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
New York, 1988

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.

ST/TCD/5

UNITED NATIONS PUBLICATION

Sales No. E.87.II.A.8

04550

ISBN 92-1-104203-8

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FOREWORD

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

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

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

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

1/ United Nations publication, Sales No. 60.II.B.3

2/ United Nations publication, Sales No. E.71.II.A.18.

3/ United Nations publication, Sales No. E.71.II.A.16.

4/ United Nations publication, Sales No. E.76.II.A.5.

5/ United Nations publication, Sales No. E.82.II.A.8.

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

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

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

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

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

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

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

Explanatory notes

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

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

A blank indicates that the item is not applicable.

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

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

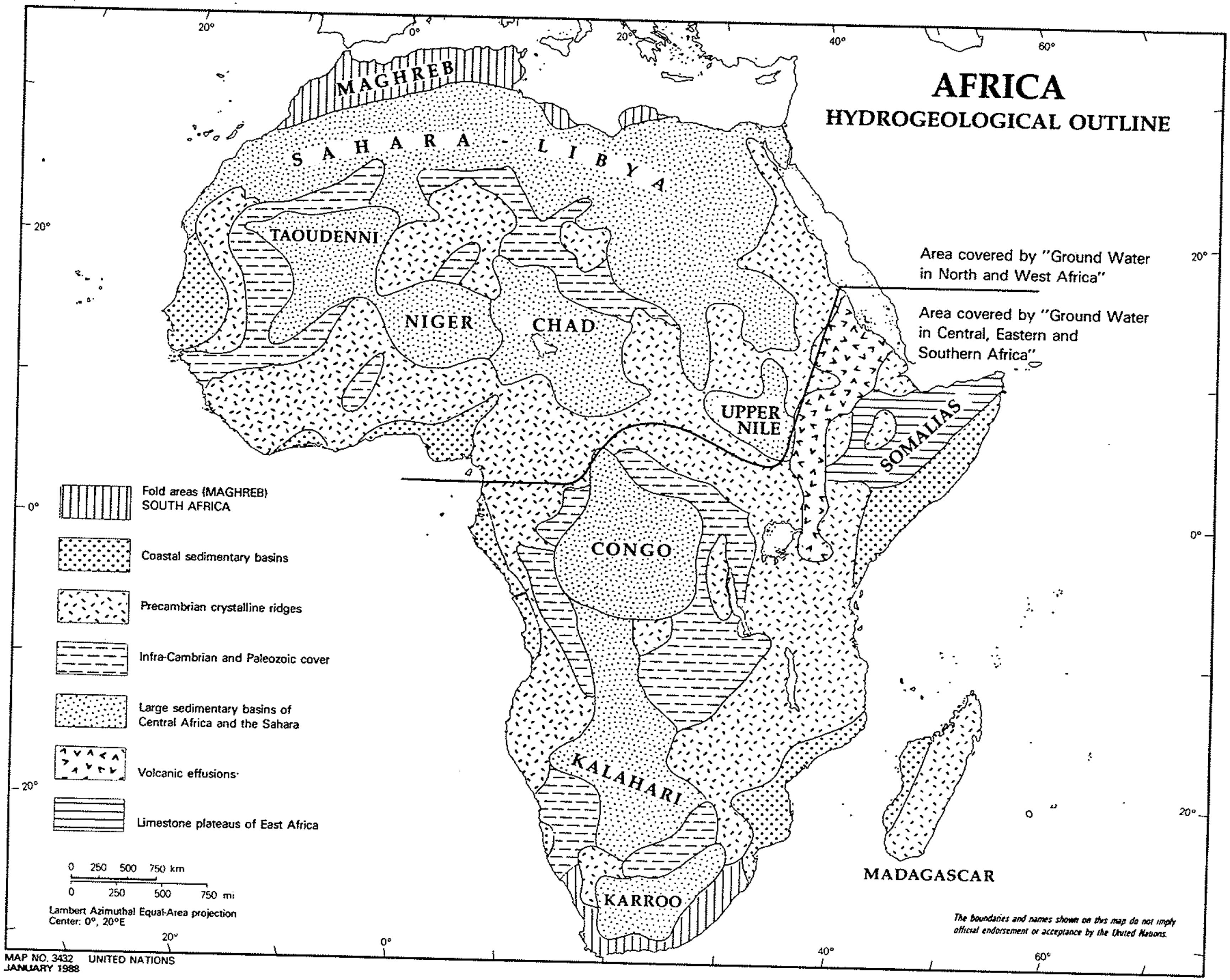
Use of a hyphen (-) between dates representing years, e.g., 1975-1978, signifies the full period involved, including the beginning and end years.

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

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

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

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


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

PART ONE

OVERVIEW

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

I. LARGE AQUIFER SYSTEMS

This vast territory of 17.2 million km^2 with 300 million inhabitants can be subdivided on the basis of geological, morphological and climatic considerations into a number of large aquifer systems in which the ground-water resources can be reasonably well distinguished from the standpoint of their accumulation, their fossil or renewable state and their accessibility.

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

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

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

iv) The crystaline Precambrian basement rock underlying these sedimentary basins emerges in great masses at the west-east axis of the Sahara: Tiris-Adrar, Yetti-Karet (Mauritania-Algeria). The Hoggar mountains which rise to almost 3,000 m in volcanic peaks (Algeria) flanked in the south by the ranges of Adrar des Iforas (Mali) and Aïr (Niger), Tibesti (Chad), Ouaddai (Chad), Darfour (Sudan) and the majority of the territory to the east of the Nile as far as the Red Sea. As far as ground water is concerned, this is a mainly barren region, with the exception of a number of alluvial deposits at the foot of the mountains. When present - a fairly rare occurrence - the ground water is far from abundant and in many cases heavily mineralized.

v) To the south of this ancient backbone the general situation of the aquifers is fairly similar to the one found in the north; here too there are enormous sedimentary basins subject to a desert climate, with hard and unproductive Paleozoic strata in the west (Tagant, Mauritania), except for a number of limestone layers, and with sandstone strata in the east: intercalated continental (Azaouad in Mali), the Aïr sandstone in Niger and the Nubian sandstone further east, which contain fossil aquifers.

vi) The Chad basin, occupied in its centre by the eponymous lake which is shallow and has declined in size over the last decade, is formed by a complex of sediments of various ages, mainly recent, Quaternary and Cenozoic, in which the ground-water resources are considerable: in places artesian, but with relatively low unit yields per well, for the clay strata are frequent and extensive.

vii) The basement-rock areas of West Africa which cover the majority of the territory of Guinea, Sierra Leone, Liberia, Côte d'Ivoire, Ghana, Togo, Benin, Burkina Faso and Cameroon, as well as large areas of Mali and Nigeria. The rocks are exposed to Sudano-Sahelian climatic conditions and are water-bearing in their altered and fractured parts. At its northern edge the crystalline shield of western Africa is flanked by a sandstone rim of Precambrian or Paleozoic age which constitutes a major aquifer in Mali and Burkina Faso. The unit yields obtainable from the wells or boreholes are not large except in a few cases (Bobo Dioulasso sandstone) but they are usually sufficient for village and livestock needs. The sedimentary basins in the central part of Niger, along the axis of which run the River Niger and its main tributary the Benoue, which has its source in Cameroon, are made up mainly of gray argillaceous Cretaceous formations containing artesian aquifers.

viii) The coastal sedimentary basins are very different in extent, the largest being the Senegalese-Mauritanian basin which runs southwards into Guinea-Bissau. Then come the bevel-shaped coastal basin of Nigeria which narrows towards the east (Cameroon) and towards the west (Benin, Togo, Ghana), and the very narrow but economically important coastal basins along the shoreline of Guinea, Sierra Leone, Liberia, Côte d'Ivoire and Ghana. These basins contain recent, Quaternary and Cenozoic sediments with very productive sandstone and limestone layers. They are intensely exploited - sometimes overexploited.

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

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

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

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

The temperature ranges are very small in the equatorial regions (1°C) but increase in step with distance from the equator; they are from 20°C to 30°C in the Sahara.

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

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

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

The annual rainfall is two to six metres along the coast of West Africa from Conakry to Abidjan and from the Niger delta to Libreville in Gabon; one to two metres in some mountainous regions of the Maghreb and south of the line from Dakar to Mogadishu; 500 to 1,000 mm in the High Atlas, in the coastal regions of Algeria and Tunisia and in a strip 300 to 500 km wide to the north of the line mentioned above; less than one metre to the north of the line from Nouakchott to Port Sudan, with the exception of the Maghreb, the majority of this region receiving less than 20 mm.

Climatic zones

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

- Mediterranean zone with dry summers (hot season) northern Maghreb.

- Steppe zone with the following subdivisions:

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

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

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

- Desert zone with Saharan climate (Sahara).

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

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

Aridity and evaporation

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

The surface aquifers (lakes) undergo large variations in level owing to the imbalance in some years between the headings "evaporation" and "recharge". This is particularly true of Lake Chad. It is also true of the unconfined ground-water aquifers when the piezometric surface is shallow in comparison with the soil. Evaporation produces - and can be measured by - concentrations of salts in the aquifers. The question of the depth to which evaporation takes place is disputed. However, all authors agree that this effect operates for several metres (five metres on average and as deep as eight to ten metres). Some authors speak of much greater depths.

