambrian	145,000 km^2

Vast ground-water aquifers cover about one-third of the country, including most of the formations of the first three systems listed above.

The other two-thirds contains only small isolated aquifers in the granitic rocks of the Lower Precambrian and in the metamorphized and schistose rocks of the Middle Precambrian.

The masses of hard rock are generally altered in their upper strata. The thickness of the alteration layer varies: it can be up to 30 m in the limestone series and perhaps much higher in the granitic areas. Many of these mostly laterites strata contain ground-water aquifers which feed the many perennial springs, which usually have a very small discharge in the dry season. These water resources have a very low mineral content and they are of very great economic importance, for they are preferred to surface water as a means of supply by rural dwellers.

However, the laterite strata have poor permeability owing to their often high clay content. Furthermore, they deliver to their outlets water with a high sediment charge. They are therefore not being exploited under the current village water-supply programme. Preference is given to the non-altered strata owing to their more favourable properties and their limited vulnerability to recharge variation. It is possible to drill in the hard, schistose or granitic rocks with down-the-hole hammers driven by compressed air.

The essential parts of the data currently available on each of the aquifers will be found below. The information may be of regional or only local significance, depending on the number of boreholes drilled.

Much fuller data are to be obtained in 1985 with the completion of the first stage of 510 boreholes - distributed throughout the country - under the village water-supply programme.

Coastal sedimentary basin

The coastal sedimentary basin is the part of the country where the geology is best known, thanks to oil exploration works. The total thickness of the sedimentary deposits is in excess of 5,000 m; it is perhaps above 10,000 m in the continental plateau.

Quaternary

The coastal sand belts contain an aquifer recharged by direct infiltration of rainwater, resting in density equilibrium on the salt water or on an impermeable substratum. The aquifer is 25 m thick at Port Gentil. The sands have good permeability as far as Port Gentil, and at Mayumba the boreholes have yields in the order of 2 m^3/h per metre of drawdown. The transmissivity ranges from 6×10^{-4} to 3×10^{-3} m^2/s at Port Gentil. It is estimated at 4×10^{-3} m^2/s at Mayumba, where a drawdown of 2.9 m was recorded on the completion of pumping at 9.5 m^3/h (3.3 m^3/h.m.).

The water has a small mineral content (50 to 250 mg/l). The facies range from calcium bicarbonate to mixtures of calcium bicarbonate and calcium and sodium chloride. Owing to the conditions which formed the belts (abundant vegetation in the interdunal trenches), the water has a high iron content (often 20 to 35 mg/l) and is rich in organic matter; the frequent clogging of filters has affected the exploitation of the aquifer at Port Gentil. Despite a production of 8,000 m^3/day (in 1974), no intrusion of salt water has been observed.

The Mayumba aquifer is more vulnerable owing to the narrowness of the sand belt.

Pliocene to Upper Miocene series

"Cirques" series : Akosso (Pliocene) and N'Tchengue (Upper Miocene)

In the Mayumba region a number of village boreholes tap the Pliocene sand strata located at depths of 6 to 40 m. The specific discharges are between 0.75 and 3.5 m^3/h.m. The water is very sweet and of calcium bicarbonate facies.

Middle Miocene to Paleocene series

Alewana series: M'Béga and Mandorove (Miocene)

Mandji series: Animba and Ozouri 2 (Eocene)
Ozouri 1 and Ikando (Paleocene)

The formations have a predominantly argillaceous facies and their hydraulic potential is therefore very low.

Maestrichtian to Upper Aptian series

Komadji series (Maestrichtian to Senonian): Ewongué to Anguille

This series includes argillaceous sandstones, clays and compact calcareous sandstones. The three boreholes (70-73 m) drilled at Cap Estérias indicated very poor permeability of the aquifer (with yields of 1 to 4 m^3/h for drawdowns of 20 to 25 m); the transmissivity is in the order of 10^{-5} m^2/s. Despite the proximity to the sea, the water is of good chemical quality, with a dry residue below 300 mg/l.

