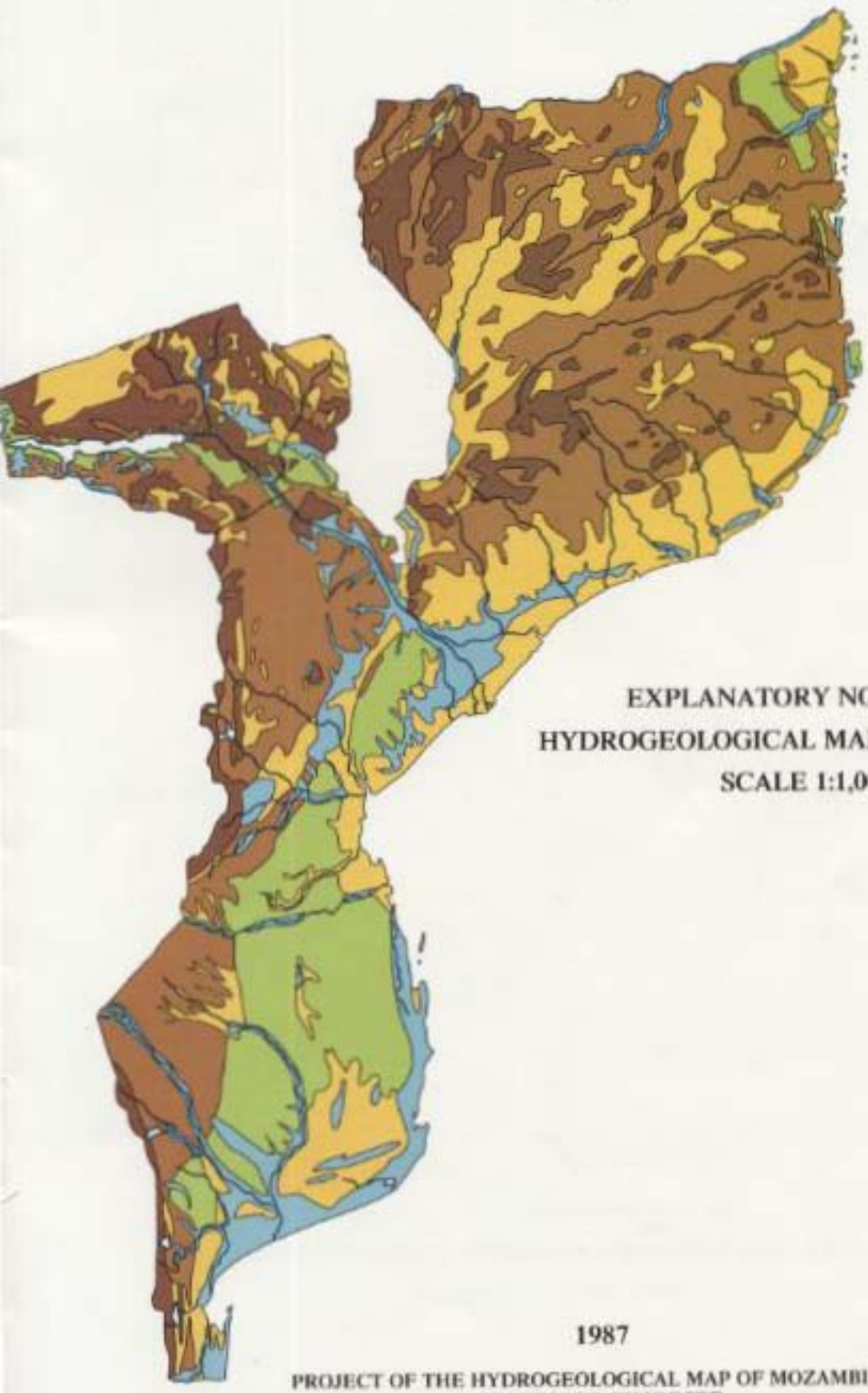
REPUBLIC OF MOZAMBIQUE

MINISTRY OF CONSTRUCTION AND WATER

NATIONAL DIRECTORATE FOR WATER AFFAIRS

D.N.A.



EXPLANATORY NOTES TO THE HYDROGEOLOGICAL MAP OF MOZAMBIQUE SCALE 1:1,000,000

1987

PROJECT OF THE HYDROGEOLOGICAL MAP OF MOZAMBIQUE
SPONSORED BY UNICEF

TO THE PEOPLE OF MOZAMBIQUE
AND ALL THE PERSONS INVOLVED IN
THE WATER SECTOR IN THIS COUNTRY

by: B.P.A. Ferro
D. Bouman

A CONTRIBUTION TO

'THE INTERNATIONAL DRINKING WATER SUPPLY AND SANITATION DECADE'

(1981 - 1990)

PREFACE

Throughout its ten years of existence, the National Directorate for Water Affairs (DNA) has tried to build the economic, technical and institutional structures necessary to fulfil its fundamental objectives: the management of the country's water resources and provision of safe drinking water and sanitation to urban and rural population centres.

The vast majority of the mozambican people live in the countryside, in small dispersed communities. The most secure source of safe potable water for these communities has been ground water. The National Rural Water Programme has therefore concentrated on developing the use of wells and boreholes. Since the end of the 1970s Mozambique has suffered the effects of prolonged droughts effecting large areas of the country. To alleviate the effects of these droughts groundwater studies and drilling programmes have been intensified.

