ST/TCD/5

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

Natural Resources/Water Series No. 18

GROUND WATER
IN
NORTH AND WEST AFRICA

UNITED NATIONS
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NOTE

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

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CONTENTS

CONTENTS (continued)

Maps and figures

CONTENTS (continued)

FOREWORD

The Economic and Social Council, by resolution 675 (XXV) of 2 May 1958, requested the Secretary-General to take appropriate measures for the establishment, within the Secretariat, of a centre to promote co-ordinated efforts for the development of water resources. It also singled out ground-water problems as one of the priority subjects in the development of a programme of studies. Large-scale Ground-water Development, published in 1960, 1/ was the first study prepared in this field by the Water Resources Development Centre (now the Water Resources Branch of the Division of Natural Resources and Energy, Department of Technical Co-operation for Development).

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

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

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

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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 hydro-geology 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.

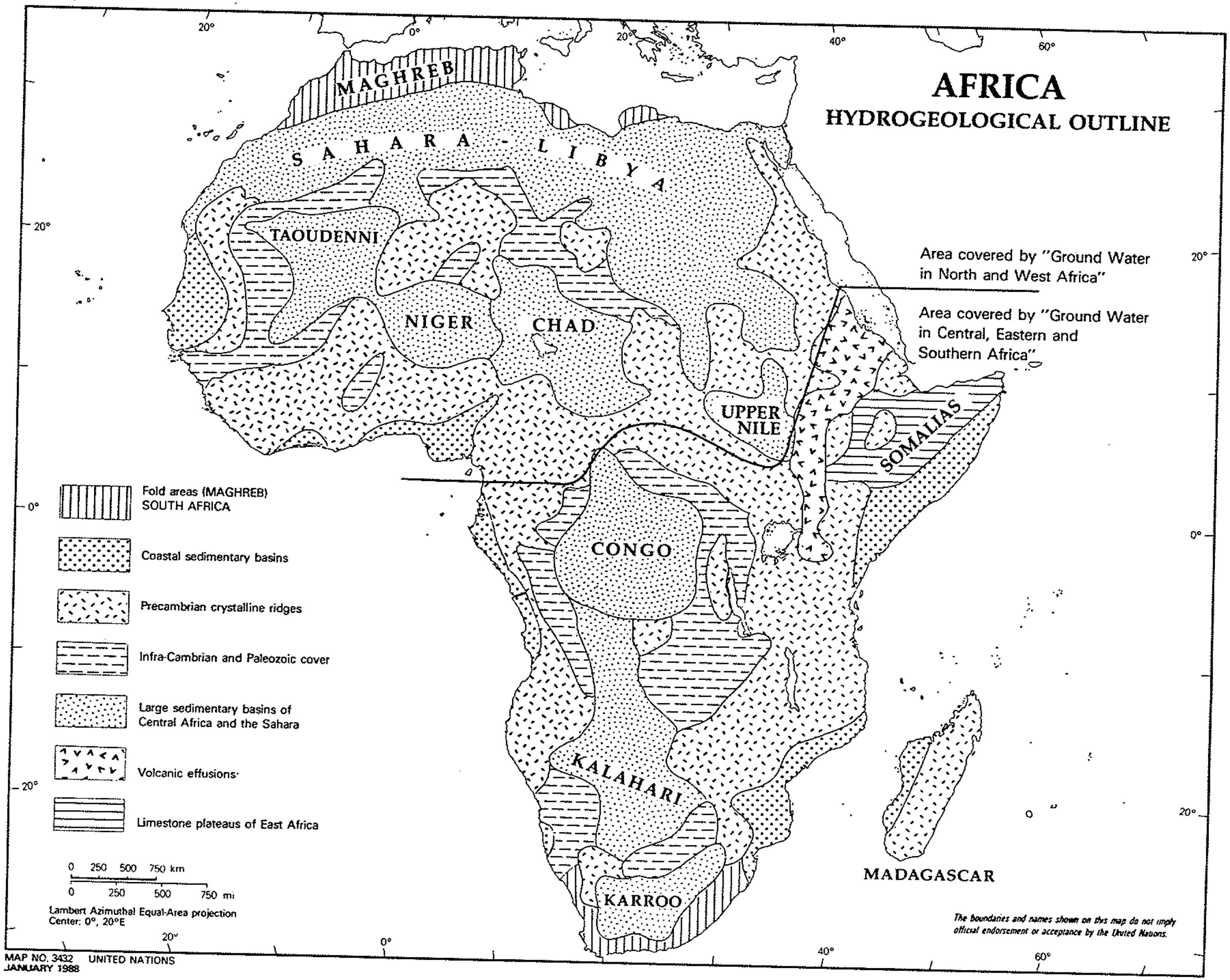
Use of a hyphen (-) between dates representing years, e.g., 1975-1978, signifies the full period involved, including the beginning and end years.

