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GROUND WATER IN NORTH AND WEST AFRICA

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NOTE

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

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FOREWORD

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

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

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

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

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.

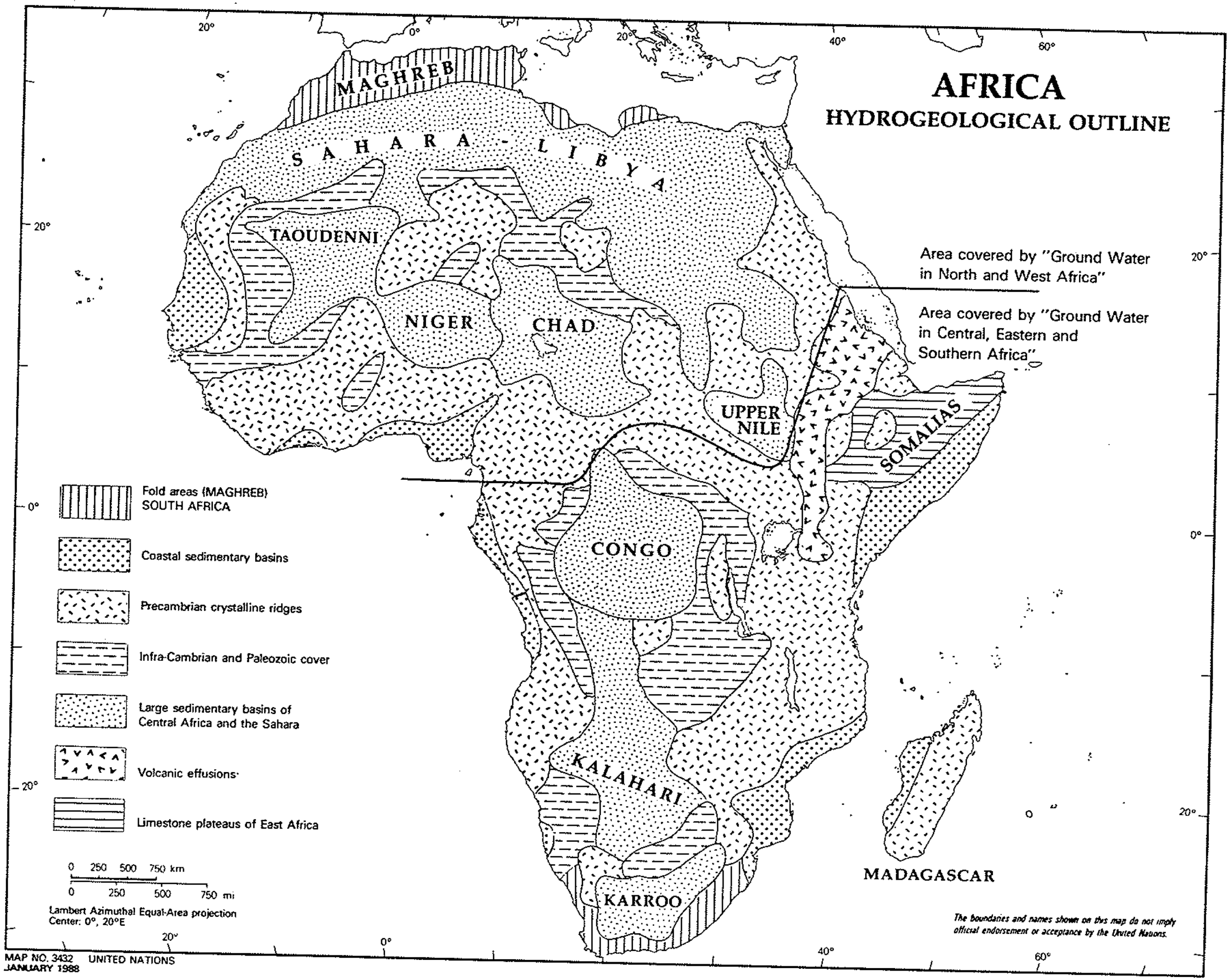
Use of a hyphen (-) between dates representing years, e.g., 1975-1978, signifies the full period involved, including the beginning and end years.

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 sand-stone	15 to 120 (artesian)	-
Tunisia	Zarzis-Djerba	Upper Miocene	50 (artesian)	-

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

Terminal continental sandstones and conglomerates (Late or Post-Cretacean

Terminal continental

Burkina Faso	Bobo Dioulasso	-	90
Mali	Gondo	-	50 to 100
Mauritania	Trarza	Sandy intercalations	(up to 300/day) 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 sand-stones	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.

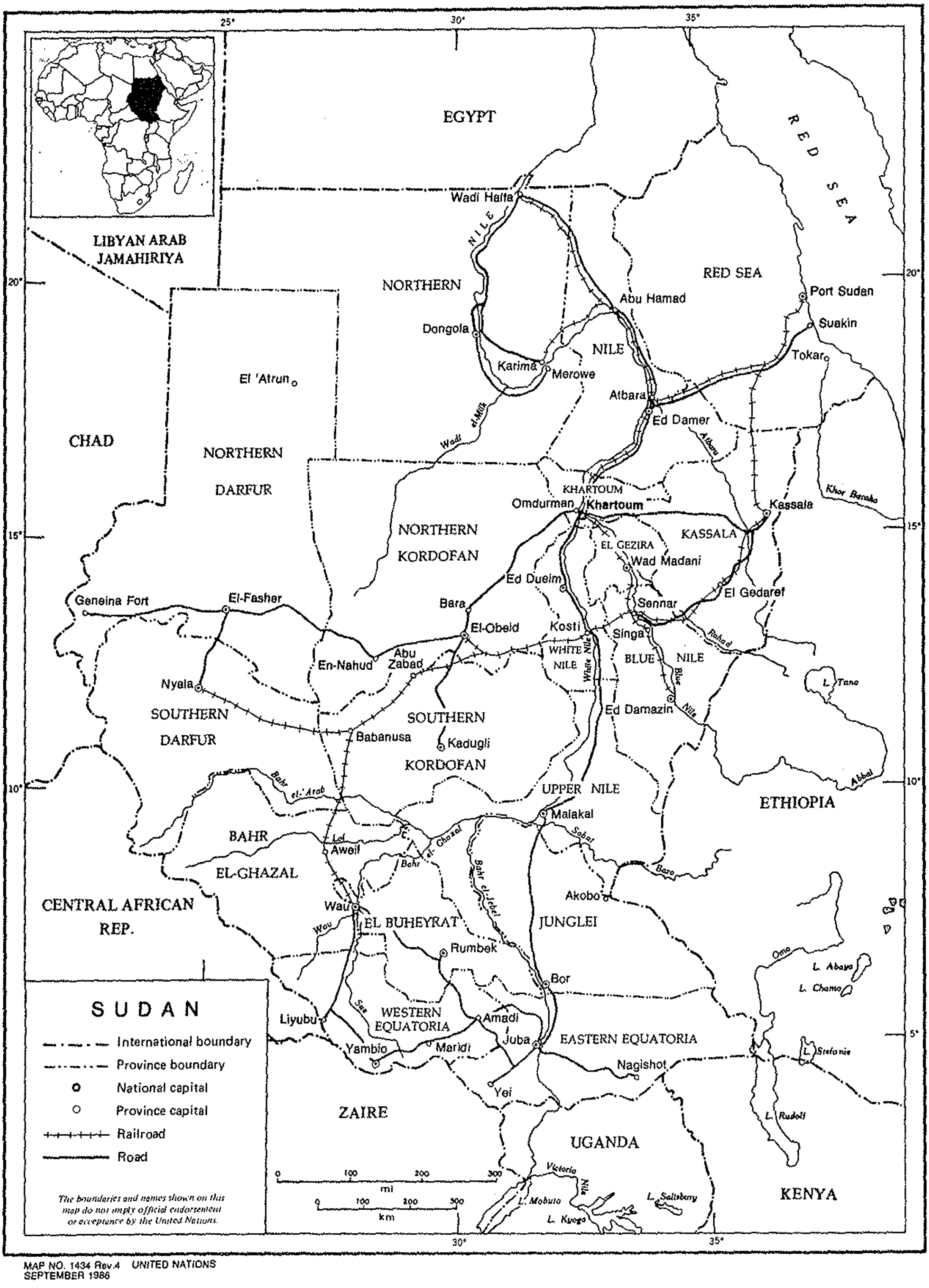
However the development of ground water is beset with many difficulties. Firstly, the areas with the best aquifers from the standpoint of the capacity of the rocks to absorb, hold and discharge large quantities of water are the desert zones where there is little or no recharge from rainfall and the coastal 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.