Conclusion

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

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

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

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

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

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

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

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

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

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

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

III. PRODUCTIVITY OF THE AQUIFERS

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

Extensive sand formations

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

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

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

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

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

Terminal continental sandstones and conglomerates (Late or Post-Cretacean

Terminal continental

Burkina Faso	Bobo Dioulasso	-	90
Mali	Gondo	-	50 to 100 (up to 300/day)
Mauritania	Trarza	Sandy intercalations	1 to 4
	Bennichab	Sandy intercalations	30
	Nouakchott	Sandy intercalations	15
Senegal	Casamance	Argillaceous sand-sandstone	6 $m^3/h/m$
Togo	Lomé-Agouévé	Variegated sandstone	5 to 40 $m^3/h/m$

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

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

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

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

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

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

These few examples show that the karstified limestones of North-West Africa can yield rates of flow often in excess of 50 m^3 per hour, sometimes as high as 100 and even several hundred in certain cases.

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

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

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

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

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

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

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

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

Precambrian and Paleozoic hard sandstones, schist-sandstones and quartzites

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

Schists (mainly Precambrian and Paleozoic) and clays

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

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

Examples of available yields per well and borehole in crystalline zones

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

In summary, a flow rate of 5 m^3/h is a good one for granites and granitogneiss; a rate of 1 m^3/h is considerable for mica schists and metamorphic schists. Better yields are obtained in the quartzy zones.

Crystalline and metamorphic rocks (basement formations, granites and gneiss

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

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

Volcanic rocks

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

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

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

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

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

Conclusion

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

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

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

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

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

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

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

IV. EXPLOITATION OF THE GROUND WATER

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

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

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

Traditional wells and drains

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

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

The well systems described in the Bible and very numerous in Iran, where they are called kanats, are widespread in northern Africa where the total length of the galleries amounts to several thousand kilometres. In Egypt and the Sahara they are called foggaras; in Morocco, rhettaras. This system makes it possible to obtain the ground water from the soil without using dewatering methods. The galleries are first built as trenches which climb underground until they intersect over a certain length the saturated formations to be drained. The length of the galleries is limited by the maximum depth of the "head well", which depends on the techniques used and the nature of the terrain.

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

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

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

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

Wells drilled and dug by modern methods

In the deserts the discovery of ground water by deep drilling is essential for oil exploration works, especially for the mixing of drilling mud and the raising of oil by injecting water under pressure. The general geological studies and the geophysical studies carried out for this purpose have led to the identification of deep confined aquifers which have then been exploited by means of artesian boreholes. Thus, even before the proclamation of their independence the African territories under British administration benefitted from the experience acquired in oil exploration in the Middle East during the second quarter of the twentieth century and from the progress made in the same period by British and Swedish manufacturers of drilling equipment for the exploitation of ground water. In French Africa drilling for water also underwent a great expansion, especially from the time when oil exploration activities were started in the Sahara, i.e. from the 1950s.

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

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

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

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

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

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

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

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

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

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

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

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

CONCLUSION

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

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

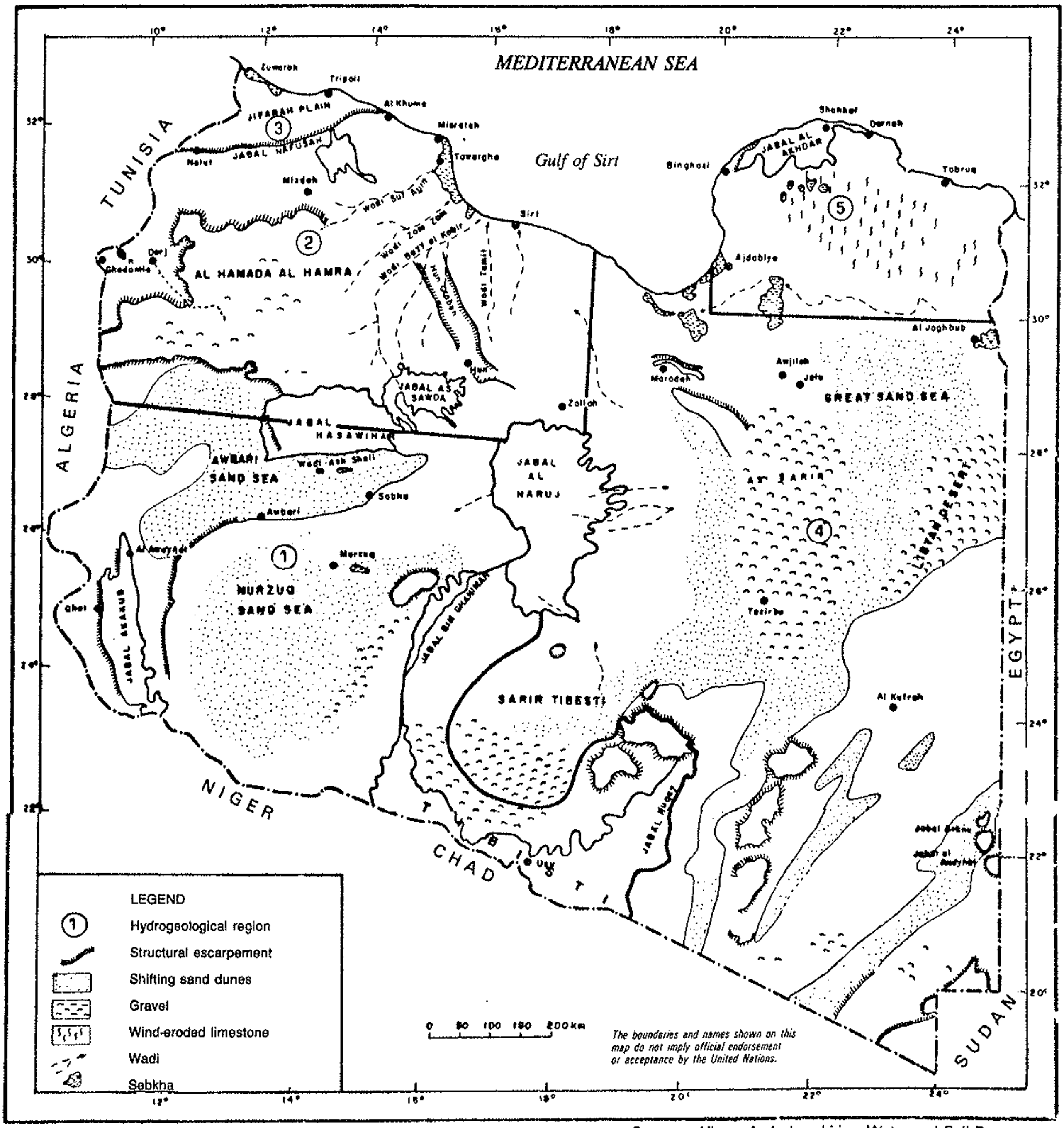
Furthermore, ground-water prospecting and the drilling and digging of wells are usually difficult and expensive operations owing to the weakness of the infrastructures, the unfavourable natural conditions, the remoteness of the zones to be reached and the wide dispersal of the villages, as well as the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

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

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

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

LIBYAN ARAB JAMAHIRIYA
MORPHOLOGY



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Source: Libyan Arab Jamahiriya, Water and Soil Department

LIBYAN ARAB JAMAHIRIYA

Area: 1,775,600 km^2

Population: 3.36 million (United Nations estimate, 1983)

I. BACKGROUND

Topography

Libya is a country of vast plains. It has 1,900 km of Mediterranean coastline. The main mountains are the Jabal Nafusah and the Jabal Akhdar in the north along the coast, the Jabal Sauda (803 m) and the Jabal Haruj (1,200 m) in the center, and the Toammo (1,022 m), Tibesti (2,300 m at Kamet) and Archenu (1,460 m) in the south.

The Jabal Nafusah (600 to 800 m) dominates the triangular coastal plain of Gefara, which has much better climatic conditions and soil and water resources than the rest of the country. It is therefore densely populated and has the capital, Tripoli, and several major urban centres. This plain supplies most of the country's farm production.

A similar situation, although on a lesser scale, is found in the north of the country, where Jabal Akhdar (500 to 800 m) dominates the coastal plain of Benghazi where the town of that name is located.

South of the Jabal Nafusah lies the vast desert plateau of Hamadah al-Hamra (500 to 600 m).