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 <u>Harmattan</u> - 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 <u>Harmattan</u> 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 sand-stone	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.

MALI

Area: 1,240,000 km^2

Population: 7.53 million (United Nations estimate, 1983)

I. BACKGROUND

Mali is a landlocked country of vast plains. In the south of the country laterized sandstone plateaus dominate vast expanses of hills and plains. The largest plateaus are the Mandigue in the west with its escarpment dominating the valley of the Upper Niger and falling away gradually northwards; in the south and south-east the Dogon plateau which extends eastwards in a line of residual buttes, including Hombori which is the highest point in Mali (1,155 m). These plateaus are bounded in the north by large, partly sandy plains; in the south they give way to hills covered with laterite cuirasses.

North of the Niger loop and the interior delta vast sandy plains (ergs) stretch as far as the borders with Algeria and Mauritania. The Adrar des Iforas in the north-east of Mali is a southwards extension of the crystalline massifs of the Hoggar.

Climate

Most of the country is subject to climatic conditions of the Sudano-Sahelian type with high average annual temperatures (26°C to 30°C), rainfall concentrated in May-June and September-October, and a long dry season of six to nine months.

From south to north there are four climatic zones with decreasing rainfall and relative humidity and increasing evapotranspiration.

The South-Sudanese zone bordering on Guinea and Côte d'Ivoire receives more than 1,300 mm of rain during a six-month wet season. The annual thermal range is low here.

The North-Sudanese zone lies between the 1,300 mm and 700 mm isohyets. Bamako, the country's capital, is situated at the heart of this zone. The rainy season lasts four to six months. The average temperatures are higher in summer than in winter.

The Sahelian zone lies between the 700 mm and 200 mm isohyets; it has a long dry season and short rainy season, with rain falling on only about 30 days a year. The annual thermal range is 12°C.

The South-Saharan desert zone has intermittent rainfall of up to 200 mm and very wide thermal ranges.

The interior delta of the Niger, which covers an area of about 30,000 km^2 in the Sahelian zone constitutes a small inland sea during the flood period from October to December and it then has a local micro-climate.

Like all the other Sahelian countries, since the beginning of the last decade Mali has been suffering the effects of many years of low rainfall, the harshest consequences of which have been felt by the rural and pastoral populations.

Surface water

Mali's hydrographic system extends over the south and centre of the country. The desert area in the north has only a few traces of ancient drains and there is no runoff.

The country is crossed by two major African rivers: the Senegal flowing westward in its upper basin; and the Niger flowing eastwards in its middle course. Half of the length of the Senegal lies in Mali. The river rises in Guinea on the slopes of the Fouta Djallon. Its upper course, called the Bafing, receives the two other upstream branches on its right bank - the Bakoyé and the Baoulé. Downstream of Kayes the river is swollen by the Faleme, which forms the frontier with the Republic of Senegal. The river's mean flow at Galougo is 669 m^3/s; in the high-water period (September) the flow is 2,800 m^3/s, falling to 15 m^3/s in the low-water period (May). The dam under construction at Manantali is located on a rocky shelf of the Bafing, upstream of its confluence with the Baoulé.

The Niger also rises on the northern slopes of the Fouta Djallon. Two-fifths (1,700 km) of its total length (4,200 km) lie in Mali. Its main upstream tributary is the Sankarani, on which the Sélingué dam has been built.

As it leaves the Mandigue plateau upstream of Koulikori its valley gradually widens until from Ke-Macina it becomes a vast alluvial plain which is flooded in the high-water period; this is the "interior delta of the Niger" which ends near Timbuktoo. At the beginning of the delta, near Mopti, the Niger receives the Bani; this river is 900 km long and its upper course, called the Bagoé, is swollen by the Degoé, Bafing and Banifing.

From Timbuktoo to the Labbezanga rapids on the Niger frontier the river describes a huge loop in a sandy desert area cut by the rocky shelf of Tossaye.

Owing to its great length, the morphological configuration of its valley and the climatic zones which it crosses, the Niger's hydrographic system varies in its different sections in Mali. At Koulikoro the crest usually occurs in September, whereas at the beginning of the interior delta it occurs at the end of October (Mopti) and at the outlet of the delta in December (Kalara). Further downstream, at Gao, the crest occurs in January.

The mean flow of the Niger at Koulikoro is 1,550 m^3/s.

Within the interior delta and at its edges are found systems of lakes fed by the flood waters, the most important of which is Lake Faguibine, west of Timbuktoo. Many of these lakes have become seasonal or have dried up following the recent drought and the consequent drop in the levels of the rivers.

The sandstone plateaus and the hilly areas are intersected by a dense hydrographic system of temporary streams created by the winter rainfall. In the partly sandy plains of the Sahelian zone the flow is intermittent and often disrupted by accumulations of sand, as in the Vallée du Serpent which used to drain the Nioro-Nara plain.