EGYPT
LIBYAN ARAB JAMAHIRIYA
CHAD
RED SEA
NORTHERN
NILE
NORTHERN DARFUR
NORTHERN KORDOFAN
KHARTOUM
KASSALA
EL GEZIRA
WHITE NILE
BLUE NILE
SOUTHERN DARFUR
SOUTHERN KORDOFAN
UPPER NILE
ETHIOPIA
BAHR EL-GHAZAL
EL BUHEYRAT
JUNGLEI
CENTRAL AFRICAN REP.
WESTERN EQUATORIA
EASTERN EQUATORIA
ZAIRE
UGANDA
KENYA
Wadi Halfa
Dongola
Karima
Merowe
Abu Hamad
Atbara
Ed Damer
Port Sudan
Suakin
Tokar
El 'Atrun
Omdurman
Khartoum
Kassala
Wad Madani
Ed Dueim
El Gedaref
Sennar
Singa
Kosti
Ed Damazin
Geneina Fort
El-Fasher
Bara
El-Obeid
En-Nahud
Abu Zabad
Nyala
Babanusa
Kadugli
Malakal
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Wau
Akobo
Rumbek
Bor
Liyubu
Yambio
Maridi
Amadi
Juba
Yei
Nagishot
SUDAN
International boundary
Province boundary
National capital
Province capital
Railroad
Road
The boundaries and names shown on this map do not imply official endorsement or acceptance by the United Nations.
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MAP NO. 1434 Rev.4 UNITED NATIONS
SEPTEMBER 1986

SUDAN

Area: 2,506.000 km^2

Population: 20.36 million (United Nations estimate, 1983)

I. BACKGROUND

Sudan is the largest country in Africa. It has a coastline of 700 km on the Red Sea and has borders with eight African countries: two Arab countries of North Africa - Egypt and Libya; three Central African countries - Chad, Central African Republic and Zaire; and three East African countries - Kenya, Uganda and Ethiopia. The country runs from south (close to the equator) to north (just south of the Tropic of Cancer) for about 2,000 km, and from east to west for about 1,300 km.

Sudan is crossed from south to north by the Nile Valley and it has vast flat expanses where the monotony is broken only by low hills and small mountain chains, such as the Imatong mountains in the south, the Red Sea Hills in the east, and the Jabal Marra and the Nuba mountains in the west. The country's highest point (3,224 m) is in the Imatong mountains close to the border with Uganda. The Red Sea Hills rise to 2,700 m. The Nuba mountains, isolated hills in the middle of Kordofan province, rise to 1,374 m in the Jabal Dair. The Jabal Marra is a volcanic massif running north-south for 200 km in western Dafur.

About half the country is between 300 and 500 m in altitude, with two per cent of the land below 300 m and three per cent above 1,500 m.

Most of the country lies in the hydrographic basin of the Nile. Western Darfur is part of the Chad basin. The coastal basins of the Red Sea should also be mentioned.

The north-west quarter of the country is desert and has no hydrographic network.

Climate

The climate is dominated by continental influences. It is of the tropical and subtropical type. The rain falls in summer. The winters are dry. The coastal areas are subject to the influence of the Red Sea; the winds are charged with moisture as they cross the Red Sea and they deposit it as rain in the coastal areas. The rainfall increases from the north (nil at the Egyptian frontier) to the south-west (1,500 mm) and the isohyets generally run east-west, except in the higher areas.

The interannual irregularity of the rainfall is much greater in the north. Like the whole of East Africa, Sudan has been suffering from drought for 10 years. The rainfall has generally been less than half the normal amount.

With the exception of the far south, about 90 per cent of the rain falls between July and September, with two-thirds in July-August. Most of the rainfall is of the convective type: short violent local storms.

Sudan is a hot tropical country. The highest temperatures are recorded in the central plain between Khartoum and Abu Hammad, with an annual average of 29°C. The highest temperature ever recorded in Sudan was 52°C at Wadi Halfa on 29 April 1903. The lowest (2°C) was also recorded at Wadi Halfa on 26 December 1917.

The temperature rises in January; the minimum temperatures are between 6°C and 20°C and the maximums between 24°C and 36°C. In summer (April) the central plain (Khartoum and Gezireh) have the highest temperatures; the maximum ranges from 34°C to 40°C and the minimum from 16°C to 24°C.

The ranges are wider in the dry north than in the wet tropical south. They are in the order of 18°C to 20°C in the northern and central plains and 12°C to 14°C in the south.

The part of the country which is drained towards the Chad basin contains the seasonal wadis - Wadi Kaya and Wadi Azum - which rise on the western slopes of the Jabal Marra. The eastern slopes of the Jabal Marra are drained by Wadis Bulbul, Kaya and Gendi towards the vast swamps of Bahr el Arab. The main coastal wadis on the Red Sea are Khor, Arbaat, Khor, Mog (near Port Sudan) and Khor Handoub.

There are two seasonal watercourses of great importance: the Khor El-Gash and the Khor Baraka in Kassala province, which rise in Eritra and have a very marked torrential regime. Their waters are muddy. Their courses terminate in deltas at the Red Sea.

The Nile is the country's only permanent watercourse; it is the dominant feature of the physical geography and from the human and economic standpoint. The main course of the Nile begins at Khartoum where the White Nile and the Blue Nile converge. Further north the Nile receives the Atbara then crosses the Nabri desert towards Egypt. The White Nile rises in the plateau of the lakes and it provides 16 per cent of the waters of the Nile. The Blue Nile drains the plateaus of Ethiopia and contributes 84 per cent of the water. The limits of the basins of the Blue Nile, the White Nile and the Atbara are not clearly defined.

II. GEOLOGY

Sudan has the following geological units and structures:

- Crystalline basement rock (Precambrian);
- Nawa formation and Paleozoic sandstones (Cambrian-Carboniferous);
- Nuri sandstone (Jurassic-Cretaceous);
- Basaltic outcrops (Tertiary);
- Coastal deposits (Late Tertiary);
- Umm Ruwaba formation (Pliocene-Pleistocene);
- Surface deposits (Late Pleistocene).

The country's geological history can be summarized as follows:

A long period of erosion which toninued up to the Upper Palezoic period removed most of the marine sedimentary cover which had been deposited in shallow water on the crystalline basement rock, with the exception of a few isolated pockets at Wawa (Kodofan), near the Chad frontier, near the Jabal Uweinat and in the north-west of the country.

In the Mesozoic (Jurassic-Cretaceous period plastic sediments of Nubian sandstone were deposited. These were eroded and have survived only in the depressed areas of the basement rock and its Paleozoic cover.

The tectonic movements of the Rift system (Middle-Upper Tertiary) led to the formation of vast structural basins such as those of Bara, Dinder and Baggara. A volcanic phase then produced the Jabals Marra, Meidob and Tasgabo and the basaltic flows of the Bayoda desert and the Gedarif region. This volcanic activity continued throughout the Upper Tertiary and Early Quaternary periods. In the Pliocene-Pleistocene period these basins received thick fluvial and lacustral deposits which constitute the formation known as Umm Ruwaba. The north of Sudan was subsequently subject to a dry climate. Strong winds caused heavy erosion of the Nubian sandstone and the most recent sediments, producing the vast expanses of sand and sand dunes which cover most of the northern part of the country and the regions of Kordofan and Darfur.

A description of the main formations now follows:

Crystalline basement rock

This consists mainly of orthogneiss and paragneiss and Precambrian schists which are divided into three main groups:

- Acid gneiss;
- Quartzites;
- Schists and grauwackes.

These rocks are heavily folded, faulted and injected with intrusive rocks, mainly granites and quartz veins.

Paleozoic sandstones and Nawa formation

Paleozoic sandstones outcrop mainly in the west of the country. Cambrian-Ordovician fluviatile sandstones are found in the upper basin of Wadi Hower which forms a continuation of the Ennedi plateau as far as the Chad frontier. Some of these formations are covered with sandstone sediments of the coastal and fluvial-deltaic type of Lower Siluran age.

Carboniferous sandstones rest in discontinuity on the crystalline basement rock on the Sudanese slopes of the Jabal Uweinat. They consist mainly of sandstone intercalations with intersected stratification which contain many remains of fossilized plants. The Nawa formation outcrops in very few places; it is found in the spoil of wells or boreholes in the area between latitudes 12°21' and 12°50' N on longitude 29°50' E. These rocks samples consist mainly of sandstone-arkose and brown or green fine or medium grained schists. The Nawa formation contains considerable amounts of mica, which distinguishes it from the Nubian sandstone.

Nubian sandstone

This formation covers 28 per cent of the country and outcrops mainly in Kordofan, Darfur and the Khartoum region. In the south it is overlain by thick unconsolidated sediments of the Umm Ruwaba formation, while in the rest of the country it outcrops in the plateaus or suboutcrops below a cover of surface formations of variable thickness. This formation is well stratified with layers of schist or conglomerate and with little or no slope. The elements are of average size and homogeneous. Its origin is disputed, but it was probably produced by deposits accumulated in fresh water. In the north the formation is divided into three groups:

1. Basic silicified sandstone and conglomerate;

2. Soft or hardened white, purple and variagated schist and sandstone;

3. Yellow or brown sandstone.

The Nubian sandstone varies greatly in thickness, attaining over 4,000 m in the deep structural trenches of the northern region.

It is generally thought to vary in age from Upper Jurassic to Lower Cenozoic.

Umm Ruwaba formation

This formation covers 20 per cent of the country, forming two big trenches in the centre and south; the main trench - Bara - covers a vast area in Kordofan, Darfur and the southern region; the other trench is found in the area of the Blue Nile and its tributaries, the Rahad and the Dinder.