It is therefore not surprising that the initiative to prepare this Hydrogeological Map of Mozambique originated with the group in DNA working most directly with rural water supplies. It is also no surprise that UNICEF, which has always been the DNA's main support in the rural water supply sector, should immediately agree to provide financial support for the project.

When the idea of preparing a 1:1,000,000 Hydrogeological Map was first conceived, many doubts were raised about whether we should proceed. The available information was very limited and had not been collected together, and it was extremely difficult to carry out field-work to obtain additional data. The Map would also only allow a preliminary evaluation of potential groundwater sources.

However, we finally came to agree that the preparation of the Hydrogeological Map would be useful. Firstly, it would provide the stimulus for a concentrated effort to collect and categorize the data accumulated from many years of investigations and drilling throughout the country, data which would gradually become lost with time. Secondly, it would reinforce the technical and organizational capacity of DNA and thus open up the possibility of similar but more complex activities in the future. Finally, because it would be an easily understood document to assist the spread of knowledge about the country's underground water resources, and would thus assist with planning their use.

Now, almost two years after taking that decision, it has proved to be the right one. We owe much to the competence and dedication of the team responsible for preparing the Hydrogeological Map. To Bernardino Ferro and Dick Bouman we present our sincere thanks in acknowledgement of their commitment to the project. It is also right to recognise here the important contribution made by DNA's Hydrogeology Section to the development of a clear and systematic understanding of groundwater in the Republic of Mozambique, and in particular the valuable support given over many years by the Netherlands and Switzerland.

I fully expect that this successfully completed work of hydrological mapping will be only the start, and that other more detailed projects will shortly follow.

Maputo, October 1987
Arnaldo Lopes Pereira
National Director for Water Affairs

LIST OF ABBREVIATIONS, ACRONYMS AND NAMES OF ORGANIZATIONS

DINAGECA	Direcção Nacional de Geografia e Cadastro; National Directorate for Geography and Land Surveys
DNA	Direcção Nacional de Águas; National Directorate for Water Affairs
DPSH	Direcção Provincial dos Serviços Hidráulicos (substituída pela DNA); Provincial Directorate for Hydraulic Services (substituted by DNA)
DSGM	Direcção dos Serviços de Geologia e Minas (substituída pelo ING); Directorate for Geological and Mining Services (substituted by ING)
DSH	Direcção dos Serviços Hidráulicos (substituída pela DNA); Directorate for Hydraulic Services (substituted by DNA)
FAO	Organização das Nações Unidas para a Alimentação e a Agricultura; Food and Agriculture Organization of the United Nations
GEOMOC	Empresa Estatal de Sondagens; State drilling company
HIDROMOC	Empresa Estatal de equipamento hidráulico; State supplier of Hydraulic equipment
INIA	Instituto Nacional de Investigação Agronómica; National Institute for Agronomical Studies
ING	Instituto Nacional de Geologia; National Geological Institute
INM	Instituto Nacional de Meteorologia; National Meteorological Institute
INPF	Instituto Nacional de Planeamento Físico; National Institute for Physical Planning
PRONAR	Programa Nacional de Água Rural; National Programme for Rural Water Supply
SEHA	Secretaria do Estado de Hidráulica Agrícola; State Secretary for Drainage and Irrigation
UDAAS	Unidade de Direcção de Abastecimento de Água e Saneamento; National Water Supply and Sanitation Agency
UNESCO	Organizações das Nações Unidas para a Educação, Ciência e Cultura; United Nations Educational, Scientific and Cultural Organization
UNICEF	Fundo das Nações Unidas para a Infância; United Nations Children's Fund

Foreign companies and organizations, involved in groundwater in Mozambique:

AQUATER (Ital), BONIFICA (Ital), BRGM (Fran), BURGEAP (Fran), COBA (Port), DANGROUP (Damm), EUROCONSULT (Neth), GEOTECNICA E MINAS (Port), HELVETAS (Swits) ITALTECHNO (Ital), IWACO (Neth), Lutheran World Federation, Luxton Hunting and Ass (RSA), OXFAM (Belg.), PROFABRIL (Port), SELKOZPROMEXPORT (USSR), SOSOMOC (Port), TECHNOSYNESIS (Bras), UNICEF.

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ANNEX: Legend to the hydrogeological map of Mozambique, scale 1:1 000 000.

SEPARATE MAPS:

Carta Hidrogeológica de Moçambique / the Hydrogeological Map of Mozambique (scale 1:1 000 000; 2 sheets)
Carta das Captações mais adaptadas / the Groundwater Development Map (scale 1:2 000 000)

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1. INTRODUCTION

1.1 General Considerations

The Hydrogeological Map of Mozambique, scale 1:1 000 000, is the first general synthesis of the groundwater occurrence in the country. The **objective** of the Map is to give a clear and balanced review of the groundwater resources, including spatial distribution, quantitative potential and water quality.

The Map aims to serve as a general consulting document for the planning and development of water supply, as well as for agricultural, industrial and environmental programmes. It is also intended for education and training activities at intermediate and university level.

The Map is classified as a **reconnaissance map.** This, together with the relatively small scale, means that it can only be used for general planning purposes and not for too strict or detailed interpretations, as, for example, the siting of individual wells, civil works or villages, without the benefit of previous investigations and field surveys. The Map can provide an initial overall indication of the suitability of projects in a selected region, necessary to define the sites and methods for further investigations.