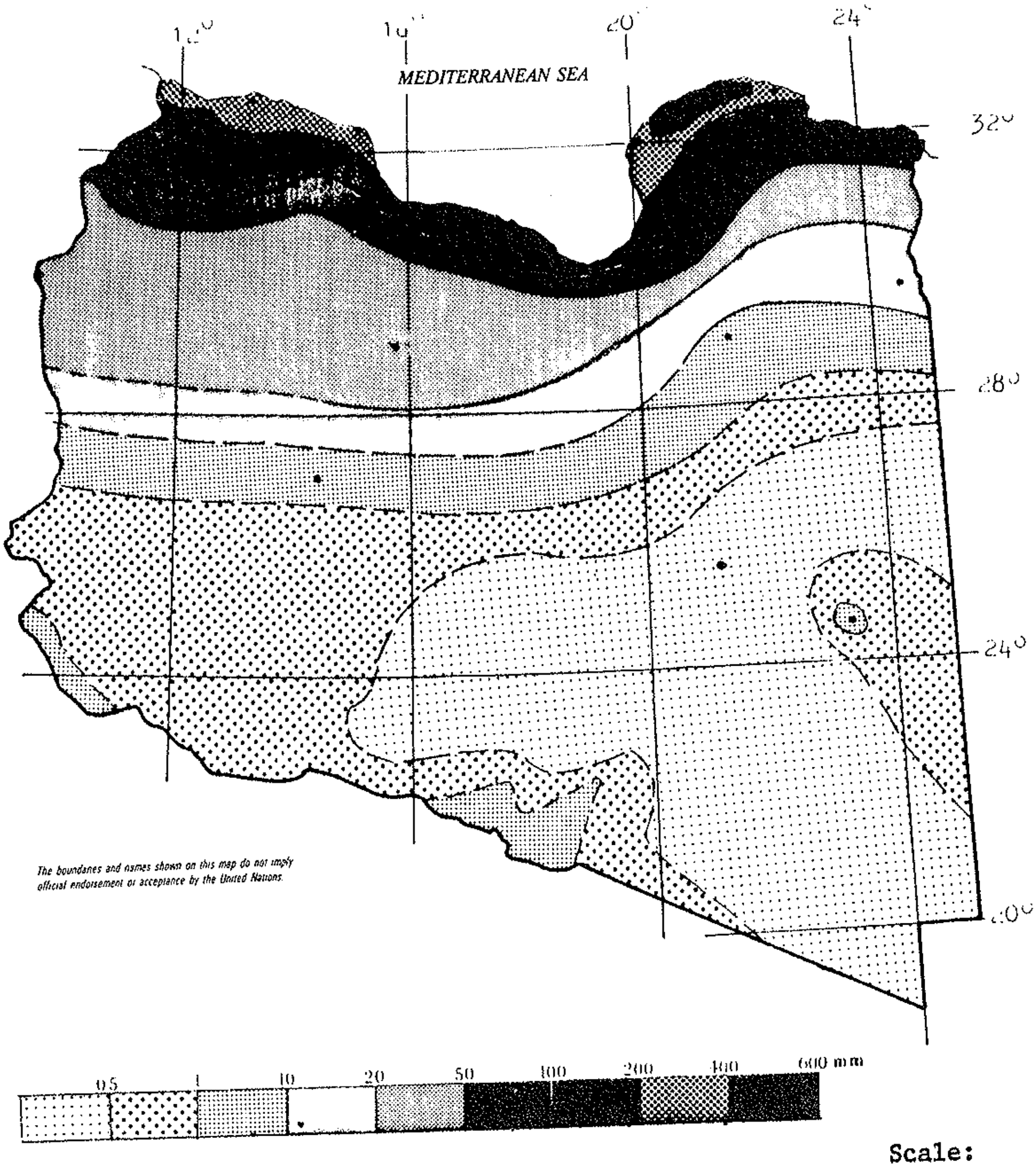
The Murzuq basin ("Edeyin"), which is covered with sand dunes, is found in the south-west of the country. Its northern part is known as Edeyin Awbari. In the south-east of the country lies the immense Kufrah basin which reaches the Egyptian frontier and rises to an altitude of 100 m in the north and 800 m in the south. In the north are found expanses of gravel and sand dunes and in the south expanses of gravel, stones and rocks with many small areas of sand dunes. There are other flat and desert areas: the Syrt desert north of the Jabal Haruj and the Sarir Tibesti to the south. The first area is a westward extension of the Kufrah-Sarir and rises from the coast to an altitude of 250 m at the foot of the Haruj. The second area is linked to the Kufrah basin by a fairly narrow strip of land between the Haruj and Nuquay mountains; it is bounded in the south and west respectively by the Tibesti and Bin Ghunaymah mountains. The Sarir Tibesti desert lies at an altitude of about 500 m.

Climate

The climate is influenced by the Mediterranean in the north and the Sahara in the south. The lack of continuous and high relief in the north of Libya - in contrast to the countries of north-west Africa (Tunisia, Algeria and Morocco) - renders the coastal area vulnerable to the flows of hot dry air from the south. There are five climatic zones:

Subtropical Mediterranean zone, which is small in extent and bounded by the Jabal Akhdar.

LIBYAN ARAB JAMAHIRIYA
AVERAGE ANNUAL PRECIPITATION



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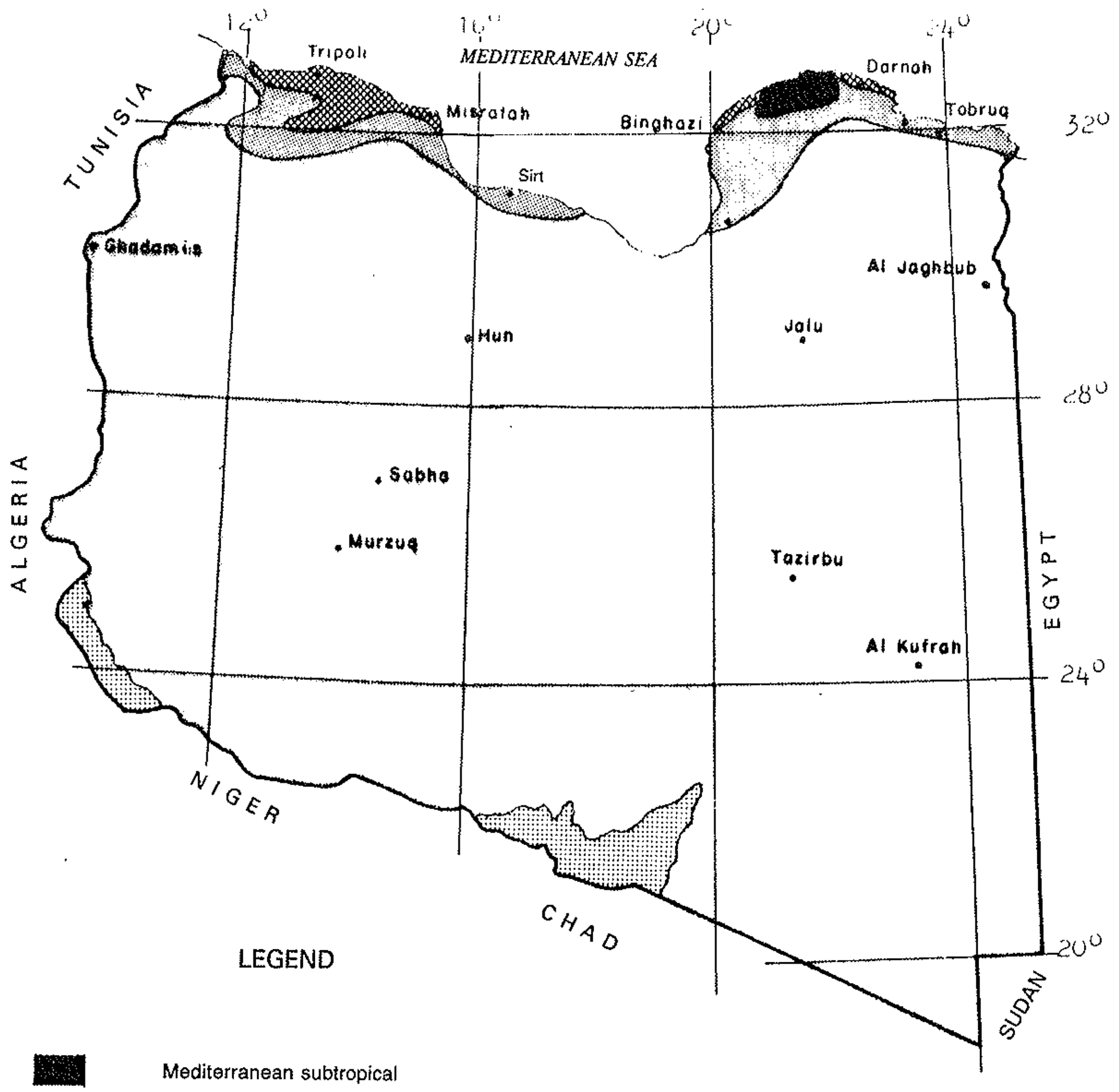
LIBYAN ARAB JAMAHIRIYA
CLIMATE ZONES



LEGEND

- Mediterranean subtropical
- Semi-Mediterranean
- Steppe
- Desert
- Unclassified mountain climate

The boundaries and names shown on this map do not imply official endorsement or acceptance by the United Nations.

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Scale
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Semi-Mediterranean zone, with a narrow coastal strip in the west which widens in the east to include the whole of the Gefara plain and the eastern part of the Jabal Nafusah and terminates at the Town Of Misratah; it then reappears along a narrow strip between Benghazi and Darnah.

Steppe zone, which lies along the southern slopes of the Jabal Nafusah and Jabal Akhdar and also includes the area between Ajdabiya and the eastern frontier with Egypt.

Desert zone, which extends over the rest of the country with the exception of the mountainous areas in the south and south-west.

Mountain zone, in the south-west (Ghat) and south (Tibesti).

The temperature at the coast is 10°C to 14°C on average in winter, with a minimum of 0°C; in summer the hot dry winds from the Sahara can raise the temperature as high as 40°C.

Further from the sea is the steppe zone the temperature ranges are wider. At Al Aziziyah, for example, the world's highest temperature was recorded: 58°C in September 1922. However, the average for July is 24°C to 28°C, as against 10°C to 14°C in January. Temperatures of -3°C have been recorded in winter. It can snow on the upper slopes of the Jabal Nafusah and Jabal Akhdar.

The daily variations are even more marked in the desert zone. The averages range from 26°C to 41°C for July and from 8°C to 16°C for January. At Ghadamis the absolute minimum is -2°C in November, -5°C in December, -6°C in January and -8°C in February; the absolute maximum is 45.7°C in April, 46.8°C in May, 50.6°C in June, 49°C in July, 49.8°C in August, 45.2°C in September and 45.8°C in October.