The limestones can be karstified and thus of particular interest for exploitation: a karst has been identified, for example, at the edge of Akwango bay.

Sibang and Azilé series (Turonian)

The formations consist of limestones, marls and argillaceous sandstones with fairly low permeability. The series has been identified to a depth of over 500 m under Libreville. The maximum operating yield is 50 m^3/h (for filter lengths in excess of 55 m) with drawdowns of over 40 m. The transmissivity is in the order of 10^{-4} m^2/s. The storage coefficients are estimated at 10^{-3} at depths down to about 200 m and at 3 x 10^{-4} at depths from 200 to 400 m. The water is sodium carbonate with sodium bicarbonate and sulphate. The dry residue increases with depth: 200 to 300 mg/l for water tapped at depths down to 150 m, then 450 to 700 mg/l at greater depths. The sulphate content increases in the deep strata owing to penetration of the roof of the Cenomanian red series which contains large quantities of gypsum. The mineral content can exceed 5 g/l.

The water of the lower Sibang series has a high fluoride content (up to 1.2 mg/l) owing to the presence of phosphated strata.

Red series and Cap Lopez series (Cenomanian)

The facies are generally marly to sandy-marly. The lagoonal strata can have a high gypsum content. As a general rule, the formations appear unsuitable for ground-water exploitation. This is certainly true in the south in the Sette Cawa region, where the formations are impermeable (three boreholes from 49 to 71 m).

Madiela series (Upper Albian to Upper Aptian)

Here the drilling has identified: an upper system, with sands, marls, dolomites and possibly gypsum; a middle system, with sandstones, limestones and dolomites; and a lower system, with limestones.

Two boreholes drilled near Ntoum indicate the probability of poor to average permeability:

- The Donguila borehole, 108 m deep, penetrated sandstone dolomites with very little fissuration, for pumping at 37 m^3/h caused a drawdown of 7.9 m, i.e. 0.34 $m^3/h.m.$; the transmissivity is estimated at 7 x m^{-5} m^2/s;

- The banana plantation borehole (G 11) was halted at 70 m after penetrating marls and calcareous sandstones; the characteristics are similar to those of the Donguila borehole: 0.3 m^3/h and 10^{-4} m^2/s approximately.

The water has a dry residue of 325 to 450 mg/l; the facies is calcium carbonate.

To the north-east (Ntoum) and north-west (Nkoltang) of the latter borehole there are outcrops of older strata consisting of limestones with much more permeable karstic features.

Permeable strata are also found in the dolomitic formations in the south of the country in the Gamba anticline, south of Lake Ndogo.

Upper Aptian to Neocomian series

The system of the so-called Cocobeach formations is marly and thus of low permeability. Only one stratum - the Gamba sand-sandstone series - is of real hydrogeological interest; it is located north of Ntoum.

Vembo Shales

The upper Cocobeach series - Vembo Shales: Ezanga - has been identified to a depth of 109 m near the town of Cocobeach. The borehole had a yield of 0.2 m^3/h, demonstrating the very poor permeability of the strata.

Gamba series

Several stratigraphic mining research and reconnaissance holes have indicated, north of Ntoum beneath 26 to 44 m of Vembo Shales, a sand-sandstone series 175 m thick. The water is artesian in the topographically low sectors. The solar-programme borehole drilled at Akok taps only the upper 8 m of the series. Pumping at a rate of 8 m^3/h caused a drawdown of 18 m, i.e. 0.4 $m^3/h.m.$ The water has a mineral content of 150 to 200 mg/l. The facies is calcium and magnesium bicarbonate.

Remboué series

Outcrops of this predominantly marl series are found north-west and south-west of Bifoun. Research must be carried out in the intercalated sandstone banks.

Kango series

This series outcrops extensively from the sector north-west of Kango almost as far as Lambaréné. The marly deposits can be considered semi-impermeable.

Terminal Jurassic to Permian series

Ndombo series

This series outcrops north-east of Ntoum in the form of hills containing a permeable sand-sandstone system with abundant recharge from rainwater infiltration which feeds the rivers in the dry season with a specific discharge of over 10 $l/s/km^2$.