Geology

Mali's main geological systems are the Birrimian crystalline basement rock, the mainly sandstone and pelitic sedimentary formations of Lower Cambrian and Paleozoic age, the Permian dolorites, the Mosozoic intercalated continental deposits, the marine sediments of the Upper Cretaceous and Eocone eras, the continental terminal and the surface formations of varied origin and age.

Crystalline basement rock

This rock is well represented in the south of Mali. It also outcrops in the Kayes region and in the middle of the Adrar des Iforas. It consists of ancient folded and metamorphized sedimentary and irruptive rocks: micaschists, gneiss, greywackes, cipolins, quartzite, gabbros and andesites, as well as granites of varied mineralogical origin and composition.

Lower Cambrian and Paleozoic sedimentary formations

These formations have built up in the vast basins which extend over more than two-thirds of Mali.

In the Taoudenit basin which covers the whole of the central and northern parts of the country, the Lower Cambrian formation outcrops in a large circle at its southern edge. It consists of a mainly sandstone series, sometimes more than several thousand metres thick, alternating with sandstone bars of variable granulometry and mineralogy and with pelitic sequences which form the Sudano-Sahelian plateaus. Above the Lower Cambrian formation lies a thick Cambrian series of fine facies consisting of argilites and siltstones with some intercalations of sandstone, limestone and jasper in its upper part. Most of the Cambrian formation is over 1,000 m thick in the Nara trench.

In the central and northern parts of the Taoudénit basin the Paleozoic series includes Cambrian-Silurian sandstones and calcareous schists, Devonian calcareous and bituminous schists, and Carboniferous sandstones and limestones.

The Lower Cambrian formations in the Gourma basin are folded and partly metamorphized. The facies is mostly schistic with sandstone-quartzitic and limestone intercalations.

Permian formation

This formation is represented by doloritic volcanism, which is particularly well developed in central Mali where it intrudes into the Lower Cambrian and Cambrian formations in the form of dykes, sills, batholites and laccolites.

Intercalated continental formation

This formation covers an area of more than 125,000 km^2; as a rule it is difficult to distinguish it from the overlying continental terminal formation.

It consists of poorly consolidated continental deposits with sandstone-sand and gravel facies and sequences of multicoloured clay. It is more than

400 m thick in the Nara trench and may exceed 1,000 m at the eastern edge of the Iullemeden basin.

Upper Cretaceous and Lower Eocene formation

These sediments, of marine and locally lagunal origin in their lower part, are found in the eastern part of the country bordering the Adrar des Iforas and further south in the Sudanese straight and the Iullemeden basin. The facies are mostly limestone and marl-limestone with some fine sandstones and schists in the upper part.

"Continental terminal"

This complex Neogene series covers an area of 270,000 km^2 and is several tens of metres thick except in the south-east of the country where it is more than a thousand metres thick and may include Eocene strata. It consists of sandstone and non-consolidated sands, clays and argillaceous sands with laterized and silicified layers. In the Iullemeden basin, the basic detritic series is overlain by a clay-sand complex topped by argillaceous sandstone with large amounts of concretion and ferruginous oolites. Lignite and pyrite are common throughout the series.

Surface formations

- Laterites and ferruginous cuirasses are particularly common in the sandstone plateaus and the areas of Birrimian basement rock. They are of various ages and the oldest, which jut up from the smooth high surfaces, probably date from the Eocene era;

- Quaternary alluviums, mostly of fine facies, are common in the Niger basin;

- Fixed or mobile sand dunes cover vast areas north of the 14th parallel N;

- Lacustral tuffs and sebkha deposits are found in places in the Saharan and North-Saharan areas. The Taoudénit salt deposits are the best known and have long been exploited.

II. GROUND-WATER RESEARCH

Government bodies

The study and development of ground water are the responsibility of the National Water and Energy Office (DNHE) which is part of the Ministry of State for Capital Development. The DNHE carries out basic hydrogeological research, controls the well and borehole development projects, and collects and stores all ground-water data. A wells service was set up in 1974 in the same Ministry; it is responsible for large-diameter installation.

The specialized offices of the Ministry of Rural Development and the Ministry of Agriculture are responsible for several ground-water development projects.

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Research background

The first hydrogeological studies were made by the Water Service of the Department of Public Works of the AOF, including inventories of traditional water points and sinking of reconnaissance wells and boreholes. These operations and studies were summarized in a "hydrogeological map of Sudan" (J. Roure, 1957). After Mali's independence in 1960, the research was concentrated on certain regions then given priority: Gourma, northern Taoudênit basin, and Gondo plain. These studies gave most attention to the geological aspects.