These are unconsolidated series with little stratification consisting of sands, silts and clays. However, layers of pebbles can occur at the base of the series where it is in contact with the underlying basement rock or the altered surface of the Nubian sandstone. The sand or clay content is probably due to the Nubian sandstone, and the clay content to the basement rock. The Umm Ruwaba formation consists of lenticular sand and clay units with great lithological variation in the vertical-lateral direction and in the vertical direction. However, the following sequences have generally been identified, from top to bottom:

- Greenish clays with nodules;

- Sands with very coarse rounded grains;

- Greyish crumbly and soft clays.

The formation varies in thickness from 50 m (above the east-west uplift of the crystalline basement rock which divides the Bara trench into two sub-basins) to 1,400 m (along the main axis of the trench in the vicinity of the town of Bara and in the south). This great thickness and the composite and loose nature of the sediments indicate rapid sedimentation by short rivers in a continental or lacustral environment.

The age of the Umm Ruwaba formation is not known with any certainty; it is thought to date from the Pliocene to Pleistocene period. The sediments are younger than the peneplain attributed to the Middle Cenozoic period; moreover, they are covered by Pleistocene deposits up to the Recent black clays and Kordofan sands.

Surface deposits

These include the Nile alluviums, the fill deposits of the valleys, the Kordofan sands, the black clay plains and the coastal deposits of the Red Sea. All these deposits, which range in age from Pleistocene to Recent, cover most of the oldest formations with a variable but fairly thin layer.

The Nile deposits form the plains and the Ancient and Recent terraces of the river and of its tributaries to a depth of up to 60 m. They consist mainly of well-sorted silts and clays with occasional sandy strata. The nature of the alluvial fill accumulated by the temporary watercourses depends on the pattern of the watercourse. In the Piedmont areas these deposits consist of medium to coarse poorly-sorted sands with gravel and lenses of clay in places. The finer material is carried further downstream before being deposited. The clays and silts of the spreading plains are found only around minor arms along the river's course and in its delta; they can be up to 30-50 m thick.

The Kordofan sands consist mainly of eolian sand deposits in the form of vast layers of stabilized dunes covering most of the northern part of the country. These sands consist of fine or medium well-rounded grains of quartz, usually coloured light-brown or dark-red by the oxides. The thickness of the sand cover varies considerably, from a few centimetres to about a hundred metres. These dunes usually run north-south in line with the main direction of the wind. However, north-east transversal dunes of the Barkhane type are also quite common.

The black clays cover the plains of Gezireh, Rahad, Dinder and Butana, extending southwards to the Sudd region on the northern slopes of the Nuba mountains and to the vast plains north of the Nile-Congo watershed. This formation has a remarkably uniform clay content of 60 per cent, with few coarse elements but many limestone nodules and concretions. The black clays of southern Kordofan and Darfur usually rest in continuity on the unconsolidated sediments of the Umm Ruwaba formation, indicating that their sedimentation was the last phase of the deposition of this formation.

The Red Sea littoral formations consist of sequences of mixed marine and continental facies resting in discontinuity on Tertiary deposits and older formations. A highly developed network of wadis, including Khots Barka, Arbaat, Eit and Mog, drain the Red Sea Hills, carrying down large quantities of gravel, sand silt and clay and depositing them in the coastal area. These continental sediments are sometimes 50 to 75 m thick. The marine sediments along the coast consist mainly of complex deposits of coral reefs which form a layer 15 metres deep on top of the older sediments.

III. GROUND-WATER RESEARCH IN SUDAN

At only a little distance away from the Nile, ground-water aquifers provide the only permanent stocks of water in Sudan. They guarantee the supply and even the existence of almost 75 per cent of the population and the livestock, whose total annual needs are estimated at 500 million cubic metres. This figure can be adjusted to 375 million cubic metres, for during the three months of the rainy season the people have surface water available almost everywhere. But account must be taken of the needs of wild animals, supplementary irrigation and industry, as well as of the losses due to evapotranspiration, infiltration and wastage. Up to 1987 the bodies responsible for rural water supply produced about 90 million cubic metres a year, representing less than a quarter of the requirement.

Background

Sudan's first rural water supply service was established in 1946, when a soil conservation service was set up in the Ministry of Agriculture with responsibility for studying the erosion and drying-out of the soil and the water resources available to supply the population and livestock in rural areas; it was also required to recommend measures to solve the problems and in particular to propose new legislation and taxation measures; lastly, it had the task of establishing work programmes with a timetable and an estimate of the costs. Over the next 10 years it built about 300 hafirs (small surface-water reservoirs) with a total capacity of about nine million cubic metres in the rural areas where the rainfall was sufficient. Some of these reservoirs, built in haste, were filled in by the solid deposits carried down by the waters and rendered useless.

In 1956 a department of land use and rural development was established in the Ministry of Agriculture. It had three divisions: land use, development of surface water, and water drilling. Technical responsibility for the development of water resources and supervision of drilling operations was assigned to the geological service of the Ministry of Mineral Resources. This led to the construction of 100 tubewells, 200 hafirs and four small dams with an annual capacity of 11 million cubic metres.

The Rural Water and Development Corporation (RWDC) was established at the beginning of 1967 as a response in particular to the situation caused by the drought and the degradation of the soil and to satisfy the large requirements resulting from the implementation of the rural development programme. Its technical staff included hydrogeologists, drillers, civil engineers, hydrologists, engineers, mechanics, agronomists, soil experts, sociologists and economists, working in three departments responsible for ground water, surface water and rural development. Departments of pastures and forests were added later.

The establishment of the RWDC was followed by the Anti-Thirst Campaign which was the first step in the great advance made in the area of rural water supply. In the 20 years from 1967 to 1987 about 3,200 boreholes were successfully drilled and 350 hafirs and 10 small dams were built; these installations made it possible to store about 70 million cubic metres of water a year, representing 19 per cent of the total human and livestock requirements. During these 20 years the effort was concentrated on the exploitation of ground water, which is perhaps more difficult to develop than surface water but is of better quality and less vulnerable to pollution and, in the short term, to the effects of drought; furthermore, unlike surface water, it does not require large investments at the outset.

Prospecting and evaluation of ground-water resources

This kind of research expanded rapidly after the establishment of the RWDS. A particular effort was made in the Kordofan and Darfur regions, with financing provided by grants and loans. The actual research was entrusted to foreign study companies. The Ground-Water Research Section is responsible for the activities financed in this area by the Government.

A major project financed by the British Government was carried out in northern Darfur in 1968-1974 with the object of studying ground water; it included the following operations:

- Aerial photography and photo-geological interpretation;

- Evaluation of all available data on boreholes;

- Measurement of the water levels in the boreholes and observation of fluctuations in these levels and in the salinity of the water;

- Test pumping and interpretation;

- Geophysical prospecting by geo-electrical, gravimetric and seismic methods;

- Determination of the ground-water potential of the Sharggra basin, with a view to supplying El Fasher, and of the West Nyala basin to supply the town of Nyala.

In southern Darfur the ground-water studies dealt with the aquifers of the Nubian sandstone and Umm Ruwaba formations and with the main alluvial aquifers. These studies considered the possibility of small irrigation projects.

The second ground-water exploration programme in order of importance was carried out by a Czechoslovak company over an area of 80,000 km^2 in Kordofan from 1967 to 1976. It identified the limits of the ground-water basins and determined locations suitable for water boreholes in the areas of crystalline substratum of the Precambrian basement rock. The researchers used geophysical prospecting methods and then took core samples and made diagraphic studies. The holes were lined and equipped with filters. After test pumping the installations were handed over to the RWDC equipped with pumps, reservoirs and protective fencing. The geophysical operations consisted of magnetic and gravimetric measurements (6,100), electrical soundings (1,770) and seismic-refraction profiles (nine): 78 boreholes were installed with a total depth of 14,000 m and 30 were put into production. These studies brought about a considerable improvement in the knowledge of the ground-water basins and they identified several other basins such as Iyal Bakhit. Lastly they succeeded in establishing water points in areas considered barren.

Other work financed by bilateral aid programmes included the geophysical and hydrogeological research carried out between 1976 and 1985 by the Geological Service of the Netherlands at El Gedaref, El Jebelein, Kassala and Nyala. German missions have been studying ground water since 1958, for example at Kordofan and more recently at Khartoum (1979); in 1985 a scientific mission of the University of West Berlin began to study the Nubian sandstone aquifer in Sudan and Egypt.

The United Nations Development Programme has financed studies of the Jabal Marra (1958) and Kordofan (1967) and more recently a regional project on the main aquifer of north-eastern Africa (Nubian sandstone).

IV. MAIN AQUIFER SYSTEMS

River aquifers

The Nile silts and the fill deposits of the valleys are Sudan's largest surface aquifers. Most of them contain large quantities of water of good quality, particularly in the areas of crystalline basement rock, owing to their hydrological properties: high storage and transmissivity coefficients. The ground water drawn from these alluvial aquifers is an important resource used for domestic and irrigation purposes in several northern areas and at Kassala in Kordofan and in Darfur. The ground water of the alluvial formations is usually contained in unconfined aquifers at shallow depths (a few centimetres to 15 metres) below ground level. The ground-water horizon is highest during or shortly after the rainy season and it then gradually declines for the rest of the year. In some alluvial aquifers in exceptionally dry years the water level falls below the furface of the rock substratum. In contrast, when the static water level is above the top of the aquifer, pools and swamps are formed which can remain throughout the year. This is the case at Sudd in the southern part of the country.