A borehole 49 m deep, intended to supply Cocobeach, penetrated a series of fine-grained sandstone bonded below 25 m. The springs originate in conglomeratic strata or fracture zones. Pumping at a rate of 20 m^3/h caused a drawdown of 21.4 m, i.e. 0.9 $m^3/h.m$. The transmissivity is estimated at 2×10^{-4} m^2/s. The water has a mineral content of about 200 mg/l. The facies is calcium bicarbonate.

South-east of Cocobeach, the sandstone aquifer runs south-west and becomes confined under the Vembo Shales. Its pressure is transmitted, despite considerable tectonic fracturation, to the Gamba sandstone aquifer, explaining the latter's artesianism.

The Ndombo aquifer itself can also be artesian in the low areas of the plain. This is the case of the Ndouaniang borehole drilled through 60 m of Kango clays. The head was 6 to 7 m above ground level. The water has a low mineral content (about 70 mg/l); it is calcium bicarbonate and fairly acid (pH 6.0). The Ndombo aquifer has a considerable potential. However, in order to reach optimal productivity, the boreholes must be fairly deep, so as to penetrate one of the conglomeratic strata and a sufficient number of fissures.

Mvone series

This series has two lithological systems:

- Marly semi-impermeable deposits, and
- Coarse crumbly conglomeratic sandstones, where hydrogeological research is still to be carried out.

Agaoula series

This series consists of a sandstone-marl system which probably has very poor permeability.

Bateké plateaus

The Bateké plateaus series extends over Gabon, Congo and Zaire and consists of soft sandstones with clay intercalations. This permeable system constitutes a vast reservoir with a large recharge from rainfall: the effective infiltration is above 90 cm in an average year. The aquifer is drained by rivers which flow in deep-sided valleys. Their low-water flow indicates high rates of ground-water flow of up to 25 to 30 $l/s/km^2$.

The first borehole in this series in Gabon (G 17) was drilled near Lakoni. It was 100 m deep and penetrated medium sands (0.2 to 0.5 mm) in the first 70 m. Tapped at between 50 and 70 m, these sands have a transmissivity close to 8×10^{-4} m^2/s. Pumping at a rate of 11 m^3/h caused a drawdown of 16 m, i.e. 0.7 $m^3/h.m$.

The water in this series has a very low mineral content, with a dry residue of about 40 mg/l and high acidity (pH 5).

Several boreholes drilled under the village water-supply programme had higher permeabilities, and half of them had specific discharges in excess of 10 m^3/h.m.

Upper Precambrian

Mpioka series

These formations form the core of the Nyanga syncline and include schists, sandstone schists, and argillites with intercalations known as the schist-sandstone series and constituting a porous reservoir of regional extent; the springs are perennial but of low discharge. The permeability of the schistose strata depends on their degree of fissuration. It is generally fairly low. The best yields are obtained in the fractured sandstone aquifers.

The 17 village boreholes installed in Nyanga province can be classified as follows by specific discharge (m^3/h.m.):

	< 0.1	0.1 to 0.5	0.5 to 1	1 to 3.4	
Schists	4	7			boreholes
Sandstones (and schist-sandstones)		1	1	4	boreholes

The water has a very small to moderate mineral content (50 to 200 mg/l); the facies is calcium bicarbonate or a mixture of calcium and sodium bicarbonate. It is very acid (pH 5.5 to 6).

The Noya series, which outcrops to the east of the Agoula series and extends into Equatorial Guinea, has the same schist-sandstone facies as the Mpioka series.

Schist-limestone series

This series appears in the plain within the circumference of the Nyanga syncline and extends into Congo. It consists of carbonated rocks (limestones, dolomites, marls) with frequent karstic phenomena: disappearance of watercourse and sinkholes and resurgences. The rivers generally run NW-SE with NE-SW deviations. The lateritic cover can be up to 30 m thick. These surface layers must be fully lined in order to prevent intrusion of argillaceous water. Most of the formations have average to high permeability.