It was not until 1967 with the start-up of the UNDP/United Nations project MLI/67/507 that a systematic approach was taken to the various aspects of ground-water research and exploitation. The study methodology and the criteria for installation of wells and boreholes and the drilling techniques were gradually established. The hydrogeological conditions and the possibility of developing ground water in various lithological units were also determined. During the implementation of project MLI/74/001, which followed on from project MLI/67/507, the development techniques were tested successfully although on a small scale. The transition from the phase of reconnaissance to the phase of intensive development as part of an emergency programme to counter the effects of the drought entailed the gradual refinement of the methods used, in particular the geophysical ones, with a view to minimizing the borehole failure rate and thus reducing the unit cost of the productive installations. This phase began with the implementation of UNDP/UNICEF project MLI/76/004 which provided training in the field for a large number of DNHE's national technical staff; this project was followed by several village and pastoral water supply projects, including UNDP project MLI/82/005.

Study methodology and installation of boreholes

South of the 14th parallel N, where almost all Mali's population and economic activity are found, the main exploitable water resources are contained in small local fissure aquifers. The traditional hydrogeological methods of drilling research in fissured formations are usually used in conjunction with geophysical prospecting. The experience acquired over 15 years, during which several thousand boreholes were drilled, shows that, except in very favourable local hydrogeological conditions where the water-bearing zones are in continuity over a large area, the best results are obtained when the drilling work is carried out in close conjunction with geophysical studies. The results of each drilling are immediately compared with the hydrogeological and geophysical assumptions on which the drilling was based; these assumptions are systematically reinterpreted and taken into account in subsequent drilling operations. This procedure has improved the drilling success rate in a series of UNDP projects by more than 25 per cent to an average of 70 to 75 per cent in 1983 in a sector with average hydrogeological conditions.

The traditional hydrogeological methods include studies of the terrain (geology and geomorphology), inventory of traditional water points and study of the structural conformation by means of photogeological interpretation.

A geophysical study programme is established on the basis of the hydrogeological picture. Depending on local conditions, use is made of electrical, magnetic or seismic methods, usually in conjunction with each other.

- Electrical methods: profiling (aerial geophysical prospecting) and isolated soundings are used systematically, for they usually offer the best means of solving the problems and are easy to use. They identify discontinuities in the substratum associated with less resistant anomalies and establish a provisional lithological section for the drilling operation.

- The magnetic method using a portable proton magnetometer is essential for drilling studies in sectors where doloritic intrusions are common. These volcanic intrusions are usually marked by easily identifiable anomalies in the magnetic profiles. These profiles can be obtained and qualitatively interpreted by the hydrogeologists.

- Seismic refraction is used only for very discontinuous aquifers with small permeable zones where the boreholes must be very accurately located.

Drilling techniques

The lateritic surface formations and the underlying fissured water-bearing formations are usually of satisfactory consistency for small-diameter drilling. The pneumatic down-the-hole hammer technique has proved by far the most effective in these conditions. In most cases the holes are drilled with a diameter of 6.5" to depths of about 15 m below the top of the squifer; the hole is then fully lined with 5" or 6" metal or PVC tubing. The hole is then drilled down to its final depth with a diameter of 4.5" and no tubing is installed in this rock section of good consistency.

In basement rock areas the thick surface and alteration formations are penetrated by rotary mud rigs. The fissured substratum is drilled by pneumatic down-the-hole hammer.

Some boreholes in fissured formations, especially those designed to feed water-supply networks, are fully lined; filters and a layer of stabilizing gravel are installed in the ring space and the wellhead area is concreted.

The sandstone intercalated continental and continental terminal formations are drilled with mud rigs and the holes are fully lined and equipped with filters.

The discharge of the productive wells is measured during short air-lift production tests (one to three hours) carried out by the drilling team. In the case of wells discharging more than 5 m^3/h and therefore suitable for the installation of more sophisticated means of drawoff than hand pumps, 12 to 48 hours of test pumping is carried out by the traditional air-lift method or with groups of submersible motorized pumps.

III. GROUND-WATER RESOURCES

Ground-water resources are found in two types of aquifer: discontinuous aquifers with mainly fissure permeability and continuous aquifers with intergranular permeability. Although most of the ground-water resources are stored in continuous aquifers, their geographical location renders them much less important from the economic and social standpoint than the discontinuous aquifers, which are virtually the only ones capable of meeting the village requirements and a large part of the pastoral requirements.

Discontinuous aquifers

Crystalline and metamorphic formation of the Precambrian basement rock

The ground water exploitable by borehole is found in the fissured areas of the bedrock substratum and in the coarse-grained sands. The permeability is irregularly distributed and generally low; it depends on the degree of fracturation and especially on the proportion of clay in the coarse-grained sands and on the thickness of these formations. The specific yields of the installations are low, ranging from a few m^3/h up to 20 m^3/h. The success rate of the drilling is high, above 80 per cent, when the surface formations are thick and saturated for a considerable depth. It is much lower when the surface thickness is small or the formations saturated for only a small depth. The average depth of the producing wells is about 60 m. The intermittent recharge of the water-bearing zones causes large seasonal fluctuations in the water level (between two and six metres). The water is aggressive with pH values between 5.5 and 7.7; the salt content is usually small with a dry residue below 0.5 g/l.