In the alluvial fill the ground water flows in the same direction as the surface water, i.e. downstream.

During the high-water periods the flow is from the bed towards the banks, thus recharging the aquifer, and it is in the opposite direction during the dry season, with drainage from the banks towards the bed. The rate of flow within the aquifer depends on the surface gradient and the transmissivity of the alluvial aquifer. Accordingly, the rate of flow of the ground water is higher in the upper part of the aquifer than in the lower part; it is about 25 to 40 cm a day (Darfur, Kassala, Jabal Marra).

The results of the test pumping in the alluvial aquifers are given in table 1. The transmissivity coefficient ranges from 200 to 1,500 m^2/day. The storage coefficient is also high: 13 to 25 per cent, as is to be expected in an unconfined aquifer.

Table 1

Hydrogeological properties of a number of alluvial aquifers in Sudan

Location	Depth of well (m)	Static water level (m)	Specific yield (1/s/m)	Permeability K (m^2/d)	Transmissivity T (m^2/d)	Storage coefficient (%)
KASSALA						
K. El Gash	30	10		40	1,000	0.13
DARFUR						
W. Kutum	18	3.5	4.2	14	200	0.20
W. Azum	38	3	30	45	1,500	0.20
W. Aribo	20	1.5	30	50	1,000	0.25
W. Nyala	17	2	10	50	600	0.20
W. Bulbul	10.5	1.8	35	65	600	0.24
NORTH						
El Seleim Basin	93	6	40	10	500	0.15
Kerma Basin	94	5.7	65.8	12	10.50	0.15

Boreholes in the alluviums of the Blue Nile can deliver more than 500 m^3/h (the highest yields in the Sudan). The wells drilled at El Seleim and Kerma, where a fossil loop of the Nile overlies the Nubian sandstone, can deliver up to 500 m^3/h. The boreholes of Khor El Gash, Wadi Asum and Wadi Nyula can deliver 50 to 100 m^3/h. The ground water of the alluvial aquifers can be recharged by infiltration of flood water, rain water or surplus irrigation water. The discharge is mainly through evaporation and ground-water flow and, to a lesser extent, human activities, in particular irrigation. Recharge and discharge cause fluctuations in the water level which rises in the rainy season and declines in the dry season.

The safe annual yield of the El Gash alluvial aquifer is about 170 to 240 million cubic metres; at Wadi Kutum it is 20 million cubic metres, but the drawoff is below 50,000 m^3/year. Lastly, at Wadi Asum and Wadi Aribo, close to the town of Zalengei, it is 81 million cubic metres with a drawoff of about 50,000 m^3/year. The drawoff from the aquifers of Wadi Bulbul and Wadi Kaja in southern Darfur is about three million m^3/year. The ground water of the wadis is now used to irrigate small plots along their narrow beds. The ground water drawn from alluviums usually contains little mineral salt and is thus suitable for domestic and irrigation purposes. In the valley of Khor El Gash it has a dry residue of 180 to 270 mg/l, with a mainly calcium bicarbonate facies. Away from the bed the salinity increases to 2,000 mg/l of carbonates, sulphates and sodium chloride. This high concentration is due mainly to the return of irrigation water.

The dry residue of the ground water of Wadi Azum is about 180 to 270 mg/l of carbonates and calcium and sodium bicarbonates; it is below 150 mg/l at Wadi Aribo, mainly calcium bicarbonate, and the situation is similar at Wadis Bulbul, Nyala and Kutum. The Bile alluviums in the El Seleim and Kerma basins sometimes contain water of better quality than that of the Nile itself, with a dry residue of 120 mg/l, which is perhaps due to the presence of layers of silt acting as a semi-permeable membrane trapping the salt of the irrigation water.

For the waters contained in the alluviums the sodium absorption rate is below 10, and they can therefore be classified as good or excellent for irrigation.

Umm Ruwaba aquifer

This aquifer is second in order of importance; it has lenticular water-bearing strata of sand and pebbles which are mostly in contact with each other. The areas composed of fine elements are unproductive or even barren.

The water of this aquifer is exploited mostly for domestic use and for livestock, occasionally for small-scale irrigation (Bara and El Kheiran). It covers an area of about 800.000 km^2, mostly south of the 12th parallel N. It may overlie altered formations of the crystalline basement rock (Bara basin) or altered Nubian sandstone or other older formations (Atshan, Baggara and Sudd basins).

Description of the aquifers

(i) Bara basin. This basin occupies a trench of 68,000 km^2 running north-west/south-east in central Kordofan and eastwards as far as the White Nile, which it meets south of Kosti. It is bounded in the north-west by the Nubian sandstone and on all its other sides by crystalline basement rock of the Sodiri-Mega anticline. The Umm Ruwaba formation rests in discontinuity on crystalline rock which is very unevenly altered. The basin is divided into two sub-basins by a north-east saddle produced by an uplift of the basement rock, but they remain in hydraulic contact with each other. The basement rock is uplifted in places to form isolated or aligned reliefs above the static water level; this produces barren or unproductive zones. The Bara basin is situated in the basin of the While Nile; it is recharged in the west and north-west and it has its outlets in the south-east, towards the White Nile.

(ii) This basin includes the southern part of the syncline located between the Bayoda horst and the Sodiri-Mega anticline; the northern part is occupied by Nubian sandstone. It is in the form of a triangular trench, the apex of which is the confluence of the Blue Nile and the Rahad, while the base terminates at the basement reliefs which run along the Ethiopian frontier. The Lithology is typical of Umm Ruwaba, except that it contains much more coarse material (sand and pebbles) than usual. Very little is known about the hydrogeology and it is hoped that the current petroleum research will provide a fuller picture.

(iii) Baggara basin. This basin covers about 150,000 km^2 in southern Kordofan and southern Darfur, south of the Nuba mountains and the saddle leading to the Umm Kaddada basin, i.e. south of the 13°30' parallel N. Its south-east limit is the Bahr El Arab. In the west it terminates at the high banks forming the central part of the Jub-El-Genina horst. This basin is part of the Bahr El Arab hydrographic basin. Almost all the seasonal streams south of the watershed are lost in desert deltas or continue their course in the Bahr El Arab. This is true of Wadis El Ghalla, Shalengo, Bardab, Bulbul, Ibra, Nyala and Kaja. Here have been identified three deep trenches (3,000 m), which are interconnected in a north-east/south-west direction, together with other shallower trenches containing oil resources, but the hydrogeology is not known.

(iv) This basin takes the form of a plain of 200,000 km^2 covered with fresh-water lakes and swamps at the confluence of the Bahr El Arab, the Bahr El Ghazel, the Bahr El Jebel and the Sobat. This basin is situated in the area where the Mega syncline covered with Umm Ruwaba sediments has just split into two. The outlet is towards the north through the White Nile. It is bounded in the east by the Ethiopian platea, in the west by the Juba-Genena horst and in the south by the plateau of the lakes.

The Umm Ruwaba aquifer which occupies the basin consists of fine sediments carried down by the Nile and its tributaries. It is thought that these sediments were deposited in the form of inland deltas made up of mixed strata of sand and clay.

The aquifer is unconfined at its edges with a static water level close to ground level (2 to 10 m deep). Around Bara it is exploited by hand-dug wells for domestic purposes and to irrigate small cultivated plots (vegetables and fruit trees).

The aquifer is saturated in the south and sometimes emerges in swamps and lakes. In the centre semi-artesian or artesian conditions can occur beneath the clay strata at depths of 200 to 400 m, with a static water level of 10 to 100 m above ground level. Temporary artesian conditions have been observed in some cases. The Umm Balagi borehole which is situated at a point where the ground-water flow is blocked by an uplift of the basement rock, has been artesian for more than 10 years.

The fluctuations in the piezometric surface of the Umm Ruwaba aquifer do not exceed 10 to 30 cm; this is attributed to the very small amounts of recharge and discharge.

Ground-water flow

In the Bara basin the ground water flows south-east across the basement saddle towards the town of Umm Ruwaba, and eastwards towards the While Nile. In the Akshan basin it flows in the same direction as the surface water, i.e. northwards. In the dry season in the Baggara basin it flows south-east towards the Bahr El Arab, and then eastwards towards the Sudd basin. During the rainy season and the high-water periods of the Bahr El Arab the habitual southward flow encounters the northward flow from the river and the two flows combine to run eastwards, i.e. towards the Sudd basin. The Sudd area thus acts as a drain for all the surface and ground-water flows of the basin. The Sudd area thus acts as a drain for all the surface and forming swamps. The northward ground-water flow is very slow owing to the poor permeability of the Umm Ruwaba formation and the shallow gradient.