The 20 boreholes drilled in Nyanga province have been classified as follows by specific discharge (m^3/h.m.):

< 0.5	0.5 to 1	1 to 5	5 to 10	10 to 24
3	3	8	3	3

The boreholes installed in Ngounié province have given similar results.

The highest yields are obtained from fractures, as demonstrated at Mandji (G 15) where a fissured zone about 2 m deep provides a yield of 32 m^3/h for a drawdown of 1.0. The water has a relatively high mineral content with a dry residue between 200 and 400 mg/l; the facies is calcium bicarbonate, with pH of 7 to 7.5.

Louila and Bouenza series

These series outcrop at the two edges of the schist-limestone series: the Louila series on the west edge, and the Bouenza series in the Lébamba region. They include sandstones and quartzitic sandstones, schists and argillites, and intermediate rocks. No borehole has been drilled here.

The permeability varies with the facies, as in the case of the schist-sandstone series.

Middle Precambrian: "Francevillian"

The Middle Precambrian is known in Gabon as the "Francevillian"; several systems and sub-systems have been identified here, showing the complexity of the sedimentation. The main units consists of pelites, ampelites, sandstones, jaspers and dolomites.

A number of village boreholes have been drilled in Haut-Ogooué province; 29 of them are in the Francevillian strata and have demonstrated its poor general permeability; they are classified as follows by specific discharge ($m^3/h.m.$).

	< 0.05	0.05 to 0.1	0.1 to 0.5	0.5 to 1.4	
Pelites-ampelites	3	6	2	2	13 boreholes
Sandstones	4	3	7		14 boreholes
Dolomites			1	1	2 boreholes
	7	9	10	3	

The highest yields come from zones of contact between pelites and ampelites and from fractured dolomites.

The water with the highest mineral content (about 300 mg/l) and calcium bicarbonate facies is found in the dolomitic strata.

The pelites and sandstones generally yield water with a very low mineral content (under 80 mg/l), also of calcium bicarbonate facies, sometimes mixed with magnesium bicarbonate. The acidity is high.

The Francevillian sandstone formations of Ogooué-Lolo province are the location of eight boreholes with the following specific discharges ($m^3/h.m.$):

> 0.05	0.05 to 0.1	0.1 to 0.5	0.5 to 0.7	
2	3	1	2	boreholes

The dry residue is below 250 mg/l.

Lower Precambrian

Crystallophyllian formations

A positive 70-metre borehole was drilled in a quartz vein of the Ndjoté schists, which as a whole probably yield little or no water.

Crystalline formations

These formations consist mainly of granites in the broad sense with very low permeability, in particular in Haut-Ogooué, where 13 boreholes, although sited on the basis of electrical data have a specific discharge below 0.17 m^3/h.m.:

< 0.01	0.01 to 0.05	0.05 to 0.1	0.1 to 0.17	
5	5	1	2	boreholes

The results from seven boreholes in Ogooué-Lolo sited systematically in anomalies indicated by electrical prospecting have proved much more favourable, for all the installations discharge between 0.11 and 0.9 m^3/h.m.:

0.1 to 0.5	0.5 to 0.9	
5	2	boreholes

The most productive borehole has been tested at 18 m^3/h.

The water has a relatively high mineral content, with a dry residue between 170 and 550 mg/l. Several boreholes have been drilled in another granitic zone, near Mitzic, with positive results. It seems hat because of the difficulty of interpreting aerial photographs owing to the vegetation cover and the lateritic crust (which is often in excess of tens of metres thick), the only practicable methodology for the location of boreholes is constant separation traverse. It will perhaps be possible in the long term to establish correlations between the productivity of the boreholes and certain morphological and tectonic features (fractures in the basement rock, thickness of the alterites).

Physical and chemical properties of the water

The table below indicates the results of the analysis of water samples from boreholes, wells or springs in 29 cases out of 30 in Gabon. The other analysis was of river water.