The relative humidity falls from north to south. The highest levels occur in winter. They decline considerably in summer. The humidity ranges from 70 to 80 per cent on the coast from December to February and falls to only 50 per cent in June-July. The figures for Sabha range from 40 to 50 per cent in winter and decline to 20 per cent in summer.

The force and direction of the winds often vary from day to day throughout the seasons. The winds blow from the north and east from May to October and from the north and south-west from November to April. They blow at around 5 to 15 knots.

The evaporation rates are high, with a maximum in June-July and a minimum in December-January. The average annual values measured in the Piche evaporometer increase steadily from north to south, with 1,700 to 2,500 mm on the coast and 4,000 to 5,000 mm towards the interior (6,100 mm at Kufrah).

The rain falls in winter, mainly from October to March, and the amount declines towards the south. The maximum annual amounts are found along the Jabal Akhdar (400 to 600 mm); they decline to 200-400 mm towards Misurata in the west and Ajdabiya-Darnah in the east. The 100 mm isoyhet is parallel (150 km) to the coast which it follows for almost the whole length of the Gulf of Syrt. The rainfall is vestigial at best south of the 30th parallel N.

The opposing effects of the Mediterranean and the Sahara cause great irregularity in the rainfall pattern. Brief and violent storms are the rule, with as much as 100 to 140 mm of rain falling in a single day.

Hydrographic system

Libya has little surface water and this source provides only a small part of supplies.

The country has no permanent watercourse. The coastal wadis flow for short periods during the winter months: these flows use beds gouged in the Gefara and Benghazi plains to reach the sea. Some wadis flow from the same mountains (Jabal Nafusah, Jabal Akhdar) but towards the south.

Some wadis are larger in terms of the size of their basins and length of their courses; they rise at the eastern end of the Mamada plateau and reach the coast between Misratah and Sirt. They include Wadis Sawajjin, Bay al Kabir and Zamzam.

The Jabal Nafusah has 30 hydrographic basins with a total area of 7,500 km^2 and an annual flow of 77 million cubic metres. These basins receive 1,700 million cubic metres of rainfall a year. The wadis have a maximum flow of between 10 and 250 m^3/s for short periods (a few hours). The flow coefficients are in the order of 2 to 20 per cent.

Towards the east there are three wadis with basins larger than 1,000 km^2. Several others have basins smaller than 100 km^2. The sediment discharge can be as high as 132 $t/km^2/year$ with a mean annual flow coefficient of three per cent. Several earth dams have been built to store the flood waters.

There is a large number of small springs, but many of them have dried up in recent years on the Jabal Nafusah and Jabal Akhdar. The country's two main springs are the Ain Tawurgha east of Misurata and the Ain Zagyanah east of Banghazi. The Ain Zagyanah is a karstic spring which yields 90 million cubic metres a year; the Ain Tawurgha yields about 60 million cubic metres a year. Studies are being carried out to determine the origin of the water of these two springs and their vulnerability to sea-water intrusion.

II. GEOLOGY

Libya has geological formations ranging in age from Precambrian to Quaternary.

Precambrian. The Precambrian metamorphic basement rock includes quartzites, phyllites, marbles, schists, gneiss and intrusive rocks which outcrop in the south and centre of the country (Tibesti) and in the south-east. There are also small outcrops along the Algerian-Libyan frontier, and in the Bergaf area (Jabal Hasawinah) where the Murzuq (south) and Ghadamis (north) basins meet. Everywhere else in the country the basement rock lies at depths of between 500 and 5,000.

Cambrian-Ordovician. This formation is represented by sandstones of mainly continental origin resting in discontinuity on the basement rock with thicknesses of 500 to 1,500 m. These sandstones are average to coarse grained; they are conglomeratic at the base, usually quartzitic and with intersecting stratification. They outcrop in the south-west and centre of the country in the vicinity of the contact between the Murzuq and Sarir-Tibesti basins and they attain their maximum thickness in the middle of the Ghadamis-Hamadah basin. They are not found north of the Jabal Nafusah. In the east of the country, north of the 28th parallel N, these formations are either absent or found at very great depths.

Silurian. The Silurian formations occupy a vast area of the Jabal Tadrart on the western edge of the Murzuq basin and a narrow strip of land east of the Jabal Bin Ghunaymah on the eastern edge of the Murzuq basin. They also outcrop on the eastern slopes of the Tibesti and north of Kufrah. The Lower Silurian formations are 200 to 300 m thick. They include green schist-sandstones and finely bedded sandstones known as "Tanezzuft schists"; the Upper Silurian formations consist of solid sandstones with intersecting stratification. The series disappears south of the Jabal Nafusah and north of Kufrah.

Devonian. Devonian sandstones and schists overlie the Silurian formation in the western basins of the Murzuq and the Ghadamis. The Upper Devonian formation contains more schist but in the Kufrah basin the Devonian formations are more sandy and less thick. The Devonian formation is not found in the Sarir and Sirt basins.

Carboniferous. This formation is very thick and overlies the Devonian in continuity in the Murzuq and Ghadamis basins. It includes schists and fine sandstones interbedded with sandstone and limestone and it is 1,200 m thick in the middle of the Ghadamis basin. It is more sandy in the Kufrah basin and is not found in the other basins.

In the Murzuq and Ghadamis basins there is a sequence of continental sediments of Paleozoic-Mesozoic age covering in discontinuity the Paleozoic marine sediments. This is the "Post-Tassili" group of fine-grained sandstone; it is of variable thickness up to 600 m. The coarse continental sandstone known in the region as "Nubian sandstone" overlies these formations in discontinuity in the Murzuq and Kufrah basins: it outcrops extensively in the south of the country. It is more than 1,000 m thick in the middle of the two Mesozoic-Cenozoic basins. In the north-west, in the Ghadamis and Gefafa basins, are found sedimentary formations deposited in shallow water ranging in age from Middle Triassic to Paleocene. The Triassic formations consist of Kurrush sandstone, Aziziyah limestone and Abu Shayeah sandstone. These formations increase in size towards the north and can provide important aquifers. They are overlain by Jurassic rocks (Abu Ghaylan gypsum and Tokbal limestone) and Lower Cretaceous rocks (Kiklah sandstone). These formations form the Gefara group. The Nafusah group includes the Upper Cretaceous formations of Sidi al Sid Nalut, Tigrinna and Mizdah, which consist of limestones, dolomites, marls and a little gypsum. The Paleocene deposits outcrop in the Ghadamis basin; they include marls, limestones, sedimentary schists, with gypsum in places, chalk, dolomites and clays. In the Sirt and Sarir basins thick layers (3,000 m) of Tertiary rock (Paleocene-Miocene) overlie the Cretaceous formation. The Lower Middle Eocene formation alone can be up to 1,700 m thick in the Sirt basin and it includes dolomites, anhydrite, argillaceous limestone and, in places, chalky limestone and sandstone.

Basalts. Volcanic rocks are found extensively south of Ghargan and Jabals Sawda and Haruj (over an area of 30,000 km^2) and Jabal Nugayy (Tibesti). They are mostly olivine basalts and phonolites of Oligocene and Early Quarternary age.

Quaternary. The Quaternary deposits include immense expanses of sand dunes in the Murzuq, Kufrah and Sarir basins, as well as loess and alluviums in other regions, and coastal mountains consisting of eolian calcarinites and sebkha formations.

III. GROUND WATER

Administrative organization and research

The Department of Water and Soil (DWS) is the sole government body responsible for research, development and management of ground-water resources. It reports to the Secretariat of Agricultural Reclamation and Land Development (SARLD) and has four technical sections:

i) Water resources: supervision and technical support of drilling operations, hydrogeology, hydrology and geophysics;

ii) Dams: study of sites, construction, management and maintenance;

iii) Soils: soil studies, including tests and cartography;

iv) Irrigation and drainage: this section was set up only recently.

Water supplies for urban areas are the responsibility of the Secretariat of Utilities. The Secretariat of State for Electricity is responsible for the desalination plants which supply several coastal towns.

Before 1972 the Ministry of Agriculture was responsible for water-resources research and exploitation for both domestic and agricultural supplies. The General Water Authority (GWA) was set up in 1972 in response to the population growth and increased demand for water; it has become the sole body responsible for water for the whole country, with regional offices at Benghazi, Sabha and elsewhere. The country has been divided into five water regions, each serviced by a team of geologists and hydrogeologists. A drilling section and a geophysical section have also been established. The drilling section is responsible for the preparation of the technical specifications for purchases of drilling equipment and the supervision of the works. The geophysical section is responsible for geophysical prospecting and the diagraphic testing of wells. The hydrogeological section carries out studies and prospecting operations either with its own resources or by subcontracting to study companies or international bodies. It has a specialist group responsible for the collection and interpretation of data, particularly with respect to fluctuations in static water levels and water quality, as well as a hydrogeochemical laboratory.

In co-operation with the United Nations Development Programme, a large group of water-resources and hydraulics experts was invited to initiate and run study and works programmes for their Libyan counterparts, most of whom are young graduates without field experience. These experts also act as technical advisers.

Several institutional changes have since been made. For example, the GWA acquired the status of ministry in 1977 and became the Ministry of Dams and Water Resources; the Department of Water and Soil was established later. Dams and soil have thus been brought under the authority of a service which previously was concerned only with water.