The properties of the Umm Ruwaba aquifer are given in the following table:

Table 2

Location	TD(m)	SWL(m)	M(m)	Q(m^3/h)	SpC(1/s/m)	K(m/d)	T(m^2/d)
BARA BASIN							
Umm Shelikeit	233	86	91	5.5	0.55	1.2	105
Shawa	226	22	45.5	5.5	1.40	0.7	35
Hedeid	137	24	70+	15.2	0.73	2.9	75
Umm Ushra	233	11.4	200+	16.0	1.2	5.0	210
Umm Sheila	121	48	100+	5.5	0.5	1.9	50
BAGGARA BASIN							
Tiwal	220	25	200+	14.4	8	22	880
Umm Berida	153	90	70+	14.4	8	26	845
Hariza	155	100	52+	14.4	4.5	18	600
Shaffa	119	92	21	14.4	3.1	9	320
El Malam	225	70	150+	14.4	1	4	140
Serrir	268	67	200+	14.4	1	3.8	130

TDL Total depth of well
SWL: Static water level
M: Aquifer thickness
Q: Discharge of the well
SpC: Specific capacity
K: Permeability
T: Transmissivity

The transmissivity coefficient ranges from 30 to 200 m^3/day in the Bara basin. The lower values are found in areas of fine elements where some of the wells are of defective construction. The permeability coefficients range from a minimum of 0.7 m/day to a maximum of 5 m/day. In its centre the aquifer is artesian or semi-artesian, with a storage coefficient of 10^{-5} to 10^{-3}. The volume of water stored has been calculated on the basis of an average coefficient of 5×10^{-2}.

Since the Umm Ruwaba aquifer is in hydraulic contact with the underlying aquifers (Nubian sandstone and older formations), the transmissivity values of the wells penetrating the whole formation are higher than those of the boreholes which penetrate only the Umm Ruwaba formations. However, as the boreholes are not lined for the whole of their productive depth, the transmissivity and storage values are probably lower than the potential ones.

The storage coefficients obtained are not reliable. The average value of 5×10^{-2} mentioned above is perhaps a reasonable estimate.

Ground-water resources

It is thought that the Bara basin has a considerable recharge from direct infiltration of rainfall (in the El Kheiran area for example), and from surface runoff (for example, south of the town of Umm Ruwaba). The recharge is considerable in the El Baggara basin; it is provided by frequent temporary flows from the Nuba mountains, the slopes south of the watershed of the Nile and the Bahr El Arab, and the volcanic mass of the Jabal Marra.

Table 3 gives the figures for the ground-water resources of each of the basins of the Umm Ruwaba aquifer.

Table 3

Estimate of the ground-water potential of the Umm Ruwaba aquifer

Hydrogeological system	Ground-water stocks (km^3)	Annual Recharge (hm^3)	Annual drawoff (hm^3)
Bara	45	15	4
Atshan	23	70	20
Baggara	1,300	30	10
Sudd	110	340	20
TOTAL	1,478	455	54

This table shows that the aquifer is far from being exploited to its full capacity. In fact, the present level of drawoff is less than 30 per cent of the safe yield.

The water is usually of good quality; it has a low mineral content or is slightly saline. The dry residue is generally below 1,000 ppm, sometimes below 80 ppm. However, there are some saline pockets with concentrations of 6,000 ppm; the salts may have been deposited by evaporation in the lacustral areas prior to the deposition of the Umm Ruwaba formation itself. In the Bara basin the salinity is generally low (150 ppm) near the recharge areas such as El Kheiran; it increases gradually towards the basin's outlet. However, this phenomenon is reversed and low concentrations are found in the vicinity and to the south of the town of Umm Ruwaba owing to the recharge from Khot Abu Habb. Saline pockets (5,000 ppm) occur north of the saddle of the crystalline basement rock which divides the basin into two sub-basins. Other pockets of 6,000 ppm occur near the Jabal El Kon.

The average salinity of the aquifer in the Baggara basin is 340 ppm. The lowest salinity levels are found close to the recharge areas, i.e. in the north, west and south-west, close to the mouths of Wadi El Ghalla and the other wadis which drain the Nuba mountains.

Areas with salinity levels above 400 mg/l are found in the deep trenches of the central part. They may be caused by the presence of strata containing evaporites. Owing to the stagnation of the ground water, the concentrations of salt in the Sudd basin are high or very high: 270 to 6,500 mg/l, with average values of 1,500 mg/l which increase with depth and towards the north, i.e. towards the basin's outlet. The facies are mainly of the carbonate and sodium bicarbonate types when the salinity is low or moderate, and of the chloride and sodium sulphate types in the areas of high concentrations; in some cases there are heavy concentrations of nitrates.

Apart from the small areas of high salinity, the water of the Umm Ruwaba aquifer is usually fairly soft and is suitable for human and animal consumption. However, in some cases when the concentration of nitrates exceeds the admissible amount (35 mg/l), the water cannot be used and the wells and boreholes must be condemned. However, the water can usually be used for irrigation.

Nubian sandstone aquifer

The Nubian sandstone aquifer is the most reliable and the largest in Sudan and indeed in North-East Africa. The water-bearing strata consist of sandy beds with high storage and transmissivity coefficients. However, vast areas of Nubian sandstone outcrops are barren because they are too thin and the static water level of the aquifer is lower than the "wall" of the formation.

As a rule this aquifer is an under-used if not a virgin resource, for up till now it has been exploited in only a few places and only for domestic purposes.

This is a potential resource of considerable importance for the country's future.

The aquifer covers about a million square kilometres, mostly north of the 12th parallel N. In this area it includes a number of interconnected or isolated depressions. South of the 12th parallel N it is generally overlain by the Umm Ruwaba formations which fill the vast trench in the form of a Y covering southern Kordofan and Darfur and the Sudd region in southern Sudan.

Description of the aquifers

The Sahara basin (1) forms a rectangular trench two million square kilometres in area running north-north-west/south-south-east in northern Darfur. In the north the basin extends beyond the Libyan and Chad frontiers and may encompass the Kufrah oasis. Its lower limit is not known. It can be divided into three sub-basins: Wadis Hawa, SaniyaHaiyeh and Tima. The Umm Kaddada basin (2) covers about 100,000 km^2 in central and eastern Darfur and in Kordofan. The Nahoud basin (3) is a saucer-shaped area of 10,000 km^2 in central and western Kordofan filled with Nubian sandstone. It was produced by complex orogenic movements and erosion. In the south it has a subdivision (Nahoud-Saata-Gefauwi) of very considerable ground-water potential. In other parts the Nubian sandstone is barren.

The Iyal Bakhit depression is smaller in area and it is one of the regions of Sudan which suffers most from lack of water. The Nilo-Nubian basin (4) is the biggest basin, extending for 300,000 km^2 in central and northern Sudan. Its upstream part corresponds to the Nile-Bahr El Arab watershed which starts in eastern Darfur and crosses central Kordofan along the Kagmer mountains. In the north it extends beyond the Egyptian frontier. It is divided into several sub-basins: Gezireh, between the White Nile and the Blue Nile; Atbara, between the Atbara watercourse, the main course of the Nile and the Bayoda horst; and Wadi El Milk, a syncline of the downstream part of this wadi and of other sub-basins as well. The El Gedaref basin (5) is a circular area of 28,000 km^2 in central Kassala; it extends eastwards beyond the Ethiopian frontier. The Nubian sandstone forms horizontal strata crossed by thick sills of basic volcanic rock which are heavily faulted.

Conditions of deposit and flow of ground water

The thickness of the Nubian sandstone has been established from drilling data or estimated by geophysical prospecting. It can be either very thin or very thick - up to 4,000 m at the edges where the aquifer is mostly unconfined and the water level lies only about 10 m below ground level. As the thickness increases, the aquifer tends to become confined and the static water level can be as deep as 100 m. In some cases the ground water emerges as springs: at Ain Faro and Kologol, for example, where it is close to ground level and produces oases such as Bir Natron, Nekheila, Lequia, Liquia Omeran and Selima. A borehole drilled at Idd El Tein in the El Gedaref basin, where the Nubian aquifer is covered with basaltic sills, touched a pocket of carbonic gas under pressure, producing a gusher of gasified water which rose 50 m above ground level.

The seasonal fluctuations in ground-water levels in the Nubian sandstones are very small owing to the enormous volume of water stored. Near the recharge zones (upstream) where the free aquifer is in direct contact with the watercourses which feed it, these fluctuations are in the order of one metre. In the central parts of the basin where the aquifer is confined or semi-confined, the fluctuations do not exceed 30 cm. So far no permanent rise or fall has been observed in the static water levels of the various basins.

The flow of the ground water is in conformity with that of the surface water which recharges the aquifers: northwards in the Sahara and Nilo-Nubian basins. The gradient is steeper in the recharge areas, reaching 1/300 just north of Maidob and falling steadily northwards. The flow rate is about 1 to 12 m/year (Wadi Hower).

In the Umm Kaddada basin the flow is generally southwards, indicating that the main recharge is provided by the temporary wadis flowing from the basin's watershed. The flow gradient eases from 1/250 at the El Malha crater to 1/800 at Umm Kaddada, 100 km further south. In the Shagara and Sag El Naam sub-basins the water first flows southwards then veers east in the Saniya Karro strait. The flow rate is 1.5 m/year at Umm Bayada and 60 m/year in the Sag El Naam area.