These analyses, which extend over about 20 years, were made by several laboratories at Libreville or Dakar or in France. Some of them are incomplete and the final reports show that the salinity of the water can change depending on the duration of the pumping preceding the sampling. Despite these defects, which are common in series of analyses, the results do furnish useful information.

Almost a third of the analyses indicate a very small total mineral content, i.e. below 100 mg/l.

In contrast, five analyses indicate an average mineral content of 350 to 900 mg/l; these are analyses (Nos. 4 to 8) of the water of five deep boreholes at Libreville. A further 10 boreholes at Libreville give the following results:

- Low mineral content of the calcium-bicarbonate type of the water of the shallow boreholes: F1, F2, F3 and F9;
- Average mineral content of the sodium-bicarbonate-sulphate type of the water of the deepest boreholes, F4, F5, F6, F7 and Sobraga;
- Average mineral content of the sodium-chloride type of the RIVERA borehole, in which the bicarbonate content is similar to that of the other nine samples (unique in this sector).

Most of this ground water has a much higher salt content than the surface water currently used.

The exploitation of the ground water, the physical, chemical and bacteriological properties of which are almost without exception better than those of the surface water, could be continued over many decades without fear of depleting the stocks, which will be largely renewed by the enormous annual rainwater recharge.

III. EXPLOITATION OF THE GROUND WATER

The ground water is exploited mainly to supply urban areas, industries and villages. It has been intensively exploited since 1948.

The first Libreville boreholes were drilled in 1954. Apart from this town, Port Gentil and a few other centres, water supplies were traditionally taken from rivers, despite the cost of the installations and the operating costs of the treatment plants.

It was only a few years ago that the authorities began to consider the possibility of supplying places with ground water.

Urban supplies

Libreville

The first three boreholes (F1, F2 and F3) were drilled at Libreville in 1954, in the Petit Paris district. They were 122 to 154 m deep and tapped the Sibang limestone series, which consists of marls, limestones and crumbly sandstones of poor permeability: pumping at 25 to 46 m^3/h caused drawdowns of 17 to 42 m; the specific discharges varied from 0.9 to 1.5 m^3/h.m. and the water was of average mineral content (dry residue of 210 to 280 mg/l).

In view of the increasing requirements, three other deeper boreholes (450 to 500 m) (F4, F5 and F6) were drilled in 1960-1961 in the Gros Bouquet district. The deep water had a high mineral content (2.5 to 6.2 g/l) owing to contact with the Senomanian red series which encloses the evaporites. The water was therefore tapped from the lower Sibang series. Drawoffs of 25 to 50 m^3/h cause drawdowns of 47 to 61 m, i.e. bigger than those of the upper series; the specific discharges are 0.5 to 1 m^3/h.m.

The water, with a dry residue of 470 to 680 mg/l, has a higher mineral content than the water of the first aquifer. As a result of corrosion problems, the filters of boreholes F1, F2 and F3 were replaced in July 1960. A new installation (F7) came into service in 1965.

Boreholes F1 and F2 had to be abandoned in 1966; they were replaced by boreholes F8 and F9, of similar depths and in the same location.

In view of the low output of the installations and the increased demand, the SEEG decided to tap the water of the Nzémé, 40 km east of Libreville, with a first stage of 10,000 m^3/day. This stage was implemented in two phases. Almost as soon as they came on line the installations were barely sufficient to meet the consumption, which was 10,000 m^3/day at the end of October 1969, as against 6,100 m^3/day in August 1967.

The low-water flow of the Nzémé was then increased by diverting the waters of the Assango.

The exploitation of the Libreville boreholes was then gradually discontinued.

At present (1983) the capital's consumption is increasing by an annual average of 8.7 %. At the end of 1982 it was around 50,000 m^3/day, and the present installations (Ntoum IV) will have reached their limit in 1986 with an output of 68,000 m^3/day.

A new project (Ntoum V) has been launched to provide an additional 50,000 m^3/day, which should meet the demand for seven to eight years.