Lower Cambrian formations

The hydrogeological properties of these formations depend on whether they consist mainly of sandstone series with table configuration lying under a lateritic cover (sandstone plateaus) or of mainly schistic series interbedded with limestone and sandstone in a fold structure (Gourma basin).

The sandstone plateaus contain the country's main discontinuous aquifer and more than two-thirds of the wells at present in production are located here. This aquifer is divided into sections by doloritic intrusions and shelves of solid and compact rock; it constitutes a multi-layered system with stratified permeable areas associated with a number of more heavily fissured banks or banks with intergranular permeability which are linked by networks of subvertical fractures. Another hydrogeological characteristic of the sandstone plateaus is that they are in hydraulic contact with the small surface aquifers found in the lateritic formations and the intergranular altered fringe of the substratum and the underlying fissured stratum. These surface layers act as a reservoir and the much more permeable fissured zones as a drain, so that the water can be drawn off by small-diameter installations.

The Lower Cambrian sandstones are usually water-bearing for only a few tens of metres below ground level. The main stocks of water are found at a depth of 20 to 60 m and the static water level at a depth of 10 to 25 m. The piezometric surface is interrupted by the doloritic intrusions and the blocks of non-fissured bedrock; as it is very irregular, the water usually moves vertically by infiltration or evaporation.

The seasonal fluctuations in the level are large, sometimes in excess of 5 m, with an average of 2 to 3 m. Annual fluctuations are observed and there has been a general decline of several metres in the level following the period of drought during the last decade.

The permeability is very variable and depends on the degree of fracturation. The transmissivity coefficient determined during test pumping is between 2×10^{-5} m^2/s and 3.1×10^{-2} m^2/s, with averages of between 10-4 m^2/s and 10-3 m^2/s. The heterogeneity of the water bearing zones is demonstrated by the impermeable-screen phenomena revealed by several tests.

The average yield of the producing wells is about 5 m^3/h, with a success rate of 50 to 90 per cent, depending on the area and the drilling method. The water is mostly aggressive with a low salt content and an average dry residue of 0.3 g/l. Isotopic and piezometric studies have demonstrated that this aquifer has a good recharge and large exploitable resources, even though they are irregularly distributed.

In the Gourma basin the aquifers are small and closely connected with certain limestone and sandstone strata. The depth of the static water levels is more than 50 m. The permeability is low and the yield of the producing wells rarely exceeds 1-2 m^3/h. The aquifers appear to have little recharge, if any at all. To date the failure rate has been about 75 per cent. The development potential is therefore small, even for pastoral water supplies, and requires large investments.

Cambrian schists

This mainly pelitic formation is generally impermeable and contains small aquifers linked to secondary fissure permeability. The aquifers have much smaller lateral and vertical extension than those of the Lower Cambrian sandstones.

The drilling success rate is not above 50 per cent even when combined with systematic use of geophysical methods. The exploitable stocks in the boreholes are generally found at depths below 40 m, sometimes 60 m, and the yields are small. The static water level is found at a depth of between 5 and 25 m, almost always in the fissured substratum and not in the altered fringe or the surface formations. The stocks are therefore small but the exploitable resources are not negligible, for the seasonal infiltration causes piezometric fluctuations of several metres.

The transmissivity determined during test pumping is between 1×10^{-3} m^2/s and 5×10^{-5} m^2/s, with yields of between 4 and 20 m^3/h. Impermeable screen phenomena are very common, confirming the very discontinuous nature of this aquifer.

The salinity of the water is usually below 1 g/l. However, brackish water is found in places with a salt content of up to 17 g/l. The water always has a low pH value.

The average depth of the producing wells is about 55 m. The wells are lined with tubing as far as the top of the first large deposit of water.

Continuous aquifers

Intercalated continental. This formation represents Mali's main aquifer potential by reason of the size of its stocks and its great permeability. As it is located in the North-Sahelian and Saharan zones, its hydrogeology is known only in the western part and at the southern edge of the Adrar des Iforas, where it is exploited by a number of pastoral boreholes and wells.

In the Nara trench, where the ground-water horizons are deep (between 50 and 90 m), high transmissivity values (above 10^{-3} m^2/s) are associated with the sand-gravel strata, with yields above 20 m^3/h per well. At the edges of the trench clay and silt layers predominate over sand layers and the transmissivity and the yield of the producing wells decline. In this unit the water table is practically horizontal and the seasonal fluctuations nil or very small. The water is of good chemical quality.