Many hydrogeological studies were made before 1977 by the Agricultural Development Council (ADC), a body established to develop the land and launch agricultural projects, for example the study on the western part of the country carried out by the French Study Group in Libya (GEFLI). Petroleum research has also provided abundant data on ground water.

With a view to exercising effective control over the drawoff of ground water, the Department has prepared and is obtaining approval for strict legislation on water use and issue of drilling licenses. This legislation is also designed to limit the risks of ground-water pollution and it prohibits any increase in the extraction of water in certain sectors, along the coast in particular, in order to prevent contamination by sea water.

Modern techniques are employed in the study and evaluation of ground-water resources. Advanced technologies must be used, for water boreholes in Libya penetrate to 1,000 m and even deeper. Boreholes have had to be drilled to 2,000 m and deeper in order to study certain aquifers. Complete diagraphic studies are made of the majority of the deep boreholes, together with test pumping, chemical analyses and paleontological dating, in order to determine the properties of the aquifers and make the necessary correlations with the wells in the vicinity. Isotopic analyses are also made of the recharge, flow and age of the ground water and of losses through evaporation. Good results have been achieved recently by studies on the intrusion of sea water in the coastal zones and on evaporation from sebkhas. Mathematical models have also been used to estimate the water resources and simulate the future drawoff and its quantitative and qualitative impact.

The DWS has organized several kinds of training programme in close co-operation with FAO; training in universities abroad (United States, United Kingdom and elsewhere); training on the site or in study offices in Libya itself; and short courses in Libya or abroad. A water resources institute has also been set up in Tripoli to train senior technicians.

Hydraulic regions

Jones (1971) divided the country into 19 hydrogeological regions, mainly on the basis of geological criteria; each region has several aquifer systems which have various and complex interrelationships. Pallas (1978) introduced a more detailed classification based on hydrogeological factors and for practical reasons he reduced the number of regions to five:

- Murzuq basin;

- Jabal Nafusah, Sawfajjin basin, western Sirt and Hamdah;

- Gefara plain;

- Sarir and Kufrah basins;

- Jabal Akhdar system.

Murzuq basin - area: 300,000 km^2

1. Lower Paleozoic aquifer: Cambrian-Ordovician, Silurian and Devonian (the Lower Silurian formation known at "Tanezzuft schist" is not water-bearing). This aquifer extends towards Algeria, Niger and Chad. The Cambrian-Ordovician sediments outcrop extensively in the Jabal Fezzan. The aquifer is recharging in the whole of the centre of the basin. It consists mainly of sandstone of varied texture and composition interbedded with schists, particularly in the upper part.

The water-bearing strata in this system consist of the following formations:

- Hazawinah, Hauaz, Melezz and Memouniat (Cambrian-Ordovician, thickness 200-1,400 m);

- Tadrart, Ouan Kasa, Uwaynat, Wannin (Devonian, thickness 40-600 m).

The piezometry declines from south-west (700 m) to north-east (250 m).

Owing to the lack of rainfall (7 to 21 mm/year), the recharge is practically nil; this has been demonstrated by isotopic analysis, which has shown that no tritium is present. Carbon-14 dating indicates an age of 6,000 to 14,000 years.

The natural depletion of the aquifer is probably in the order of 0.1 mm/year; this occurs through evaporation in the sebkhas and the exploitation of wells along Wadi Ash Shati where the slope of the aquifer is 1.3 per cent as against 0.2 to 0.3 per cent in the rest of the basin. The transmissivity values are around 10^{-5} for the artesian aquifer.

The quality of the water in the Paleozoic aquifer is generally good to very good. The dry residue is usually below 1 g/l and sometimes below 150 mg/l. However, the water quality deteriorates towards the north-west.

The Cambrian-Ordovician and Devonian aquifers have similar properties; this seems to indicate that they are interconnected (the similarity even extends to the isotopic composition). The water is mostly of the sodium chloride type, very corrosive and fairly warm (35°C to 40°C.

2. Carboniferous aquifer: this consists of a thick impermeable stratum of argillaceous schist between the previous aquifer and the aquifer lying above it, which is described below.

3. Upper "Nubian" aquifer: this aquifer is situated in the basin's centre and is covered with Quaternary eolian deposits in the form of sand dunes and a "sand sea".

It consists of coarse and thick sandy conglomerates intersected with clay strata. The thickness declines from 1,000 m in the middle to 200-300 m at the edges.

The aquifer is apparently not recharging, owing to the lack of rainfall and the heavy evaporation. Carbon-14 dating indicates that the water is about 21,000 years old. The ground water flows towards the north-east. The transmissivity values ranges from 1.3×10^{-2} to 2.8×10^{-3} m^2/s. The storage coefficient is in the order of 2×10^{-4}. The porosity of the Nubian sandstone is 20 to 40 per cent. The water is more saline in the shallow wells owing to evaporation and the recycling of irrigation water. The facies is of the sodium chloride type with a dry residue of 160 to 180 mg/l for the deep wells and 1 to 4 g/l for the shallow wells.

Jabal Nafusah, basins of Sawfajjin, western Sirt and Hamadah

This is a group of hydraulically interconnected sub-basins located in a zone which is very arid, except for a strip in the north where the rainfall is 200 to 300 mm/year. The following are the main aquifers:

1. The Cambrian-Ordovician aquifer is an extension of the lower aquifer of the Murzuq basin; it is located in the central part of Hamadah at great depths and cannot therefore be exploited; it is exploited in the south, where it is not recharging. It plays an important role in the recharge of the Lower Cretaceous sandstone aquifer and the Upper Cretaceous limestone aquifer. The transmissivity ranges from 10^{-2} to 10^{-3} m^2/s. The storage coefficient is 10^{-1} in the unconfined zone and 10^{-3} to 10^{-5} in the recharge zone. The water quality is exceptionally good in the south but it deteriorates towards the north in step with the decline in the hydraulic gradient.

2. The Lower Cretaceous aquifer or Kiklah aquifer is by far the most important reservoir in the north-west of the country. It consists of fine to coarse sandstones interbedded with silt, schist and clay, and it is recharged from the belt of Lower Cretaceous outcrops which runs along the western edge of the Jabal Nafusah and by the Cambrian-Ordovician aquifer. It is also thought that part of the recharge may come from the Algerian Atlas.

The aquifer is exploited by boreholes at depths of 700 to 1,000 m which are either artesian of sub-artesian springs. The water quality of the Kiklah aquifer is generally good and its dry residue does not usually exceed 1 to 2 g/l.

3. The Upper Cretaceous aquifer or Mizdah aquifer is well developed south of the Jabal Nafusah, central and eastern Hamadah and the Misratah area. It consists of limestone interbedded with marl and is 100 to 300 m thick. In the Al Jufrah area it is exploited for the irrigation of two farming areas by means of artesian boreholes. In this area the Mizdah aquifer is in contact with the Paleozoic aquifer. The ground water flows towards the north-east. The transmissivity is 3.6 to 10^{-3} m^2/s and the storage coefficient is around 10^{-3}: the aquifer's capacity declines towards the west. It is recharged by direct infiltration of rainwater and surface runoff on the southern slopes of Jabal Nafusah, the northern slopes of Jabal Gargaf, Jabal Sawda and Jabal Haraj, and by underground contact with the Paleozoic and Lower Cretaceous aquifers. The water quality of the Mizdah aquifer varies greatly throughout the

area. At Jufrah the dry residue is fairly low at 1.3 g/l, but it increases towards the west, reaching 4.4 g/l in the Hamadah. The water has a low pH value; it is corrosive and warm. The upper Cenomanian Nalut aquifer in the north-east also deserves mention. However, this aquifer has poor properties and it is very saline in the north and north-west.

4. The Cenozoic aquifers (Eocene, Oligocene, Miocene) include thick deposits of limestone and dolomites separated by thick layers of clay, marl and argillaceous schist in the western Sirt basin in the north, and by layers of argillaceous marl and schist in the western Sirt basin north and east of the Hun graben. The dry residue is usually greater than 5 g/l, except in a few places where perched aquifers are found.

In the coastal zone between Misratah and Khums there is a Miocene-Pliocene Quaternary aquifer of somewhat better quality which is used for small-scale irrigation and drinking water. It is recharged by rainfall and by lateral contact with the Nalut aquifer. Excessive pumping has caused a deterioration in the water quality through sea-water intrusion.

This multi-layered aquifer discharges through the Tawargha and Ka'am springs, which have yields of 63 and 11 million cubic metres a year respectively, through evaporation from the big coastal sebkhas of Tawargha and Mishah, and through a large number of boreholes.

The Gefara plain - area: 15,000 km^2

This triangular plain occupies the north-west of the country between the Jabal Nafusah in the south and the Mediterranean in the north. It is of great economic importance, for it contains 40 per cent of the country's population and many of the urban areas, including the capital Tripoli. Much of the plain is irrigated and it supplies more than half of the country's farm production. The main aquifers are:

1. The Quaternary aquifer which constitutes the "phreatic" aquifer and also includes formations of Upper Miocene, Pliocene and Quaternary age in central and northern Gefara; these formations are 30 to 150 m thick; they are hydraulically interconnected and behave as a single unit. The aquifer's saturated layer is 10 to 90 m thick. Close to the coast the aquifer's transmissivity is in the order of 2×10^{-3} to 10^{-2} m^2/s and in the interior 2×10^{-2} to 10^{-1} m^2/s; the storage coefficient is 6×10^{-2} to 10^{-1}. The wells penetrating the Quaternary aquifer yield 20 to 60 m^3/h.