The **Legend** follows the recommendations made in the International Legend for Hydrogeological Maps, published by UNESCO in 1970 and revised in 1983.

Emphasis is put on the **upper** aquifers in unconsolidated material that can be used by dug wells. This means that in some cases deeper, more productive aquifers are not directly represented by the hydrogeological map-units.

The Map and the Explanatory Notes are the result of a **desk study.** They have been prepared by a small team of four persons in a relatively short period. Basic data were scarce and unevenly distributed, consisting of individual drilling records and previous regional surveys. A complementary study has been made, using satellite images. The Explanatory Notes are a summary of a more detailed internal report, entitled "Hydrogeology of Mozambique, state of the art" (Ferro, Bouman 1987) and are published in both the English and the Portuguese language.

1.2 Background

The compilation of a hydrogeological map of Mozambique was proposed by the National Water Supply and Sanitation Agency, UDAAS, which required a reference document for the proper planning of **rural water supply.** In August 1985 this proposal was accepted at a joint meeting of interested organizations. The National Directorate for Water Affairs, **DNA,** took responsibility for the project, provided an office and contracted personnel. The project was financed by DNA with a sponsorship of UNICEF for the foreign currency component. The project started in February 1986 and covered a period of 18 months, excluding the printing phase.

The **team** engaged in the project consisted of:

- Bernardino P. de Almeida Ferro, Msc, senior geologist and project coordinator with more than 20 years of experience in Mozambique.
- Dick Bouman, Msc, hydrogeologist with 2 years of experience in Mozambique.
- Justino Eugenio Bahane, technical assistant
- João Manuel, cartographic draftsman of the National Geological Institute.

An additional contribution was made by the Mozambican counterpart Adriano Manuel Fonseca Saraiva, by the technical adviser of UNICEF Stevan Radojicic, and by the UNESCO consultant Albert Mente, who visited the project in August/September 1986.

1.3 Acknowledgements

Thanks are due to all the organizations and persons who made a contribution to the project and publication of the Hydrogeological Map of Mozambique, whether by providing ideas, advice, information or material, or by placing their installations at the project's disposal.

For providing basic data, reports and satellite images, considerable thanks are due to the National Geological Institute, ING, the Soil Department of the National Institute for Agronomical Studies, INIA, the state drilling company GEOMOC and the Geohydrological Section of DNA, including the groundwater data bank.

For their personal contributions, the authors would like to thank the national director João Manuel Reynolds Marques and the geographer Patricia Oberreuter Tapia of ING, the FAO remote sensing specialist Kees Bronsveld, the UNICEF technical adviser Stevan Radojicic, the UNESCO consultant Albert Mente and the DNA technical assistant Jorge Gero Tomocene.

Thanks are also due to Steven Hugman and teachers of the Centro Audio-Visual de Linguas in Lisbon for the corrections on the English text.

2. THE COUNTRY

2.1 General Characteristics

Mozambique is **situated** on the east coast of Southern Africa, between 10°27'S and 26°52'S latitude and 30°12'E and 40°51'E longitude. It covers about 800 000 km^2. The territory is divided into 10 provinces and 128 districts (Figure 1, Table 1).

Table 1: Characteristics of the provinces and the country (after INPF 1985)

Provinces	Number of Districts	Area (km^2)	(%)	Population (1980) (Inh)	(%)	Pop. Density (Inh/km^2)
Niassa	15	129 056	16.1	514 100	4.2	4.0
Cabo Delgado	16	82 625	10.3	940 000	7.7	11.4
Nampula	18	81 606	10.2	2 402 700	19.8	29.4
Zambezia	16	105 008	13.1	2 500 000	20.6	23.8
Tete	12	100 724	12.6	831 000	6.9	8.3
Manica	9	66 661	7.8	641 200	5.3	10.4
Sofala	12	68 018	8.5	1 065 200	8.8	15.7
Inhambane	12	68 615	8.6	997 600	8.2	14.5
Gaza	11	75 709	9.5	990 900	8.2	13.1
Maputo	7	26 358	3.3	1 247 100	10.3	47.3
Country	128	804 380	100	12 129 800	100	15.2

According to the census of 1980, the **population** was over 12.1 million. The population is unevenly distributed. More than 50% lives in the coastal belt. Only 17% lives in urban areas. The estimated average population growth rate is 3.03% per year. Demographic projections calculate with 5.0% for the urban and 2.6% for the rural population (Table 2).

Table 2: Demographic characteristics 1980 and 1990 (after INPF 1985)

Area		Population 1980	Annual growth rate (%)	Projected Population 1990
Provincial capitals				
Maputo	(Maputo)	755 000	5	1 232 000
Beira	(Sofala)	228 000	5	372 000
Nampula	(Nampula)	158 000	5	258 000
Chimoio	(Manica)	71 000	5	117 000
Inhambane	(Inhambane)	61 000	5	98 000
Quelimane	(Zambezia)	60 000	5	97 000
Tete	(Tete)	48 000	5	79 000
Xai-Xai	(Gaza)	46 000	5	75 000
Pemba	(Cabo Delgado)	43 000	5	69 000
Lichinga	(Niassa)	39 000	5	63 000
Other urban centres		491 000	5	799 000
Rural population		10 130 000	2.6	13 092 000
Country		12 130 000	3.03	16 351 000

The **morphology** of the country can be characterized by distinct units: coastal lowlands, middle plateaus, upland plateaus and mountainous areas. This division generally coincides with certain altitudinal intervals: 0 to 200 m (44% of the surface area), 200 to 500 m (29%), 500 to 1000 m (21%) and over 1000 m (6%). The units are bounded by more or less pronounced escarpments, giving rise to a step-like cross-section, rising from the coast inland. The coastal lowlands mainly coincide with the sedimentary terrains, whereas the other units are underlain by the crystalline rocks of the Basement Complex.