The requirement could be 175,000 m^3/day by the year 2000. In these circumstances, all possibilities of mobilizing water resources must be considered, including the resources of the aquifers in the Ntoum region: Madiela (limestone facies) and the Gamba and Ndombo series. The first action for this study was taken in 1979. In the sand-sandstone aquifers, the boreholes must be sufficiently deep to traverse the largest possible number of favourable strata (conglomeratic banks and fissured zones).

Port Gentil

Between 1951 and 1967 the population of Port Gentil increased from 9,500 to 27,000 and its annual water consumption from 350,000 to 1,500,000 m^3.

In 1968 the forecasts of population growth and water needs up to the year 2000 were as follows ("strong hypothesis"):

	1970	1980	1990	2000
Population	32,500	52,000	76,000	108,000
Domestic water consumption (m^3/day)	3,750	7,500	12,500	20,000
Industrial water consumption (m^3/day)	1,270	2,800	4,500	6,000
Total water consumption: C (m^3/day)	5,020	10,200	17,000	26,000
Water production: P = C x 1.17 (m^3/day)	5,900	11,900	19,800	30,000
Requirement in dry season: P x 1.15 (m^3/day)	6,800	13,700	22,900	35,000

The rising consumption, due in particular to the increased petroleum activities, prompted the planners to think in the short term of pumping river water from an arm of the Ogooué, 35 km from Port Gentil at Mondorobe.

The pumping station is now (1983) in operation, and the capacity of the 500 mm delivery pipe will have to be doubled in 1984-1985. Up to 1978-1979, Port Gentil took its water from the aquifer of the Quaternary sands by means of a series of small installations:

a) 105 wells, 6 to 7 m deep, laid out in five rows. In each row the wells are 120 m apart and have slotted liners at depths of 2.25 - 3.75 m (below sea level) surrounded by a filter block 0.80 m in diameter. The slotted liners are attached to a main suction line discharging into a central wet box. In 1987 the 105 wells delivered and average of 3,650 m^3/year, i.e. 35 m^3/day = 0.4 l/s per well;

b) Eight boreholes 25 to 30 m deep. These holes are set every 500 m in two parallel lines 350 m apart; each delivers 500 to 800 m^3/day, i.e. about 5,000 m^3/day in all;

c) 22 boreholes 15 to 20 m deep, drilled in 1975-1976. They are 120 to 130 m apart and deliver a total of 5,000 to 6,000 m^3/day.

The water from these wells and boreholes has remained very sweet and the problem of renewal of the resource has never arisen. Studies on this topic concluded, on the basis of the average annual rainfall of 2,000 mm, that the recharge was 1,100 to 1,200 mm and that it did not fall below 750 mm even in very dry years, i.e. 2 mm/day or 2,000 m^3/day per km^2. Infiltration over an area of 3 to 4 km^2 in 1970, and about 15 km^2 by the year 2000, would thus make good the drawoffs. The main problem of exploitation was the high concentration of iron in the water, producing clogging with hydroxide deposits which are very difficult to eliminate, so that the wells and boreholes have to be replaced periodically with similar installations. A decision therefore had to be taken to abandon the exploitation of ground water at Port Gentil and turn to river water.

Rural supplies

Most of the main interior centres take their supplies from surface water. The SEEG is thus responsible for the water supply at Akiéni, Bitam, Franceville, Koulamoutou, Lambaréné, Lekoni, Makokou, Moanda, Mouila, Mounana, Ndende, Ndjoté, Okondja, Oyem and Tchibanga. In most cases the water is taken from rivers; in the case of Mouila, Ndende and Tchibanga, it is in fact ground water which is being tapped, for the pumps are installed in resurgences of the karstic systems of the schist-limestone series. The treatment plants are expensive and the operating constraints often heavy.

But there is no other solution if the large requirements are to be satisfied in regions where the aquifers have a low yield.