The static water level is declining steadily at 5 m/year in the areas of intensive irrigation. Sea water is therefore intruding along a coastal strip two to five kilometres deep between Sabratah and Tajura, 20 kilometres east of Tripoli.

In the central part the water has a dry residue of 1-2 g/l; this concentration increases towards the west owing to the influence of the gypsum and limestone intercalations at the base of the aquifer which yield heavily sulphated water. Concentrations of nitrates in excess of 45 mg/l are common, and vertifical drainage from the underlying Middle Miocene aquifer and the presence of sebkhas have the effect of increasing the salinity to over 5 g/l between Sabratah and the Tunisian frontier.

The Quaternary aquifer in the western Gefara plain is fairly small, with a saturated layer 10 to 30 m thick. It is also confined to a narrow strip running towards the west and it has good-quality water with a dry residue below 1 g/1.

The aquifer is directly recharged by rainwater and surface runoff from the wadis. The lateral contact in the south and the vertical drainage from the Middle and Lower Miocene formations are also thought to contribute to the recharge.

2. The Miocene aquifer includes the Middle and Lower Miocene formations of central and northern Gefara.

- Middle Miocene: the aquifer lies between two clay strata. Its top is at a depth of 10 to 120 m and it is 125 to 200 m thick. The average transmissivity is 5×10^{-2} m^2/s and the storage coefficient is 1×10^{-3}. The aquifer is recharged by lateral contact to the south. The water quality is poor, with dry residues of 3 to 4 g/1.

- Lower Miocene: the aquifer is formed by sandy or dolomitic limestone in western and central Gefara. It lies at a depth of 250 to 390 m to 485 m west of Sabratah, where it is 80 m thick and has a transmissivity of 5×10^{-4} m^2/s. The dry residue is 2 to 4 g/1. Towards the west the salinity exceeds 6 g/1 and the aquifer is not exploited despite its artesian properties. The aquifer is recharged laterally from the Triassic limestones to the south.

In eastern and central Gefara, where it seems to be in hydraulic contact with the underlying Upper Triassic aquifer of Abu Shayba, the aquifer consists of sandy limestone and conglomeratic sandstone. It lies at a depth of 150 to 200 m. The transmissivity is around 5×10^{-3} m^2/s and the dry residue ranges from 2.5 to 4.5 g/1, with a high sulphate content. Further east the aquifer declines considerably in thickness and the water quality improves.

3. The Triassic aquifers, of which there are two:

- the sandstone aquifer of Abu Shayba of Upper Triassic age has a maximum thickness of 350 m and underlies the eastern and central Gefara plain. It has a transmissivity of 5×10^{-3} m^2/s and a storage coefficient of 10^{-2}. The water quality is generally good, with a dry residue of less than 2 g/1, a high iron content and increased concentrations of salt and sulphates close to the coast. The aquifer becomes unconfined in the south close to the piedmont of Jabal Nafusah.

- The Aziziyah aquifer (Middle and Upper Triassic) is formed of dolomitic limestone and is exploited in the southern part of central Gefara where it is unconfined and has a transmissivity of 2×10^{-2} to 5×10^{-2} m^2/s and a storage coefficient of 5×10^{-2}. The secondary porosity is lower towards the south and the clay intercalations larger; the transmissivity is therefore lower here. The average yield of the wells is 70-110 m^3/h for the unconfined part and 30-50 m^3/h for the artesian part. The dry residue ranges from 2 g/1 in the south to 4 g/1 in the north. North of the Aziziyah fault the aquifer slopes down towards the north through a series of ladder faults and reaches a depth of 900 m near Tripoli. In eastern Gefara, it lies at a depth of 200 to 500 m and has a transmissivity of 1 to 5×10^{-3} m^2/s and a dry residue of

1.7 to 2.5 g/1. Other Lower and Middle Triassic sandstone aquifers are found in the Gefara plain. However, they are of no economic value owing to their great depth and heavy salinity.

Kufrah and Sarir basins

These basins cover a large part of eastern Libya and extend towards Chad and Egypt. They are limited in the north by the 30th parallel N and in the east by the 18th meridian E. This region is divided into two sub-basins running along the 25th parallel N:

- Hydrogeology of the Kufrah basin. The basin's hydrogeology was first studied in detail in a small zone around Kufrah. Lithological data collected during scattered oil-drilling operations are available for the rest of the basin.

A Cambrian-Lower Cretaceous aquifer with a maximum thickness of 3,000 m at its centre occupies the whole of the basin. It consists of continental sandstones interbedded with clay and silt. At present only the continental Mesozoic aquifer of Nubian sandstone (Triassic-Lower Cretaceous) is exploited, supplying water to two irrigated areas and to the inhabitants of Kufrah. The aquifer is probably saturated for a depth of 1,000 m, but the wells rarely exceed 300 to 400 m. The static water level in the Nubian sandstone is only a few metres below ground level.

The ground water flows north and north-east and the static water level falls by 400 m for an unknown reason. The boreholes have fairly high discharges (135 to 300 m^3/h) and high specific yields (10 to 50 $m^3/i/m$). The transmissivity ranges from 300 to 350 m^2/day and the storage coefficient from 1.1×10^{-4} to 1.5×10^{-2}. The regional drawdown due to pumping is closely monitored by means of a network of observation wells located close to or within the pumping zones. A maximum drop of 25 m was observed in the central part of these zones up to April 1985; the drop declines rapidly away from the centre and is only 20 to 25 cm at a distance of 30 km. It is due mainly to the drawoff of ground water: 90 to 120 million cubic metres a year. Pumping began in 1968 but the drawoff did not reach the above amounts until 1975. The phreatic aquifer, which is up to 60 m in depth, is sometimes considered as a separate unit owing to its hydrochemical properties. It has long been exploited by local farmers. In fact, it behaves in the same manner as the underlying aquifers and its water level has declined by nine metres (up to April 1985). The water is of excellent quality. For 137 deep wells the mineral content does not exceed 180 to 300 mg/1. It is usually higher in the phreatic aquifer, with a maximum of 8 g/1 depending on the location and depth of the well. Wells located close to sebkhas or lagoons are obviously more likely to be saline. The water of the deep aquifer has a low pH value and a high CO_2 content; it is therefore corrosive; the free CO_2 content is 34 to 57 mg/1 near Kufrah, thus threatening the wells and their superstructures and increasing the construction and maintenance costs.

- Hydrogeology of the Sarir (or Sirt) basin. This basin is situated north and west of the Kufrah basin. No research has yet been carried out in the Sarir Tibesti basin. The following remarks apply only to the northern part (Sarir Calancio) which has been studied since the end of the 1960s with a view to establishing two tapping fields for irrigation purposes. At present (1985) additional tapping fields are being developed to supply water to the coastal zone. This basin is younger than the Kufrah basin (Paleocene-Miocene), but the aquifers are limited to the post-Eocene formations; two of them contain fresh water:

i) The Post-Middle Miocene aquifer (PMM), which can be up to 200 m thick, consists of medium to coarse grained sands merging into calcareous sandstone with fine intercalations of clay.

ii) The Lower and Middle Miocene aquifer (LMM) in the Maradah formation, which can be 150-880 m thick. In the north it consists of marine limestones and clays with evaporites, and in the centre of alternate formations of clay, limestone, sand and coastal sandstone.

Fluvial sands and thin strata of sandstone and clay predominate in the south and south-east.

The Oligocene aquifer is 240-730 m thick and consists of coarse sands and sandstone interbedded with clay (non-marine facies) in the south and south-west.

Further north, calcareous sandstone, limestone, dolomitic rocks and clays with some evaporites (marine facies) make up the bulk of the series. This aquifer is normally in hydraulic continuity with the LMM in the exploitation zone in the south and south-west.

The Post-Eocene reservoir is therefore a multi-layered system. The vertical gradient between the PMM and the LMM is less marked in the south but it increases towards the north owing to the larger amounts of schists and carbonates. In both the aquifers the ground water flows towards the north or north-east. The piezometric maps indicate a drop of 200 m from south to north over a distance of 500 km. The hydraulic gradient is therefore in the order of 4×10^{-4}. The discharge of the Post-Eocene reservoir is effected through sebkhas and pumping. The recharge comes from underground migration from the Kufrah basin (Nubian sandstone and Cambrian-Ordovician aquifer). The hydrogeological properties have been determined from the results of several test pumpings. There are large variations in the transmissivity coefficients although most of the wells are located within a relatively narrow strip of territory running north to south. In the south, wells dug to a depth of 300 m and lined between 150 and 300 m draw water from the LMM; they indicate current transmissivity values of about 1,300 m^3/ day, but higher and lower values are also found. The storage coefficient (artesian aquifer) is 5×10^{-4}. In the north, the wells drilled in the LMM give transmissivity values of 750 to 1,000 m^2/day with a maximum of 10,000 m^2/ day for wells located in a band one to five kilometres wide and running south to north for a distance of 50 km, which in some places is considered to be a buried fossil bed.

All the boreholes in this part of the Sarir basin penetrate only part of the way into the aquifer. The test holes designed to reach relatively greater depths for the big Sarir water development project penetrate the Oligocene aquifer, crossing the saturation zone over a depth of 400 to 500 m. These holes indicate transmissivity values of 1,100 to 6,300 m^2/day. Table 1 lists the hydrogeological properties of the fresh-water aquifers in the Sarir and Tazirbu regions.