The **coastal lowlands** have a low relief, rising inland to altitudes of 200 m or more. The Mueda Plateau (up to 1000 m) in the north, the Cheringoma and Buzi Plateaus (up to 370 m) in the center and the Urrongas Plateau (up to 175 m) and the Alto Limpopo Plains (up to 550 m) in the south rise out above the coastal lowlands, despite forming part of the sedimentary terrains. The coastline is characterized by a strip of beaches, recent dunes and inland lagoons in the south; by mangrove, swampy depressions and a series of low beach ridges in the center; and by mangrove, small dunes, alternating with cliffs in the north. The alluvial valleys have fertile clay-soils and a steppe-like vegetation. The dominant extensive plains and inland dunes have poor sandy soils and a savanna vegetation. Typical crops are maize, groundnut, cassava, cashew and coconuts.

The **middle plateaus** and the coastal lowlands on the Basement Complex have poor to moderately fertile soils with open forest. They have typical rain-fed crops like maize, sorghum, millet, groundnut, cotton and sisal. On the **upland plateaus**, the soils are also poor to moderately fertile, but suitable for a wider variety of typical tropical to mediterranean crops. Fairly dense forest is the common type of natural vegetation. The landscape of both plateau types is often characterized by outstanding inselbergs or residual hills.

The **mountainous** areas occupy part of the interior of the country. Frequently the summits rise over 1800 m, up to 2436 m (Mt Binga). Because of the stoniness of the soils and the steepness of the terrain, this unit is relatively unsuitable for agriculture, except for afforestation projects.

The most important traditional food-**crops** are maize, cassava, groundnut, rice, sorghum and millet. The main cash-crops are cashew, cotton, copra, tea, sugar, citrus and sisal. It is estimated that only 6% of the total area is under cultivation, except for pastures and forestry. Less than 78 000 ha is under irrigation. **Livestock** and cattle ranching is most developed in the south and on a minor scale in the lowlands of Sofala and Zambezia and on the plateaus of Chimoio

Figure 1: Provinces, districts and cities (1985)

and Angonia. **Fishery** plays an important role in the national economy.

2.2 Geological Setting

The rocks in Mozambique belong to four main lithostratigraphic groups: Precambrian crystalline rocks of the Basement Complex (57%), Karoo sedimentary rocks (5%), Post Cambrian volcanic and igneous rocks (3%) and Meso-Kenozoic sedimentary rocks (35%) (Figure 2).

The **Basement Complex** occupies Manica, the western part of Sofala and almost the entire region north of the Zambeze. In the first region one finds remnants of the Early Precambrian Zimbabwe Craton, dominated by greenschists. The other formations of the Precambrian comprise high-grade metamorphic rocks, forming part of the Mozambique Metamorphic Belt. This belt is dominated by gneiss and a gneiss-granite-migmatite complex with local meta sediments, charnockite series and a gabbro-anorthosite complex in the center of Tete province.

In terms of crustal development, the **Post-Cambrian** is characterized by the break-up of the Supercontinent Gondwana. In an early stage (Permian to Jurassic) the continent was split up along the E-W trending Limpopo and Zambeze Belts, where deep troughs were filled with continental **Karoo sediments.** The latter formed the Middle Zambeze Basin (4%). In the north of Niassa the Maniamba Basin (1%) and some outcrops of Karoo sediments form part of a larger Karoo Basin in Tanzania. The lower series of the Karoo sediments are mainly very fine textured (mudstones) and may contain carbonaceous beds. The upper series are more sandy developed.

The Karoo terminated with a period of intensive **volcanic** activity, dominated by basaltic and rhyolitic outflows. The volcanic sequence consists of a number of superposed lava flows, emerging from tension faults and fissures along the margins of the Basement Complex and along the widening Zambeze and Limpopo Basins. A line of outcrops is found along these margins of which the Libombo Range in the southwest is the most important. The outcrops continue in a narrow strip to the north of the Zambese. The basalt along the coast of Nampula is considered to form part of the same system.

After the Karoo volcanism, local **igneous activities** continued along borders of the East African Rift System and of the Zimbabwe and Kaapvaal Cratons. The Post-Karoo igneous phenomena are dispersed and produced rocks with a wide variety of composition, genesis and age. The late Jurassic early Cretaceous batholith of the Serra da Gorongosa, consisting of gabbroic and granitic rocks, and the Middle Cretaceous alkaline lavas of the Lupata region are the most important features. More dispersed examples are the Cretaceous syenitic plutons of Milange, Chiperone and Derre and the carbonatite complexes and Upper Tertiary vents of basic to ultra-basic composition in the Sena region.

The volcanism of the late Karoo-early Cretaceous was followed by a relatively calm period with an uplift of the East African continent. As a consequence the volcanic rocks were deeply weathered, eroded and afterwards covered with continental sediments. On the other hand, a subsidence along deep N-S oriented troughs, associated with the East African Rift System, and along the axis of the Mozambique Channel, resulted in the formation of **two separate Meso Kenozoic sedimentary basins** in the south-east and north-east of the country.