In the Nahoud basin the water flows northwards and eastwards, demonstrating that the recharge comes from Wadi El Ghalla and Khor Abu Habl. The flow is slowed by the fine-grained sandstones in the aquifer. The north-south chain which crosses the Gedaref basin divides it into two with respect to both surface and ground water. The two sub-basins have different hydraulic gradients and diametrically opposite directions of flow.

The hydrogeological properties of the Nubian aquifer are given in table 4.

The aquifer's transmissivity coefficient ranges from 35 to 1,500 m^2/day, the permeability from 1 to 19 m^2/day, and the storage from 10^{-4} to 25 x 10^{-2}, indicating the transition from confined to unconfined aquifer. The well yield is between a few m^3/h and 400 m^3/h, so that the water can be used for irrigation.

Ground-water resources

The Nubian sandstones are recharged by direct infiltration of rainwater or temporary runoff from the wadis or even from the river system of the Nile. Permanent recharge is indicated by the fluctuation of the water levels close to the recharge areas and by the shape of the isopiestic curves. The low salt content of the aquifer's water also seems to indicate a constant fresh-water recharge. Furthermore, isotopic analysis indicates a mixture of ancient and recent water.

The aquifer can be exploited only in the upper levels of the formation, to a maximum depth of 200 m. The corresponding potential is given in table 5, estimated on the basis of an average coefficient of one per cent. The annual recharge has been calculated on the basis of the isopiestic curves, fluctuations in the water level and variations in the salinity of the water.

Table 4

Hydrogeological properties of the Nubian aquifer

Location	WD (m)	WL (m)	TA (m)	SY (m^3/h)	SY (l/s/m)	T (m^2/d)	K (m/d)	S
1. SAHARA								
W. Hower	37.5	6	300+	18.5	17	1500	17	0.20
Atron	236	3.3	200+	20.5	28	2500	5	
Sanya Hayey	96	53	100+	6.5				
Time	106	67	50	6				
2. UMM KADDADA								
Umm Bayada	94	25	70+	30	-	15	0.4	0.11
Al Nusub	106	74	50+	16.2	-	15	0.65	10^{-2}
Umm Kaddada	70	33	200+	13.7	0.16	20	0.86	10^{-4}
Shaqq Mamda	146	81	65+	13.7	0.12	15	0.43	10^{-4}
Shagara	263	44.5	164	24.6	6.2	150	3.1	10^{-3}
Sag El Naam	136	87	100+	22.0	20	560	19	0.14
Wad Banda	232	94	250+	5	0.23	300	2.2	10^{-3}
Sug El Camal	185	98	500	12	0.31	320	4.3	10^{-4}
Fula	241	98	2000+	12	3	200	1.5	10^{-4}
3. NAHOUD								
Howag	280	132	150+	10	1.6	220	0.84	10^{-3}
Saata	310	95.4	200+		1.3	250	1.1	10^{-3}
Cefauwi	310	102	250	5	0.5	400	1.4	10^{-3}
Maya	357	111	250	5	0.3	175	0.7	10^{-4}
Iyal Bakhit	188	111	75+	5	0.2	-	-	-
4. NILO-NUBIAN								
Khartoum	65	20	100+	85	4	250	4.3	10^{-2}
Korma	245	6.2	500+	280	9.5	1500	6.0	0.1
El Seleim	311	14.6	500+	150	3.7	600	7.1	0.1
W. El Milk	96	7.2	300+	17	2.5			0.15
5. GEDAREF	130	50	206	16	0.1	80	4	10^{-2}

WD: Well depth
WL: Water level
TA: Thickness of aquifer
WY: Well yield
SY: Specific yield
T: Transmissivity
K: Permeability
S: Storage

Table 5

Estimate of the ground-water potential of the aquifer's upper section (200m)

Hydrogeological system	Ground water in storage (hm^3)	Annual recharge (hm^3)	Annual drawoff (hm^3)
Sahara	400	27	3
Umm Kaddada	600	100	10
Nahoud	2	16	5
Nilo-Nubian	600	175	35
Gedaref	76	40	8
TOTAL	1,678	358	61

This table indicates the enormous volume of water stored and suggests that these resources are renewable to some extent, for the drawoff is much lower than the safe yield; accordingly, there is at present no risk of over-exploitation or exhaustion of the resources provided that they are used only at scattered points and this use is controlled when the water is for irrigation.

Chemical composition of the water

The chemical composition of the water of the Nubian aquifer in the various basins in Sudan is given in table 6.

Most of the ground water of the Nubian sandstones has a low mineral content. The lowest concentrations (below 1,000 ppm) are found near the recharge areas, at Sanya Hayeh (50 ppm) for example, or along the permanent or temporary watercourses which periodically recharge the aquifer: the Sag El Naam (80 ppm) for example. The salinity increases gradually downstream to 300-400 ppm in the centre of the basin. Local pockets of high salinity are found in closed basins such as East Gedaref or in areas where the ground-water flow is slow, i.e. in the Jabal Hilla in eastern Darfur.

Near the recharge areas the main mineral salts found in the ground water of the Nubian sandstone aquifer are carbonates and calcium bicarbonate. The ground water near the recharge areas and the surface water have very similar chemistry. Further downstream the water tends to have a higher sodium carbonate content.

The water of the Nubian sandstone is generally suitable for human and animal consumption. Its salinity is usually low and it contains no toxic elements; it is suitable for irrigation of all crops and for all soil types.

Table 6

Mineral content

Location	Dry residue (ppm)	Ph	Ca m.equiv.	Mg. m.equiv.	Na m.equiv.	CO_3 m. equiv.	HOC_3 m.equiv.	SO_4 m.equiv.	Cl m.equiv.	SAR and suitability for irrigation
1. SAHARA										
Air Faro	100	7.2	2.4	1.2	0.6	-	3.6	0.2	0.2	0.04 (C_1S_1)
Tima	134	7.4	1.4	0.5	0.7	-	1.8	0.3	0.1	0.72 (C_1S_1)
Sanya Hayey	54	7.1	0.5	0.1	0.3	-	0.7	0.4	0.1	0.55 (C_1S_1)
2. UMM KADDADA										
Umm Kaddada	314	7	1	0.5	1.9	-	0.9	0.7	1.2	2.2 (C_1S_1)
Sal El Naan	80	7.8	1.8	1.5	7.8	0.5	4.7	0.7	1.8	6.1 (C_1S_1)
Shagra	668	7.6	0.7	0.2	1.9	-	1.6	0.5	0.5	2.8 (C_2S_2)
Umm Bayada	530	8.5	0.4	3.7	3.5	0.9	4.9	0.4	1.4	0.23 (C_2S_1)
El Fula	500	8.2	1.2	0.8	7.0	-	4.8	2.1	1.6	6.34 (C_2S_1)
3. NAHOUD										
Nahoud	280	3.0	3.0	0.8	0.3	-	3.3	0.5	0.3	0.2 (C_1S_1)
Khmnas	160	8.0	2.1	0.5	0.2	-	1.9	0.3	0.5	0.2 (C_1S_1)
Umm Feis	220	8.1	2.6	1.1	0.3	-	2.9	0.5	0.6	0.8 (C_1S_1)
4. NILO-NUBIAN										
Khartoum	700	8	3.0	24	7.4	3	3.2	1.9	2.7	4.5 (C_2S_1)
Gezireh	-								-	-
Seleim	200	8.4	1.5	0.8	0.7	1	1.8	0.5	0.7	0.5 (C_1S_1)
5. GEDAREF										
Eastern	2840	8.2	3.6	8.6	41.3	30	20.5	1.0	1.9	16.6
Western	940	8.8	0.3	3.5	5.6	4	3.4	0.6	1.4	4 (C_2S_1)

V. EXPLOITATION OF GROUND WATER

The drought which has afflicted Sudan almost without cease since 1967 has seriously damaged the country's natural resources and caused the desert to advance 100 km southwards. At present (1985-1986) the desert is advancing at one to five kilometres a year. Sand dunes have invaded most of the agricultural land in the northern savannah which receives little rainfall and they are advancing towards the southern part where farm production is high.

The future of these regions is a source of concern and steps must be taken to protect what can be protected and to rehabilitate part of what has been lost. The availability of water resources is the key to the success of any programme to improve the environment and restore the ecological balance.

Fortunately, Sudan is better placed than other countries of the Sahelian zone to combat desertification and develop its natural resources. It has abundant water resources: rainfall, surface water from the Nile and its tributaries, and ground water. The rainfall and surface runoff vary very greatly in step with the cycles of drought and rains which affect the country. Furthermore, this water is inefficiently used and much of it is lost through evaporation or drainage. Better techniques must therefore be introduced for the collection and use of surface water so as to avoid wastage.

Ground water is the most abundant resource and also the least vulnerable to weather conditions. It is available in aquifers of average or high yield over more than half of the country. The data given above show clearly that these aquifers are very little used and that their exploitation could be considerably increased without risk of exhaustion.

Domestic and irrigation uses

At present Sudan's ground water is exploited almost exclusively to meet human and livestock needs. About 70 per cent of the human and livestock populations are supplied with ground water from six-inch diameter lined boreholes equipped with diesel or turbine pumps. The water is pumped into a raised reservoir from which it flows through five small faucets to fill family tanks and three or four watering troughs with a capacity of one cubic metre.