The PMM aquifer in the centre and north of the basin is unconfined in the south but becomes artesian in the north as the silt and clay intercalations grow thicker. Artesian conditions are found in the extreme north, with water levels of two to five metres above ground level at Maradah (25°N and 20°E). Elsewhere the depth to water in the Post-Eocene formations ranges from a few metres to more than 80 metres depending on the altitude of the ground level. Pumping in the southern part of the centre of the basin causes gravity drainage from the PMM to the LMM aquifer, but except in the buried fossil bed this phenomenon is less marked towards the north owing to the changes of facies. Vertical drainage may occur from one aquifer to the other, in particular in the central area where the LMM/Oligocene aquifer has a head of water 15 m higher than in the shallow LMM and PMM aquifers; the well hydrograms indicate hydraulic continuity.

The water quality in the Post-Eocene aquifer varies greatly both vertically and horizontally, depending on the lithological and topographical changes and the mixing of water and on the drainage between the main aquifers. As a rule the salinity increases from south to north in the direction of the underground flows. North of the 28th parallel N there is a sharp change in the water quality, with a high concentration of gypsum and anhydrite in the formations which increases the dry residue to 5 g/l. The topographical depressions and sebkhas in the north produce high concentrations of salts, particularly in the shallow aquifers. South of the 28th parallel N the water is usually sweet with a salinity value of less than 2 g/l in the productive zone, i.e. the zone lying between 150 and 300 m deep. But "pockets" of very saline water exist in the more southerly areas, and dry residues of 5 to 8 g/l have been found in the phreatic aquifer (at 30 to 50 m below ground level).

<u>The Jabal Akhdar system</u>

The Jabal Akhdar is located in the north-east of the country, north of the Sarir basin. It is an east-west anticline and its formations date from the Upper Cretaceous and Tertiary eras. The main aquifers are found in the fractured limestone rocks of the Eocene and Miocene eras which are heterogeneous, anisotropic, karstified and hydraulically interconnected at the regional level. The water level falls by more than 400 m over a fairly short distance north and south of the Jabal's axis. The crest of the range is a watershed for both surface and ground water. The flow is north and south in the central part and becomes radial with an easier gradient in the east and west. The aquifers are recharged exclusively by direct infiltration of rainwater and surface runoff.

The Miocene aquifer is unconfined. It consists of limestones and dolomites covered by Oolithic limestones and calcarenites. East of Benghazi the transmissivity ranges from 10^{-2} to 10^{-4} m^2/s with higher values in the karstified areas.

Table 1

Hydrological properties of fresh-water aquifers in the Sarir and Tazirbu region
Exploration and exploitation data (El Ramby 1980, Jones 1985)

Region or project	Aquifer and lithology	Hydrological properties				Hydrochemical properties			Production		
		Sandstone depth (m)	Depth to water (m)	Transmissivity (T) (m^2/d)	Storage (S)	Dry residue (ppm)	Chlorides (ppm)	Sulphates (ppm)	No. of wells	Discharge (m^3/h)	Since project start-up or anticipated annual drawoff
SARIR											
Sarir projects 1. Sarir-South	Post-Eocene (Oligocene, Middle Miocene)	200-300	35-74	1,240	$5x10^{-4}$	513-2,496	92-525	29-34	168	273.6	950 hm^3 since 1975
2. Sarir-North	sand, clay, sandy limestone, dolomites; fluvial, deltaic, estuarial and shallow marine lagoonal formations	200-300	26-51	250-9,000	$5x10^{-4}$	720-5,204	188-2,989	207-647	83	273.6	188 hm^3 since 1980
3. Sarir water project		400-500	64-83	1,090÷6,300	$5x10^{-4}$ $3x10^{-2}$	1,350-1,570	319-496	254-379	150	277	360 hm^3/year
4. Jazlu/ Awjilah	Post-Middle Miocene, sand, clay, argillaceous sand	80-110	33-82	1,000-2000	$0.1x10^{-3}$ $20x10^{-3}$	1,378-1,806	325-375	440-650	33	87.8	8.3 hm^3/year in 1985 25 hm^3/year thereafter
5. Maradah (farm project)	Lower Miocene, limestone, sandstone, argillaceous schists	150	artesian (2-5m ags)	550-2,080	$6x10^{-3}$ $4.4x10^{-1}$	2,840-3,330	930-1,020	770-880	12	90-144	3,153 m^3/year
TAZIRBU 1. Tazirbu project	Tertiary, sandstone interbedded with clay and limestone (in upper part) followed by interbedded clay and sand of Nubian sandstone series	500	7-22	180-450	$3x10^{-4}$	210-510	21-255	8-141	120	345	360 hm^3/year envisaged

The dry residue is in the order of 1.3 to 2.5 g/l and it is tending to increase as a result of the more intensive pumping in the Benghazi plain which has led to sea-water intrusion along the coast.

Elsewhere the Eocene aquifer consists of chalky and marly limestone. It is unconfined in the area of the Jabal and partly artesian or semi-artesian elsewhere. Generally speaking, the aquifer has low transmissivity values (10^{-3} to 10^{-5} m^2/s), except in the heavily fractured zones.

The water of the Eocene aquifer is of good quality with a dry residue of between 0.6 and 1.2 g/l. Higher concentrations are found in the Benghazi plain. South of the Jabal Akhdar the water quality deteriorates quickly and the dry residue increases to 5-10 g/l. Salt contents in excess of 10 g/l are not uncommon in the vicinity of the coastal and interior sebkhas which act as natural outlets for the ground water.

IV. EXPLOITATION OF GROUND WATER

Although the intensive research into new water resources for the ambitious development plans is continuing, the authorities are launching new projects for exploitation of ground water. New tapping areas are being brought into service close to the main towns and land recently brought under cultivation. The water is either drawn off close to the utilization points or channelled to the areas where it is needed. Vast projects are being implemented to bring ground water from the interior of the country to the coastal areas. This is the result of several years of study on the part of the Department of Water and Soil working in co-operation with several bilateral and international co-operation bodies.

Drilling activities

A water-drilling section was set up in 1972 in the General Water Authority to prepare water-drilling programmes and supervise the works. Its staff includes experienced drilling engineers and drilling supervisors. The main unit is based at Tripoli with local offices at Benghazi and Sabha. An FAO team of drilling experts consisting of an engineer and three supervisors has been giving technical support to the section for about 10 years.

A three-year degree course for technicians covering several subjects in the area of water-resources exploitation, including drilling techniques, was started towards the end of the 1970s. The graduates are taken on by the DWS, drilling companies, municipalities, regional farm services and other State bodies responsible for water exploitation.

In addition to their training in the field and in study offices, six of the drilling supervisors have received intensive training in Bulgaria. Other technicians are assigned to the tasks of monitoring the aquifers, supervising test pumping, collecting water samples for chemical analysis, and to other activities concerned with dams and surface water. Several national and foreign drilling companies have set up in Libya; most of them have deep drilling equipment. Table 6 gives an idea of the scope of the drilling activities in the basins of Gefara, Jabal Nafusah, Sawfajjin and Sirt under the direct control of the Tripoli office. Drilling operations in other areas are supervised by the Benghazi and Sabha offices. The table gives details of the drilling works carried out from 1980 to 1984 by three companies; the other 20 companies are grouped together. Several thousand wells have been drilled by small private enterprises for domestic and irrigation purposes. No data is available for the majority of them.

However, the central and branch offices of the drilling section of the DWS do have data on the drilling operations which they have supervised. Subcontractors must furnish final reports containing all the necessary information.

The rotary rigs used in Libya have a lifting capacity of 20 to 180 tons, so that they are able to drill to depths of up to 2,000 m. The deepest hole so far is 2,200 m. All drilling methods are used: mud, clean water, air-lift with normal or inverse circulation, and foam.

Some public bodies and small firms still use small cable-tool rigs, mainly in the karstic formations in the east, in shallow wells close to Tripoli and in Wadi Ash Shati.

Deep drilling techniques similar to those used in oil wells are employed in the drilling and furnishing of the wells. Wells over 800 m deep are equipped with telescopic tubing. Artesian wells are fitted with a specially designed cap to control the wellhead discharge and combat corrosion. As a rule diagraphy is used to determine the calibre, the spontaneous potential, the resistivity, and the neutron-ray and gamma-ray logs. On completion the borehole is fitted out and undergoes test pumping to determine the hydrogeological properties of the aquifer. The final test lasts 72 hours and includes pumping to increasing depths and measurement of the recovery. Water samples are taken for analysis and a final report, including all the hydrogeological, lithological and drilling data, is drafted and submitted to the inventories section.

A network of observation wells has been established in all areas of ground-water exploitation in order to monitor the fluctuations in the static water level either annually or by means of automatic recorders. The data are collected periodically and used in the preparation of hydrograms and piezometric maps.

Use

Almost all Libya's water resources come from ground-water aquifers. Agriculture consumes most water (80 per cent); next come the urban and rural populations, followed by industry. Several attempts have been made over recent decades to quantify the consumption of ground water by all users by means of direct and indirect techniques employed either separately or in combination: field surveys to establish well inventories, water meters, calculation of the water drawn off on the basis of the energy consumed (for pumping), extent and nature of irrigated areas, field surveys or interpretation of aerial photographs and satellite images, etc.

The per capita domestic consumption of water is around 250 to 300 litres a day in the towns and 100 to 150 litres a day in rural areas. The present drawoff is in the order of 278 million cubic metres.