The Northern or Rovuma Sedimentary Basin covers about 3% of the country. It extends from Lindi (Tanzania) to Ilha de Moçambique. On shore it attains a maximum width of 120 km along the Rovuma. The Southern or Mozambique Sedimentary Basin covers about 32% of the country and stretches from 17°20'S to 29°S latitude in Natal (Rep. of South Africa). Its maximum width of 440 km is attained at 22°30'S latitude.

The two sedimentary basins were subject to several marine transgressions, starting in the late Jurassic in the Northern Basin and Lower Cretaceous (Albian, Aptian) in the Southern Basin. The main transgressions occurred in the Upper Cretaceous, Eocene, Oligocene and Miocene. The sedimentary sequences are characterized by predominantly continental series of arkosic sandstones in the western parts of the basins and mainly marine and transitional series in the coastal parts. Figure 3 gives the lithostratigraphic sequences as have been published by Dingle et al (1983) and Flores (1973).

The development of the East African Rift System and its related **tectonic** events largely controlled the Post-Karoo sedimentation. As a consequence, the Karoo and Post-Karoo sedimentary formations are sometimes intensely faulted, but only little folded, with slightly developed arched structures. The best developed rift valleys are the Chire-Urema Graben and the Funhalouro-Mabote Graben, the latter forming part of the wider Mazunga Graben.

Almost 70% of the sedimentary basins have a cover of **loose material.** Very common is a 5 to 10