Each of these "water yards" usually has one or several tubewells. Large settlements have standpipes and private outlets. It is difficult to estimate the costs owing to the fluctuations in the price of the imported equipment and materials and in exchange rates.

However, in rough terms it can be said that a water yard with a single tubewell costs about US$ 50,000, including US$ 22,000 for a 200 m hole of 6" diameter, lined and equipped with a filter, and US$ 11,000 for the pump and motor.

For two holes the cost is about US$ 80,000.

It is difficult to keep the installations in permanent operation, for their dispersal over such a vast area causes serious problems of maintenance and repair; furthermore, most of them are in places of difficult access. At present there are about 25 maintenance and repair stations and workshops in operation; they service 3,000 yards over an area of one million square kilometres - a difficult task. About 50 additional stations are to be built under a two-year programme (1985-1987).

A modest charge is made for the distribution of the water, in some cases insufficient to cover the cost of fuel. It must also be remembered that the water yards are usually subject to no controls, with the result that the system deteriorates and the quality of the services declines. Studies have therefore begun to determine the most appropriate management methods. These studies have produced the following recommendations:

1. Increased charges;

2. Increased participation by the people and community organization in the management and operation of the installations;

3. Establishment of a properly defined maintenance programme with periodic checks.

The fairly recent increase in the number of installations has encouraged the people to develop their livestock holdings. However, the concentration of herds around the waterpoints has led to overgrazing and sometimes to the total destruction of the vegetation cover for 20 km around. In these areas animals which would have died of thirst now die of hunger.

In future the establishment of new installations in these ecologically vulnerable areas must be planned as part of an integrated development strategy. It must satisfy the real needs and secure substantial improvements in the social and economic conditions. The following criteria should be used:

- New water points should be located at not less than 20 km from the nearest permanent water point;

- The prospective site should be studied to determine the impact of the increased water supply on other natural resources;

- Higher charges should be made for the water so as to hold consumption at a reasonable level.

Irrigation should be limited to areas where the aquifers are shallow and high-yielding. The following criteria should be used:

- Total depth of well (which determines the amount of investment needed);

- Depth to water (which determines the operating costs);

- Specific yield expressed in l/s/m of drawdown (which affects the cost of both investment and operation);

- Chemical quality of the water (which must be suitable for the soils and the proposed crops.

In the light of these considerations, it can be said that Sudan does have areas which can be irrigated by ground water. Auxillary irrigation from ground water can be envisaged in other areas where the aquifers are fairly deep.

Exploitation of alluvial aquifers

Most of Sudan's alluvial aquifers meet the criteria set out above. In one way or another they have been exploited for irrigation but not to their maximum potential. The alluvial aquifer of the Gash basin is a typical example. Some 8,000 ha are now cultivated in the El Kassala area. The annual drawoff of water is 120 million cubic metres, while the safe yield is about 200 million, so that the irrigated area could be increased by 4,000 ha. Most of the wells are less than 35 m deep and the static water level is usually at 10 m below the surface and the specific yield in the order of 10 l/s/m. Accordingly, a well can usually irrigate eight hectares. The water is of excellent quality and suitable for many crops and many soil types.

The alluvial aquifer of the Wadi Kutum system in northern Darfur is exploited by many shallow large-diameter wells to irrigate small garden and orchard plots. The available capacity up to the safe yield is about 20 million cubic metres a year or 40 times the present drawoff. Thus, an additional 2,000 ha could be irrigated, with the ground water supplementing the rainwater. The specific yield is 4.2 l/s/m, and each well can therefore irrigate four hectares. The water quality is excellent.

The alluvial aquifers of Wadis Azum and Aribo west of the Jabal Marra could supply 80 million cubic metres a year, whereas at present only 100,000 m^3 is drawn off to irrigate small plots. The depth to be reached by the wells is less than 40 m and the depth to water is usually less than five metres. The specific yield is 30 l/s/m, and each well could irrigate 24 ha. The water is of excellent quality. The climate is fairly cool and suitable for Mediterranean crops.

The alluviums of the temporary watercourses of southern Darfur (Wadis Kaja, Bulbul, Ibra and Nyala) could supply 70 million cubic metres a year. At present these alluviums are partially exploited for irrigation and to supply the town of Nyala. This town consumes about 2,500 m^3/day, i.e. one million cubic metres a year. About 14 million cubic metres could be drawn off up to the end of the dry season. Accordingly, it is hardly possible to increase the drawoff without risk of exhausting the aquifer.

Hardly any of the alluviums of other wadis are exploited. However, they are fairly thin and the water levels are subject to great variations. Substantial exploitation cannot therefore be envisaged.

The aquifers of the El Selim and Karima basins are contained in fossil beds of the Nile, so that in principal they have constant recharge. This area used to be irrigated by a canal from the Nile. As the level of the Nile has declined over the past 15 years and the canal has not been maintained, the irrigated areas have reverted to desert. In recent times the farmers have increased irrigation from large-diameter wells or from tubes sunk in the soil and equiped with centrifugal diesel pumps. The wells are less than 50 m deep and the water level is at three to five metres, corresponding to the level of the Nile. The specific yield of a 50-meter borehole is 40 to 65 l/s/m. A single well can irrigate 30 to 50 ha. In many cases the water is of better quality than the Nile water and is therefore suitable for irrigation.

Exploitation of the Umm Ruwaba aquifer

About 450 million cubic metres a year could be drawn from this aquifer, but at present only about 40 million cubic metres are taken for domestic purposes and 15 million for irrigation. It supplies 800,000 m^3/year to 50 water yards; about 400,000 cubic metres are drawn from large-diameter wells scattered over the whole aquifer. The towns of Umm Ruwaba and Bara consume about 400,000 m^3/year.

In the El Kheira area small garden and orchard plots have been irrigated since time immemorial from large-diameter wells lined with bricks. Some of these wells have centrifugal diesel pumps. The wells are usually less than 50 m deep and the water surface is at 5 to 8 m. Each well can irrigate two to three hectares. The water quality is excellent and suitable for irrigation. It is surprising that the 300,000 m^3 of water flowing freely from two wells at Umm Balagi should be wasted, apart from a small amount used as drinking water. This amount could irrigate about 8 ha of market-garden crops and fruit trees.

The Umm Ruwaba aquifer in the Bara basin is thought capable of supplying three million cubic metres to the town of El Obeid by means of 12 boreholes; the investment is estimated at US$ 10 million, with annual operating costs of US$ 500,000.

In the El Atshan basin the Umm Ruwaba aquifer and the overlying Nile alluviums are intensively exploited to irrigate 400 ha under the Rahad project. The drawoff is 400 million cubic metres. The recharge is by drainage from the River Rahad. The ground water is of good quality.

The Baggara basin could supply 30 million cubic metres of water a year, as against the present drawoff of only 10 million cubic metres. The annual human and livestock requirements are about five million cubic metres. During the four-month rainy season these requirements are met from "rahads" and "turdas" bordering the bed of the watercourse. About two million cubic metres are provided in this way, with the balance of three million cubic metres drawn from hafirs are partially filled with silt and the total available capacity is no more than 750,000 cubic metres. There are 130 water yards supplying 2.3 million cubic metres of water. In theory there are sufficient water points. In fact a large number of them are not in service. A considerable effort must therefore be made to rehabilitate the water points and clear the hafirs.

The Baggara basin has a good irrigation potential. The most favourable areas are those where the ground water lies at the shallowest depths and where the specific yields are highest, for example in the southern parts of Umm Agaga (600,000 ha suitable for mechanized agriculture). The rainfall (600 mm) is sufficient for rain-fed crops; ground water could supply additional irrigation for certain crops. It lies at a depth of 25 to 30 m and the specific yield ranges from 200 to 700 $m^3/d/m$ of drawdown. A single well can irrigate 60 ha and the water is of excellent quality.

In the Sudd basin the aquifer is hardly exploited at all; the little water which is drawn off is used for domestic purposes. Given the abundance of surface water, this is the only use which can reasonably be made of the ground water.

Exploitation of the Nubian sandstone aquifer

The available potential of the Nubian sandstone is about 360 million cubic metres a year, whereas the present drawoff is only 60 million cubic metres (17 per cent). This is a major resource available in northern Sudan to combat the devastating effects of the drought. It is located in an extremely arid area which includes northern Darfur and its extensions into Libya and Egypt. The potential of the three sub-basins (Wadis Hower, Saniya Haiyeh and Tima) is encouraging with respect both to domestic and to irrigation and industrial uses. For a long time now the three States concerned have been considering the construction of two major international roads, one linking Darfur to the Kufrah oasis in Libya, and the other following an ancient track (Darb El Arbain) linking northern Darfur and Kordofan to the "New Valley" of Egypt. Sudan has already taken the initiative of establishing five waterpoints along the proposed road to Libya; each has two boreholes equipped with pumps and a storage capacity of five cubic metres. The works at Wadi Hower on the road to Egypt are planned for the near future. The financing is to be provided by an Italian grant for the repair of water points in northern Darfur. These water points will encourage vehicular traffic between the three countries and at a later stage they will supply the water needed for the construction of the roads. They will also facilitate the exploitation of a number of isolated mineral deposits which have been identified and the expansion of mining research in these remote areas. They might also provide the driving force for the development of the ground-water and land resources of Wadi Hower and the Nekhila and Bir Natron oases, making it possible to grow high-value cash crops or forage and thus to combat the desertification of this region and reduce the overgrazing of central Sudan by increasing the export of animals to the markets of Libya and Egypt.