The exploitation of ground water is usually more economical, for except in special cases the treatment of the water is confined to chlorination. This is why the SEEG decided to evaluate the possibilities of the ground-water aquifers. In 1981, and more so in 1982, many centres were studied by means of the electrical resistivity method: Boumango, Cocobeach, Foulenzem, Iboundji, Lebamba, Mabanda, Malinga, Mandji, Mayumba, Medouneu, Mekambo, Minvoul, Mitzic, Moabi, Moyabi, Ndindi, Ngouoni, Omboué, Onga, Ovan and Pana.

Positive exploitation boreholes have been drilled, notably at Cocobeach, Mandji, Mayumba, Moabi and Omboué.

Various water-supply projects

Several studies have been made since 1980, concerning: utilization of ground water for certain purposes, usually industrial, in particular to supply the 11 stations of the Transgabon Railway between Owendo and Booué (one borehole was drilled at Ndjoté); the implementation of the drilling programme and the installation of solar pumps; the exploitation of mineral water (Lekoni); and the development of agro-industrial complexes (Ntoum banana plantation, Hevegab hevea plantations, Ndende ranch).

Village supply, village water-supply programme

Gabon's rural water-supply programme began in 1976-1977 with a field survey covering 712 villages throughout the country. Files were established for 560 of these villages, containing social and economic data, a range of information about the water resources and needs, and proposals for ground-water research and exploitation activities; the boreholes were to be equipped with hand-operated pumps.

The location studies, using interpretation of aerial photographs and geophysical prospecting by the resistivity method, began in June 1981. The programme of works to equip 330 villages with 510 boreholes in four years was begun in February 1982.

The first sage of the works lasted about 10 months up to December 1982. With two drilling rigs in use, the following installations were completed:

Province of Nyanga: 52 boreholes, of which 46 are usable, to supply 30 villages;

Province of Haut-Ogooué: 47 boreholes, of which 41 are usable for 27 villages;

Province of Ogooué Maritime (Gamba): 8 boreholes, 2 usable:

Province of Ogooué-Lolo: 27 boreholes, mostly in granites, of which 18 are usable;

Province of Ngounié: 43 usable boreholes.

The second stage of the works was carried out in 1983-1984 in the following provinces:

Ngounié:	100 boreholes drilled,	80 equipped,	53 villages supplied;
Ogooué-Lolo:	38 boreholes drilled,	27 equipped,	20 villages supplied;
Ogooué-Ivindo:	64 boreholes drilled,	60 equipped,	41 villages supplied;
Total:	202	167	114

IV. CONCLUSION

In the immediate future and in the longer term, the development of Gabon's ground water is certainly a possibility for supplying towns, villages, industries and various enterprises; this is because the cost is moderate in comparison with the cost of using surface water and also because the ground water is of good quality.

A survey of the water resources of the whole country was made under the village water-supply programme; the amount of these resources varies greatly from sector to sector, depending in particular on the geological conditions. Over most of the country boreholes have relatively low yields but sufficient to meet the modest needs of the villages, which usually have no more than 200 to 300 inhabitants. The ground water generally has a low mineral content and is suitable for human consumption if tapped at depth. At shallow depths the ground water often has a high iron content and unpleasant colour and taste.

The hydrogeological studies have so far been carried out by foreign companies or bodies, with variable results and usually fairly high costs. The Water Department is theoretically responsible for hydrogeological studies and research, including inventories, but in fact it has no technical unit or even a specialist assigned to this work. The only Gabonese engineer, a hydrogeologist, has a managerial post in the Ministry of Energy and Water Resources.

However, there is a plan to restructure and expand the hydrology service, within the framework of this Ministry's Water Department; it will have a ground-water office, responsible in particular for inventories, documentation, hydrogeological supervision of water-drilling works, and some reconnaissance operations, with a view to preparing and making use of the ground-water studies and works entrusted to private companies or other bodies, such as the Interafrican Committee for Hydraulic Studies.

This hydrogeological unit will also have to concern itself with protection of the quality of the ground water, which is threatened by pollution by industrial - especially mining - and municipal waste water and by fertilizers and pesticides. Increasing importance will have to be attached to this work in future years owing to the increasing industrialization, especially in the areas of mining and petrochemicals.

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