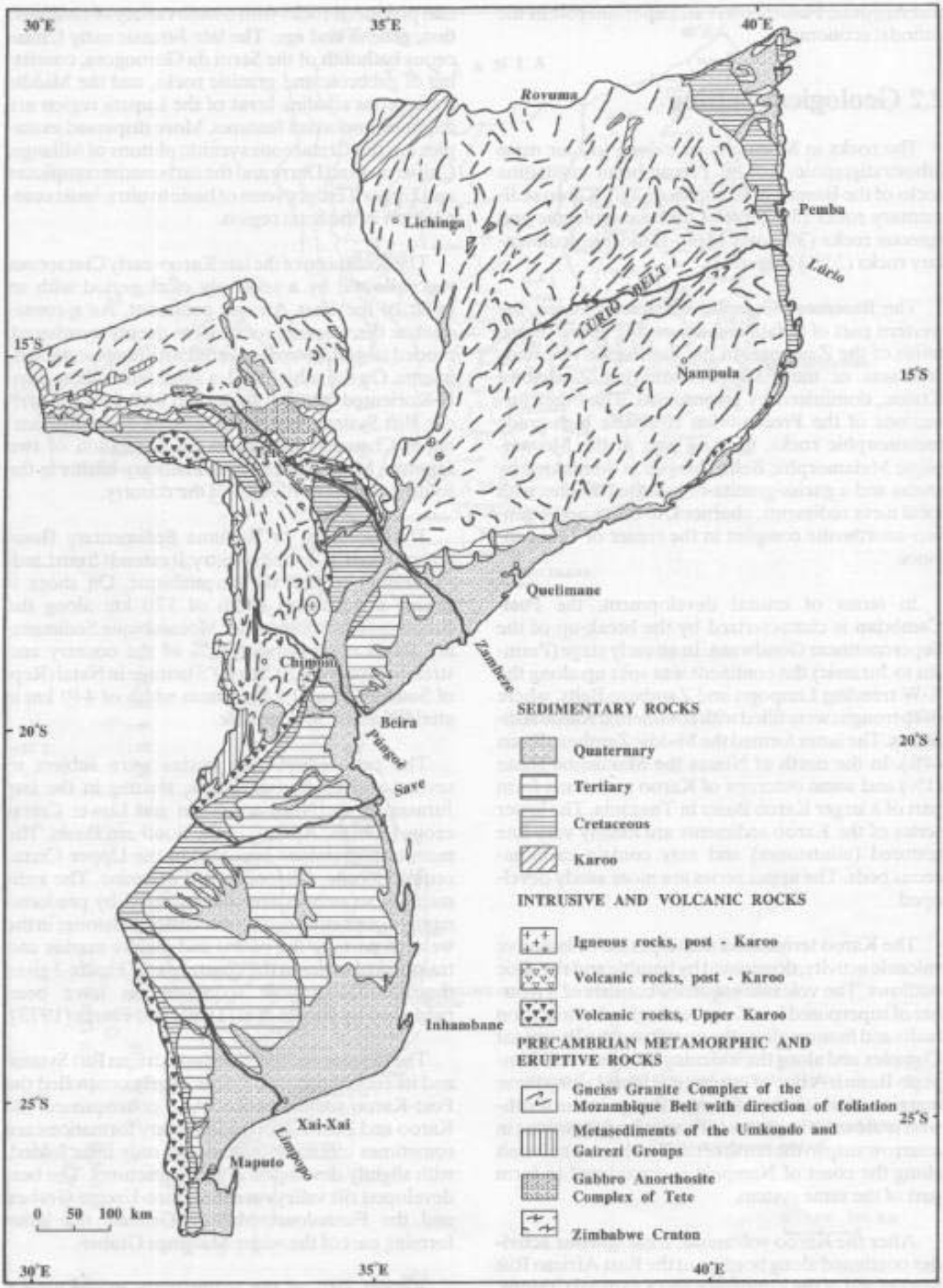


Figure 2: Geological outline

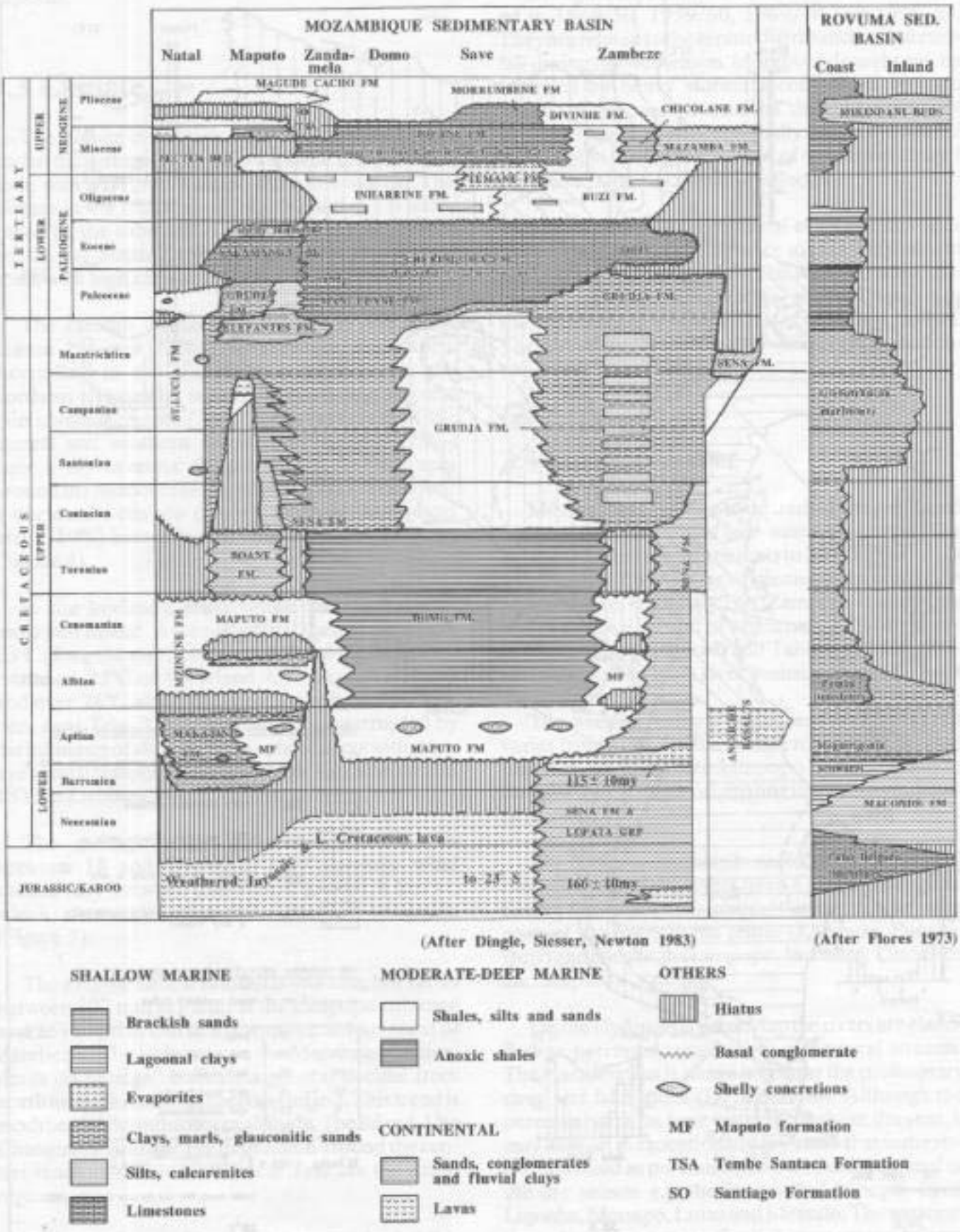


Figure 3: Lithostratigraphy of the Rovuma and Mozambique Sedimentary Basins

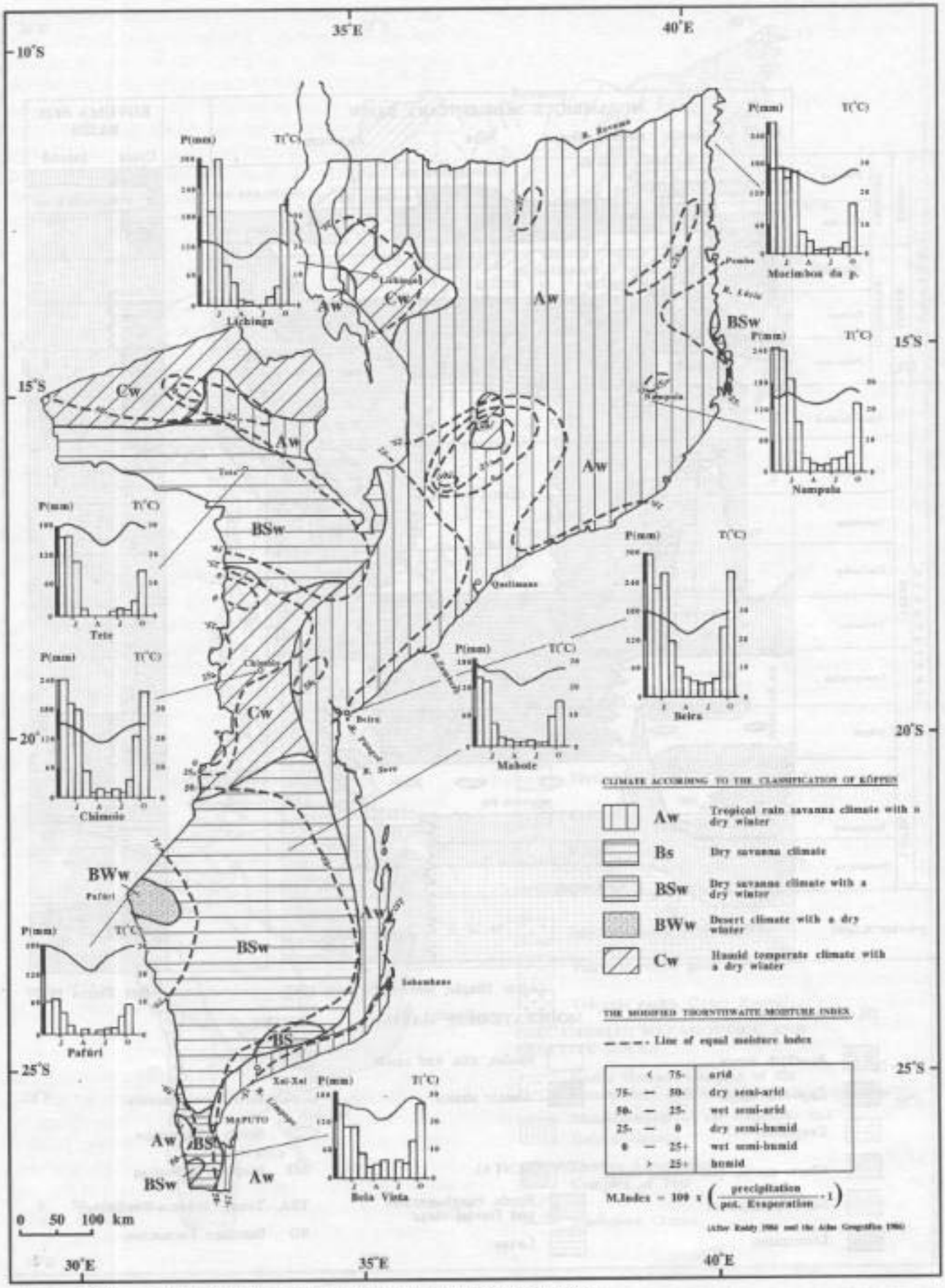


Figure 4: Climate (after Reddy 1984 and the ATLAS Geográfico 1986)

meters thick weathering layer of clayey sand above the sedimentary rocks. More developed are alluvial valley fills, eolian sand covers and rare colluvial deposits.

2.3 Climate

The climate in the region north of the Zambeze is under the influence of the equatorial low pressure zone with a NE monsoon in the warm season. The climate in the region south of the Zambeze is influenced by the subtropical anti-cyclonic zone. North Sofala and South Zambezia lay in the transitional zone, with high rainfall figures.

The **rainfall** is mainly restricted to the warm season between October/November and April. According to the classification of Köppen, the northern and coastal regions (60%) have a tropical rain savanna climate (Aw). The inland parts of the central and southern sedimentary terrains (28%) have a dry savanna climate (BSw). A small area around the border crossing of the Limpopo (2%) has a dry desert climate (BWw), whereas the upland areas (10%) have a humid temperate climate (Cw) (Figure 4).

In the lowlands, **temperature** increases northward and inland. Average annual temperatures are 23°C along the southern coast, 26°C along the northern coast, 25°C on the inland Alto Changane Plains and over 26°C along the central reach of the Zambeze near Tete. The general trend is interrupted by the influence of altitude in the upland areas with average annual temperatures of 20°C in Vila Manica and 18°C in Lichinga.