Ground water is found along Wadis Hower, Bir Natron and Nikheila and at the Laquia oasis. In Wadi Hower the wells are about 40 m deep and the water surface lies at about 6 m. The specific yield is about 20 l/s/m and each hole could irrigate about 10 ha of arable land along the banks of the wadis. As the area is inaccessible and no fuel is available, the ground water must be extracted by wind, solar or hand pumps to irrigate the small plots. The water is of excellent quality.

At Saniya Haiyeh the relatively mild climate makes it possible to grow corn and beans and other vegetables which are viable only in northern Sudan; this might contribute to the sedentarization of the Zaghawa, one of the tribes which have suffered most from the drought in 1984-1985. The depth to be reached by the wells is about 100 m; the water surface is at 50 m at most. The holes can produce 50 to 75 m^3/h and irrigate 8 to 10 ha. The water is of excellent quality. Similar conditions are found in the Tima sub-basin. The projects envisaged will facilitate the sedentarization of the Meidob tribe in northern Darfur. The ground-water potential of the Umm Kaddada basin is about 100 million cubic metres, i.e. ten times the present drawoff, which is used only for domestic purposes, including supplies for the towns of El Fasher and Umm Kaddada and the rural areas of central and eastern Darfur and western Kordofan.

The Nubian sandstone aquifer of some of the Umm Kaddada sub-basins (Umm Bayada, Saq El Naam and Shagara) offers good prospects for irrigation based on joint use of ground and surface water; most of the surface water is at present lost, whereas it could be stored in the clay soils for most of the growing season. This could be achieved by building earth banks to block the flows and facilitate infiltration in deeply ploughed soil; the ground water would be used for supplementary irrigation or crop diversification.

The efficiency of the operations and the certainty of having water when and where it is needed will depend mainly on the extent to which ground water can be used to supplement irrigation.

The surface and ground water at Umm Bayada can be used to increase the production of food crops and forage and to facilitate the sedentarization of the tribes seriously affected by the drought. If agriculture is shifted to the clay plains, the sandy areas will be able to regenerate their natural vegetation. The total depth of the wells is about 100 m and the water has to be piped for only 25 m. The yield of the wells is 30 m^3/h, which means that each well can irrigate four hectares. The water quality is excellent.

In the Sag El Naam area the aquifer is very productive, with a stock of $100x10^9$ m^3 and an available potential of 20 to 60 million cubic metres. The holes are about 150 m deep and the water is reached at 80 to 90 m. The specific yield is about 20 l/s/m and each well can irrigate 20 to 30 ha. The water quality is excellent.

In the Sag El Naam area the aquifer underlies a clay plain of 50,000 ha of arable land which receives rainfall of 400 m. The plain has an intermittent watercourse (three months a year) - Wadi El Ku and its tributaries. Joint use of surface and ground water could meet a large part of Darfur's grain needs. It could also improve the living conditions of the people and slow down the rural exodus.

In the Shagara sub-basin the ground water of the Nubian sandstone is exploited to supply the town of El Fasher with 60,000 m^3/year drawn from seven boreholes; this is approximately the available yield. The town also takes water from the Golo reservoir on Wadi El Ku, west of El Fasher.

The available yield in the Nahoud basin is 16 million cubic metres a year, and only five million cubic metres are drawn off for domestic use, including drinking water. The most productive part is the Gefauwi-Saata trench. However, the depth of the wells (250 m), the depth to water and the moderate specific yields make it impossible to use the water for irrigation, especially as it will probably be needed to supply the towns of Nahoud and El Obeid.

The Nubian sandstones in the Nilo-Nubian basin contain large amounts of water. The available discharge is about 175 million cubic metres a year; the present drawoff is 35 million cubic metres, most of it used for irrigation.

The irrigation boreholes tapping the upper part of the Nubian sandstones in northern Gezireh and near Khartoum are 60 to 70 m deep and those which tap the lower part are 120 to 15 m deep. The yields are 60 and 140 m^3/h respectively in the best cases. The unit cost per cubic metre is about two United States cents - a little less for the lower aquifer, a little more for the upper one. Irrigation is thus more economical with deeper boreholes despite a higher initial investment. This is why the small farmers put their money together to install deep boreholes.

In the northern region irrigation now tends to be based increasingly on ground water. The reason for this is the decline in the level of the Nile and the ceaseless displacement of its course, developments which are accompanied by the advance of the desert and the invasion of sand dunes to cover the irrigated land. The area of arable land in this region declined from 400,000 ha in 1960 to 10,000 ha in 1978. This caused half the population to migrate to the big towns of Sudan or to other countries. Huge volumes of water are needed to combat this situation and it can come only from the Nile or the Nubian sandstones. It is estimated that the cultivation of about 100,000 ha by means of ground-water irrigation could produce an annual re-return of about 30 per cent on the investment. At El Seleim the boreholes would be about 120 m deep, the water lying between five and 14 m deep. The well discharge would be 200 to 500 m^3/h, so that each well could irrigate 20 to 50 ha.

VI. CONCLUSION

Sudan is a vast dry country of farmers and herdsmen and the existence of available ground water is a decisive factor in its economic and social development. Leaving aside the permanent watercourses, i.e. the arms of the Nile and its tributaries, there are 80 million ha of grazing and arable land accommodating 70 per cent of the country's population, or about 50 million people, and about 80 per cent of the livestock, requiring a total of 500 million cubic metres of water. The rain which falls for three months a year supplies 30 per cent of this requirement; the balance must be drawn from ground-water aquifers. To date about 3,000 pumping stations, 1,000 hafirs and 20 small dams have been built, supplying a total of about 100 million cubic metres a year - a little over a quarter of the requirement. In 1967 a decisive boost was given to the ground-water development programmes in three main hydrogeological units: the alluvial beds, the Umm Ruwaba formations and the Nubian sandstones; together these units cover almost half of the country and supply more than half the population with water. The alluvial aquifers, which have a good recharge from surface runoff and rainfall lie at shallow depths, are widely used for irrigation. The Umm Ruwaba aquifer covers 20 per cent of the country; it includes unconsolidated detritic elements, usually fairly fine, in a complex sedimentary sequence with great lateral and vertical variations. The aquifer is unconfined, semi-confined or confined depending on its location.

The Nubian sandstones are one of the world's largest hydrogeological units and cover more than a third of Sudan; they can be up to 4,000 m thick in the centre of the basin which they fill. The aquifer is unconfined, semi-artesian or artesian depending on the distance from the edge of the basin.

As a rule Sudan's ground water is chemically suitable for human and animal consumption and for irrigation. The exploitation is still low in comparison with the available potential. This is due both to the installation costs (US$ 50,000 per water yard), the operating costs and the problems of maintenance and repair, for the installations are widely scattered and usually difficult of access. A great effort has to be made to overcome these difficulties.

A water policy must therefore be established as part of an integrated development plan for natural resources for each region of the country. Some encouraging progress has already been made in this direction.

Ground-water irrigation offers promising prospects in some alluvial regions: the water of the El Gash alluviums irrigates 7,000 ha and could irrigate a further 4,000 ha. There are other opportunities in northern Darfur (Wadi Kutum and Wadi Hower) west of the Jabal Marra, where there is an irrigation potential of 4,000 ha, and in the north of the country in the area of the fossil beds of the Nile.

The Umm Ruwaba aquifer is exploited to only a limited extent for irrigation, notably at El Kheiran (Bara basin) and at El Atshan, along the Blue Nile. It is estimated that this aquifer could be exploited for the full or supplementary irrigation of 400,000 ha in the Umm Agaga plain and in southern Kordofan and Darfur.

The Nubian sandstones of the Sahara basin could supply some 27 million cubic metres a year for the construction of the international roads to Egypt and Libya and the creation of oases along these roads where the nomadic tribes stricken by the drought could settle.

In the Umm Kaddada basin the ground water could be used for the full or supplementary irrigation of 50,000 ha at Sag El Naam.

The Nubian sandstones are exploited to irrigate several areas an important resource in the campaign against desertification in the north of the country (El Seleim and El Khewi) with respect to the creation of both wooded and grain-growing areas.

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ANNEX

UNDP Country and Intercountry Projects on Ground-Water Resources

Project No.	Project title	Duration	Executing agency	Importance of ground water 1	2	3
RAB/82/013	Transnational Project on Major Regional Aquifer in NE Africa	5 years	UN	x		
SUD/85/U/03/96/01	Rural Water Supply Programme for Drought-Affected Areas - Kordofan	1 year	UN	x		
SUD/84/009/A/01/12	Establishment of Shelter Belts in the Northern Province	5 years	UN/FAO	x		
SUD/84/006	Establishment of a Water Point Maintenance Unit in the West Bank - Equatorial Region	3 years	UN	x		
RAB/84/023	Training of Technicians in Water Resources Management and Technology in Least Developed Arab Countries	?	?	x		