The per hectar consumption of irrigation water is 5,000 to 15,000 cubic metres a year and it can be as high as 20,000 cubic metres a year in the southern regions. In the Murzuq basin, for example, the new agricultural projects launched in 1974-1976 entailed water consumption which reached 230 million cubic metres in 1983-1984 (see table 2 below). The figures given below do not include the water drawn off for small private farms and for the requirements of towns and industries.

Table 2

Drawoff of ground water for irrigation projects in the Murzuq basin

(hm^3)

(P.Illy, 1984)

Zone	Initial estimate	1979/80	1983/84	Forecast
Murzuq	115.55	76.40	83.50	222.30
Awbari	132.42	36.10	63.17	135.40
Sabha	17.40	14.20	19.20	20.00
Birak	145.81	41.20	68.30	151.20
Total	451.18	167.90	234.17	528.90

Almost everywhere the biggest consumption is by private farmers and it is continuing to grow at a very strong rate, as can be seen from the following table.

Table 3

Drawoff of ground water in the Sabha zone

(hm^3)

(P. Illy, 1985)

Use	1972	1977	1985
Agriculture (private)	25	55	115
Sabha farm project			
Livestock project	-	3	8
Urban and industrial supply	5	12	27
Total	30	70	150

According to Idrotécnico, in 1978 the use of water (hm^3) in the Wadi Ash Shati and Jufrah zones was as follows:

	Wadi Ash Shati	Jufrah	Total
Domestic	2.5	1.8	4.3
Private agriculture	90.0	2.9	92.9
Farm projects	40.5	26.1	66.6
Total	133.0	30.8	163.8

In a recent study which it made for the DWS on the various possibilities of supplying water to the Gefara plain FAO cited the data used in estimates of the amounts of water consumed in the plain during several periods from 1948 to 1978.

Table 4

Use of water in the Gefara plain from 1948 to 1978

(hm^3/year)

Year	Pumping for agriculture	Pumping for urban consumption	Total pumping
1948	12	12	24
1953	16	23	39
1958	80	25	105
1973	343	75	418
1978	463	95	558

Table 5 gives an estimate of the drawoff of ground water based on earlier studies, on an extrapolation of population growth, on farm and industry forecasts, and on plans for new tapping areas to supply water to the coastal zone from the Kufrah-Sarir and Murzuq basins.

Table 5

Ground-water drawoff in Libya */

Hydraulic region	1985 drawoff (hm^3/year)		Forecast drawoff in 2000 (hm^3/year)		Comments
Murzuq	465	45	1,150	95	Including water delivery project
Jabal Nafusah, Hamadah, Saw-fajjin, W. Sirt	210	60	270	130	
Gefara	600	120	700	220	
Kufrah & Sarir	370	40	1,280	75	Including water injected for oil extraction Including water delivery project
Jabal Akhdar	100	105	190	210	
Total	1,745	370	3,590	730	
	2,115		4,320		

*/ Modified, according to WSD, FAO, Idrotécnico, Pallas, Illy and others, with extrapolations based on the projects planned, the water delivery plans, and the population growth.

Table 6

Drilling operations in North Libya (western & central) 1980-1984 */

Enterprise	No. of rigs	1980 wells	1980 metrage	1981 wells	1981 metrage	1982 wells	1982 metrage	1983 wells	1983 metrage	1984 wells	1984 metrage
Local firms (Libya)	20	4	1,439	13	2,672	10	2,325	4	1,827	5	2,640
Bulgarocomin (Bulgaria)	14	2	943	14	2,672	18	8,916	16	11,045	21	15,987
Stojexport (Czechoslo.)	5	9	4,994	20	10,222	20	9,805	13	5,771	13	5,305
Others		15	4,290	105	17,616	38	14,378	28	6,533	7	1,854
Total **/		30	11,668	152	33,182	86	15,444	61	25,176	46	25,786
Average well depth		389		218.3		412		412.7		560.6	

*/ Only sites supervised by DWS

**/ These figures represent about 50 per cent of the operations in the whole country.

V. PROBLEMS

It is clear from the foregoing that the demand for ground water will double between now and 2000. The existing problems will therefore grow more acute, especially in the coastal areas and the areas in which the fresh-water aquifers are small and rest on salt water. The Gefara plain now has a huge deficit in its water balance, which was already in excess of 350 million cubic metres in 1980 and has caused a considerable decline in the water table and sea-water intrusion in the coastal aquifers. The penetration is already in the order of 3 to 5 km inland from the coast.

At Bin Ghashir, 30 km south of Tripoli, the old wells tapping the first aquifer have dried up and have been abandoned. It has been necessary to drill to depths of 250 to 300 m to exploit the second aquifer.

Elsewhere, when the upper aquifer is in hydraulic contact with an underlying saline aquifer, as is the case on the coast from Misurata to Ajdabiya, the intensive pumping from shallow wells dug along the wadis to tap the lenses of ground water recharged by rainfall have caused the level of the salt water to rise. In many oases close to sebkhas the excessive pumping has caused the intrusion of saline continental water into fresh-water aquifers.

The implementation of new agricultural projects, especially when it involves the drawoff of irrigation water from deep fresh-water aquifers, has also caused problems: as the deep aquifers provide the recharge for the phreatic aquifers, these latter aquifers have been directly affected by the decline in the water level. This is the case in particular at Ghadamis and Jufrah and in many other locations. At Jufrah, a place known for the quality of its palm trees, farmers are compelled to drill to considerable depths to find the water to save their already endangered trees, which used to grow naturally by drawing the water they needed from close to the surface.

Several natural springs in the Jabal Nafusah andJabal Akhdar have recently dried up. Until very recently they played an important role in supplying water for small settlements and livestock.

Subsidence has already taken place as a result of the extraction of ground water in the Sarir area. The over-exploitation of ground water has imposed heavy economic burdens on both private and public sectors. The drilling of very deep wells which give water of average or poor quality and at high temperature entails the installation of corrosion-resistant materials and powerful submersible pumps, and the use of large amounts of energy and advanced technologies, particularly where drilling is concerned. It also entails high operating and maintenance costs, not to mention the cost of cooling and/or treating the water when necessary. Moreover, the ground-water resources have proved insufficient to meet the requirements of the densely populated coastal areas; this has meant recourse to the desalination of sea water, treatment of waste water, construction of dams to store the waters of the wadis before they are lost to the sea, and the implementation of the largest project ever conceived for the delivery of ground water, in an amount of one billion cubic metres a year, through hundreds of kilometres of large-diameter channels from the south to the north.

At present a series of dams stores surface runoff water; the total capacity is 378 million cubic metres which will rise to 686 million cubic metres when the construction programme is completed. These dams are designed to permit the recharge of the aquifers, but so far it has not been possible to determine their degree of success in this. Jones (1984) reported that a small project consisting of 12 wells situated behind the dams on Wadi Tilal West and Wadi Haniyah in the Sirt area could give good reresults in only ten years, maintaining a lens of fresh water above the Oligocene-Miocene saline aquifer. This experimental project, although on only a small scale, is of considerable importance for this region which has little fresh water.

A barrier formed of artificially recharged wells is planned as a means of halting the intrusion of sea water. The idea is to use treated waste water to recharge the wells, for the potential production of the treatment plants is about 60 million cubic metres a year and should exceed 140 million by about 2000. At present waste water is used directly for irrigation purposes close to Tripoli and at Az Zawiyah and in other places after three phases of treatment: primary and secondary phases with layers of biological filters and a tertiary phase with rapid gravity filtration through layers of sand, followed by chlorination.

VI. CONCLUSION

Ground water is Libya's main water resource. There are aquifers for all geological periods from the Cambrian to the Quaternary. In the north the resources are partially renewable by direct infiltration of rainwater or by surface runoff. However, it has not yet been possible to determine whether the aquifers are recharging in the south. As a rule the ground water flows from south to north and the aquifers are hydraulically interconnected at the regional level. The water quality varies greatly from place to place and is a major obstacle to the exploitation of ground water.

The excessive exploitation of ground water in the coastal area has led to a rapid decline in the water level and a very large deficit in the water balance, not to mention the intrusion of sea water and the deterioration in the water quality. Several solutions to this situation are envisaged: in the short term, strict control of drilling operations, limitation of irrigated areas, prohibition of crops which consume large amounts of water, prohibition of irrigation in summer except in the early morning and late evening in order to reduce losses through evaporation, high tariffs to reduce water consumption, and promulgation of a new law on the use of ground water and quality control; in the long term, channelling of ground water from deep in the interior, construction of desalination plants to meet the needs of the coastal towns, use of waste water after treatment for agricultural purposes or to recharge the aquifers, and introduction of irrigation methods which use less water and measures to encourage the population of the large centres in the north to resettle in the small towns in the south.

The cost of ground water varies greatly, depending on location, depth of the aquifer, discharge, water quality, uses and construction methods. As a rule the wells are equipped with submersible electric pumps capable of lifting the water several tens of metres. The unit cost per cubic metre is in the order to 20 to 50 United States cents. The present state of knowledge, although satisfactory for the aquifers as a whole, must be improved, especially with respect to sea-water intrusion, training of technical staff, recharge of the aquifers, problems of corrosion of the installations and their design, collection and processing of data, pollution of the aquifers, karstic aquifers and springs, evaporation from sebkhas, hydrogeological cartography, control of the drawoff of ground water, level of the water and variations in its composition and quality.

Some of these topics are already under study; for example, evaporation in the Tawargha sebkha, sea-water intrusion along the Gefara coast, hydrogeological cartography and karstic springs at Ayn Zayyanah, where an attempt is being made to tap the water before it mixes with sea water in the coastal area.

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