The average **solar** radiation generally lies between 18 and 20 MJ/m^2/day. Average **wind** speeds vary between less than 4 to over 8 km/hr, which determines the suitability for windmills (Figure 5).

The average annual **rainfall** is 968 mm; but varies between 327 mm in Pafuri at the Limpopo entrance and 2611 mm in Gurue in the mountainous areas of Zambezia. The isohyetes on the Map-inset "indicadores da recarga" indicate a general decline from north to south and from the coast inland. This trend is modified by the influence of altitude. The inland Alto Changane Plains and the depression around the central reach of the Zambeze near Tete are the driest regions.

The variation coefficient of the annual rainfall is over 30% to the south of the Save and in the center of the Zambeze Basin. In the rest of the country, it generally lies between 20 and 30%.

Droughts are common. Severe ones were recorded in 1949/50, 1959/60, 1969/70 and 1979/84. They are related to the erratic distribution of the rainfall during the wet season. Months of drought can be followed by heavy storms accompanied by high floods. In this respect mention should be made of tropical cyclones that occasionally invade the coastal areas. In the last 20 years, 4 out of 8 cyclones caused excessive rainfall, followed by floods.

The average annual potential **evaporation** varies from 1200 mm in the Libombos to over 1800 mm in some low areas in the north. The water balance, calculated over monthly averages, shows a surplus in the areas with more than 800 mm of annual rainfall. The annual surplus can be over 400 mm in mountainous areas.