The producing wells can be up to 150 m deep and must be fully lined and equipped with filter blocks.

In the central part of the Tadoudénit basin, on the Khenachich plateau, the intercalated continental formation contains only small aquifers, generally of fresh water.

At the edge of the Adrar des Iforas the permeable layers of the intercalated continental formation intersect at various depths, sometimes in excess of 100 m, with stable water levels between 35 and 60 m below ground level. Discharges of about 10 m^3/h have been obtained from boreholes 150 to 200 m deep. The water usually has a low mineral content.

Cretaceous-Lower Eocene

This formation contains permeable layers in the limestone and sandstone intercalations which are exploited at the edge of the Adrar and in the Tilemsi valley, with yields of a few cubic metres an hour and high drawdowns. The salinity of the water varies greatly, from fresh to brackish.

Continental terminal

In terms of the size of its stocks, this is the second largest continuous aquifer in Mali. In the interior delta it is in hydraulic contact with the surface water and the Quaternary alluviums. Yields of several tens of cubic metres can be obtained from lined boreholes equipped with filter blocks when the sand strata are thick and the water lies at depths of less than 20 m below ground level close to the Niger; but the yields decrease further away from the river owing to the combined effect of head loss and evaporation. The salinity of the water also increases from the recharge area in the delta zone towards the Azaouad basin. This aquifer is exploited by several traditional wells with depths of 20 to 60 m depending on the distance from the river and the depth of the horizon.

In the Sudanese straight the water levels are usually not lower than 40 m, but they can be more than 100 m deep further west and south in the Gao trench where the continental terminal becomes very thick. Geophysical prospecting indicates that the water becomes brackish towards depths of 200 m.

Surface formations

The alluvial deposits in the central delta zone constitute a single hydraulic unit with the continental terminal. However, the possibility of exploiting them by means of small-diameter wells is clearly less owing to their finer facies.

The dune formations can contain small local aquifers, the size of which is difficult to determine and depends on the nature of the substratum. These formations are important only because of their capacity rapidly to absorb the short heavy showers and thus provide part of the recharge of the underlying aquifers.

The lateritic formations contain local aquifers traditionally exploited by the villagers and herdsmen of the Sahelian and Sudanese areas by means of tens of thousands of wells and sumpholes. These aquifers are in hydraulic contact with the underlying fissure aquifers.

Current studies

As part of its priority activity of establishing new water points, in 1982 the National Water and Energy Office initiated in collaboration with UNDP and the United Nations (project MLI/82/005) several studies with the medium-term goal of evaluating the country's ground-water sources and determining their location and mode of exploitation in the various regions.

Computerized records of the water points throughout the country are being prepared. They will serve as the basis for the inventory of the country's water resources, the identification of new development projects and hydrogeological summaries.

Piezometric observation networks are gradually being established in the main aquifers; they cover the various climatic zones and monitor the natural fluctuations in the water levels. In the 1983 rainy season, even though the rainfall was less than usual (60 to 70 per cent of the average), the levels showed a general recovery in the Sahelian and Sudano-Sahelian areas, with average ranges of about one metres in the aquifers of the fissured substratum (Lower Cambrian sandstone and Cambrian schist) and of almost five metres in the aquifer of the lateritic cover.

Detailed studies have been undertaken at several sites of intensive pumping with a view to estimating the local ground-water resources and the recharge in the area of discontinuous aquifers. The first results indicate that at Tioribougou the direct infiltration represented about 20 per cent of the rainfall in the 1983 season, which was estimated at 530 mm, with an effective storage coefficient in the Lower Cambrian table sandstones of about five per cent; the renewable resources can therefore be estimated, as an initial approximation, at about three cubic metres per day per hectare for the local aquifer. These detailed studies were to be continued and multiplied during the period 1983-1986 and extended to other hydrogeological and climatic regions, so that an informed approach can be taken in the establishment of the balance of ground-water resources.

IV. EXPLOITATION OF GROUND WATER

Government bodies

The Ground-Water Division of the National Water and Energy Office (DNHE) is responsible for the technical control of all drilling projects for ground-water development and it manages all the village water-supply projects. In 1984 it employed about 70 qualified persons, half of them engineers (hydro-geologists, geophysicists, drillers), and the other half geological technicians, specialist foremen and administrators. There are a further 50 contractual staff: labourers, drivers, drilling hands. The DNHE has seven regional bases: Bougouni, San, Gao, Bamako, Kita, Timbuktoo and Mopti-Sévaré.

The body responsible for drilling operations installs large-diameter wells of modern design for both village and livestock purposes. In the past it encountered a number of difficulties and the results were sometimes disappointing owing to the lack of hydrogeological reconnaissance work.

The adoption of stricter management methods and closer collaboration with the DNHE with respect to basic hydrogeological studies for the installations should enable it to play its proper role in the development of ground water. At present it has about 300 permanent and contractual staff; it has a head office at Bamako and six regional offices; it operates in 14 sectors.

Position of ground-water development in 1983

Up to 1976 most of the boreholes were drilled during reconnaissance missions to evaluate the possibility of developing the main aquifers or during implementation of small local water-supply projects.

Since 1976 a number of large regional village water-supply projects have been undertaken; their number and size have grown with time.

The work carried out under the main projects up to July 1983 is listed in table 1.

The inclusion of the boreholes installed under small local projects and those installed before 1970 produces a total of 4,300 boreholes installed in Mali, including 2,500 classified as producing, with a minimum yield of 0.8 to 1 m^3/h. Of this total, about 1,500 are at present equipped with pumps: 1,300 with hand or foot pumps; 50 with solar-energy pumps; and 150 with motorized pumps.

About 450 large-diameter wells were installed between 1974 and 1983 by the body responsible for the wells operation.

As the Rural Water Service installed a similar number of wells between 1958 and 1973, the country now has 900 "modern" village and pastoral wells (with concrete lining and standpipe).

Water-point projects in the period 1983-1986

Work is to be continued under all the big village water-supply programmes launched in the last decade. Several new projects have also been undertaken since 1983-1984. The plan was to install some 4,300 boreholes, almost 90 per cent of them for village water supplies. Given an average success rate of about 65 per cent, the number of new producing holes can be estimated at about 2,800, which means that the number of producing boreholes would have doubled by 1986. The amount of work planned under the various projects is indicated in table 2. The number of wells was also to increase by almost 600 during the same period.

In 1986 the drilling equipment available to the DNHE under the various projects should have totalled 16 to 18 units manned by qualified national technicians. The total implementation capacity was to be close to 1,400 holes a year.

Overall estimate

The number of new water points to be established in the medium term is very large and it illustrates the amount of work still to be completed and the amount of financial resources to be found, even for a small daily allocation per inhabitant (20 to 30 litres).

Village water supply. Mali has almost 10,000 rural settlements of less that 2,000 inhabitants. With one hand pump for 200 inhabitants and at least two pumps for each settlement, the number of water points needed to meet the needs of the rural population totals more than 30,000, of which less than 2,000 have so far been installed.

Table 1

Ground-water development studies in Mali up to July 1983

Project	Financing	Purpose	Drilling unit (1983)	Drilling operations: No.	Average success rate (%)	1982/83 campaign	1982/83 success rate (%)
UNDP projects (1967-83	UNDP UNDP/UNICEF	Hydrogeological reconnaissance - village water supply	1 FORACO SM-70 1 AC Aquadrill 441 1 AC Aquadrill 661 1 Failing 1500	1,655	50	196	70
MALI AQUA VIVA (1976-83)	NGO/EC Central Fund	Village water supply	2 FORACO SIS-66 1 FORACO	1,300	80	157	85
HELVETAS (1977-83)	Swiss co-op	Village water supply	1 FORACO SIS-66	420	80	75	80
Bandiagara (1978-83)	CARITAS	Village water supply	1 STENUIK HST-35	234	70	57	70
JICA (1978-83	Japanese co-op	Village water supply	1 TOP-200 1 TOP-300	36	90	15	80
ODEM (1977-83)	World Bank	Pastoral water supply	1 FORACO SIS-66	74	60	9	90
Mali South 1 (CMDT) (1983)	ABEDA	Village water supply	1 POLYDRILL-500 (enterprise)	18	80	18	80
Gao-Anderabou-kane road (1977-78	UNSO/ Netherlands co-op	Village and pastoral water supply	1 Failing 1500	15	-	-	-
West Sahel (1977-82)	Saudi Fund	Pastoral water supply	-	326	45	-	-
Kayes-Yélimané (1974-75)	FAC	Village water supply	-	26	45	-	-
Bafoulabé-Kéniéba (1974)	World Bank	Village water supply	-	61	40	-	-
			Total	4,165	65	527	

Table 2

Ground-water development projects in operation in 1983-1986

Project	Period	Financing	Purpose	Works planned
1. Continuation of earlier projects				
MLI/82/005	1983-85	UNDP UNDP/EDF? V	Village and pastoral water supply	750 boreholes 6 wells
Mali Aqua Viva	1983-85	FAC EC Central Fund	Village water supply	320 boreholes 25 wells
Helevetas	1983-86	Swiss Cooperation	Village water supply	300 boreholes
Bandiagara	1983-86	CARITAS	Village water supply	200 boreholes/ wells
PRODESO	1983-84	Saudi Fund	Pastoral water	34 wells
JICA	1983-84	Japanese co-operation	Village water supply	20 boreholes
Kaarta	1981-84	USAID	Village water supply	12 wells
Mali South 1 - CMDT	1983	ABEDA	Village water supply	42 boreholes
Gao-Menaka	1983-86	ADF	Village and pastoral water supply	275 wells
2. New projects				
UNICEF (Mopti - Timbuktoo)	1983-85	UNICEF/UNDP	Health/educ. infrastructure	144 boreholes
Route du sel (Timbuktoo-Taoudenit)	1983-84	UNDP	Creation of oasis	35 boreholes
Mali South 2 - CMDT	1984-86	EC Central Fund/ World Bank	Village water supply	450 boreholes
CEAO (Kayes-Koulikoro)	1983-85	EC Central Fund	Village water supply	480 boreholes 61 wells
Liptako-Gourma	1984-85	ADB/Kuwaiti Fund	Integrated dev.	51 boreholes 95 wells
Ground-water Koulikoro-Segou	1984-85	Saudi Fund	Village water supply	400 boreholes
Kita	1984-86	World Bank	Village water supply	580 boreholes
Ground water (Gondo)	1984-86	EDF V	Village water supply	100 boreholes 80 wells
Ground water (Kati-Bamako-Kangaba)	1984-86	Italian co-operation	Village water supply	350 boreholes
ODIK (Kaarta	1984-86	Canadian co-operation	Integrated dev.	100 boreholes
			Total: 4286 boreholes: 588 wells	

Table 3

Water-point requirement for village water supplies

Administrative region	Number of settlements with fewer than 2,000 inhabitants	Water points		
		Needed	Existing	Balance
Kayes	1,356	4,260	152	4,108
Koulikoro	1,792	5,403	551	4,852
Sikasso	1,654	5,315	508	4,807
Ségou	2,109	5,883	553	5,330
Mopti	1,931	5,992	150	5.842
Timbuktoo	667	2,225	8	2,217
Gao	340	1,352	27	1,325
Total	9.849	30,430	1,949	28,481

Urban water supplies. According to the 1976 census, there were 300 settlements with more than 2,000 inhabitants. Now, some 10 years later, there are probably more than 350, as a result of population movements caused by the persistent drought. The number of boreholes needed for water supplies in these settlements depends on several factors, in particular the local hydrogeological conditions and the effective yields of the holes. The total will be about 1,500 to 2,000 boreholes.

Pastoral water supplies. The requirement for pastoral water points situated mainly in the Sahelian zone should be evaluated on the basis of the national livestock development programme. The requirement is for several thousand water points scattered over areas of difficult access for which little hydrogeological information is available. Pastoral water points also require special installations to facilitate the speedy watering of the herds: large-diameter wells, motorized pumps, storage facilities, etc.

Problems of exploiting ground water

In the short and medium-terms the exploitation of ground water should not give rise to any serious problems with respect to water quality and conservation resources.

The salinity of the main exploited aquifers is low and they are recharged periodically during the rainy season by direct infiltration or migration of surface water. Furthermore, the dispersed mode of exploitation for both village and pastoral water supplies does not have a serious impact on stocks. In the areas of lateritic surface formations, the surface aquifers traditionally exploited by village wells will have their levels reduced by the exploitation of the underlying fissure aquifers. However, this effect could be limited if pools were quickly established above the villages to facilitate the artificial local recharge of the surface aquifers.

In certain regions such as Gourma, where the aquifer is deep and has no apparent recharge, the levels may decline as a result of the exhaustion of local stocks, which appear very limited owing to the small size of the permeable zones.

V. CONCLUSIONS

In the long term the development of ground water should be capable of meeting the water requirements, in quantity and quality, of the rural population and of the transhumant livestock which constitutes one of the country's main resources. It will help to stabilize village dwellers by furnishing them with a permanent water supply regardless of climatic uncertainties and in some cases offering them additional income from the small irrigation projects associated with the modern wells.

The ground-water potential is of course limited. The deposits are contained in aquifers with poor permeability and storage properties but which are sufficient for small-scale widely dispersed exploitation and for village and livestock needs. In addition, the winter rains and the migration of surface water guarantees a sufficient volume of renewable resources throughout the part of the country south of the 15th parallel N where almost all population lives.

In recent years the ground-water projects have been concerned mainly with the establishment of boreholes and other installations which could be completed quickly. But the authorities have not been neglecting the digging of large-diameter wells, for they do not have the pump maintenance problems common in pastoral areas. In 1983 the average cost of a cubic metre of water at the wellhead was between 80 and 120 Mali francs, with an installation cost of about FM 5 million for boreholes and FM 10 to 14 million for modern wells.

The national ground-water development policy takes into consideration both the hydrogelogical conditions and the way of life of the people. Now that a local industry has been established for the manufacture of hand pumps, the conditions seem to be met for the country to take charge in the medium term of the whole of its "water chain".

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