2.4 Surface Water

Mozambique can be considered a quite privileged country in terms of surface-water resources. The average annual run-off amounts to 213*10^9 m^3/yr, of which only 97*10^9 m^3/yr originates from rainfall on Mozambican territory. The Zambeze contributes half of the total run-off of which only 17% originates in Mozambique. Figure 6 and Table 3 give the characteristics of the main river basins.

The average **run-off coefficient** is 12.8%, but varies from 1.5% for the rivers crossing the erosion plains in the south (the Limpopo and Incomati) to 26% for the Licungo, originating in the rainy uplands of Zambezia.

The rainy season contributes to 70% of the annual run-off. Most of the rivers have a torrential **regime**. Severe floods are very common in the downstream parts of the rivers in the center (Zambeze, Púngoè, Buzi) and the south (Limpopo, Incomati, Umbeluzi and Maputo).

On the Hydrogeological Map the rivers are **classified** as perennial, seasonal or ephemeral streams. The classification is partly based on the preliminary river and lake index (DPSH, 1969). Although the perennial streams have water throughout the year, it may happen in exceptionally dry years that some rivers, classified as perennial, have no flow at the end of the dry season e.g. the Incomati, Limpopo, Save, Ligonha, Monapo, Lurio and Messalo. The seasonal rivers have water throughout the wet season but are otherwise dry. Frequently the river bed still functions

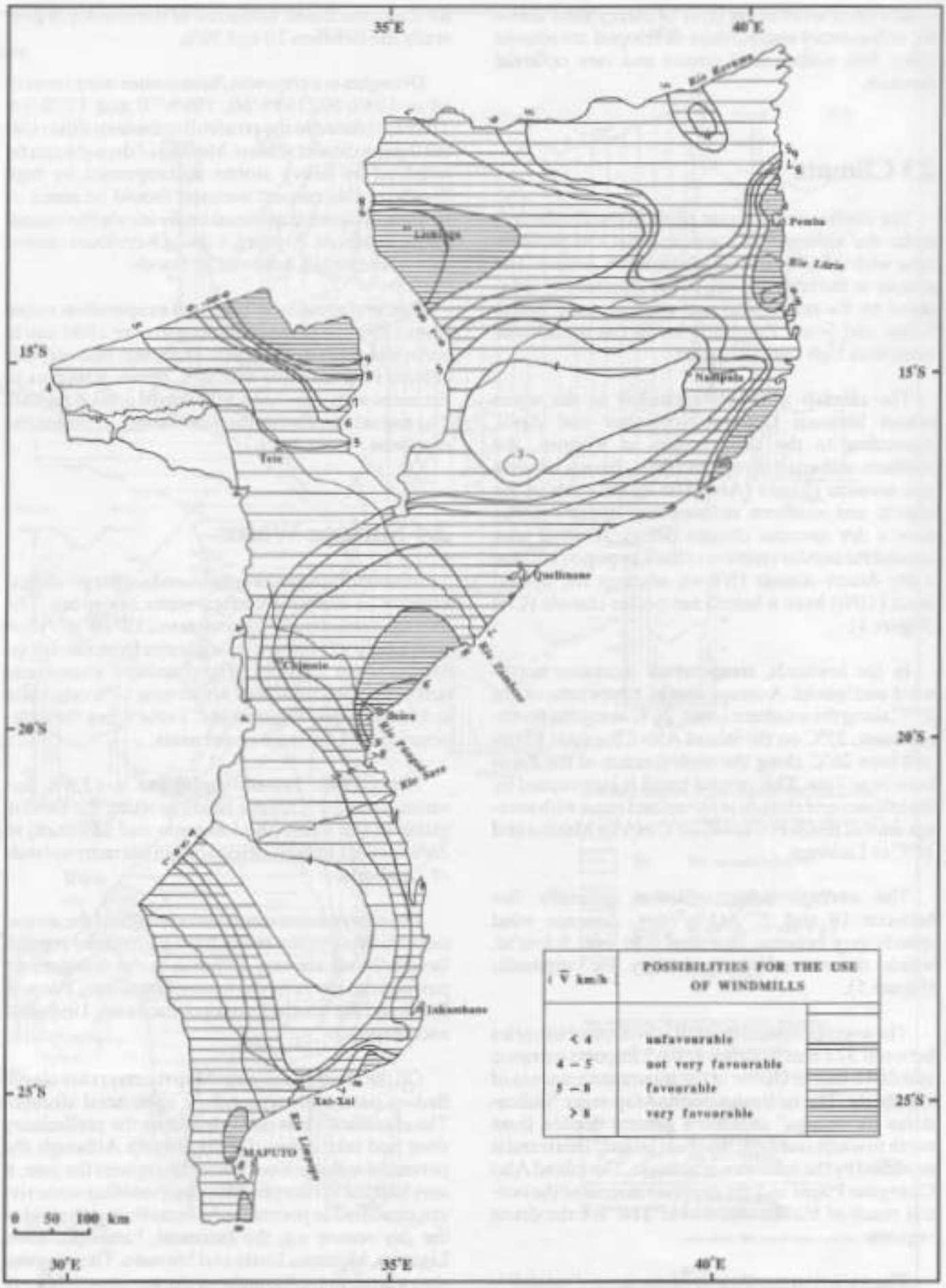


Figure 5: Average wind speed (after Reddy 1984)

Table 3: Characteristics of the main river basins (after DNA/UNESCO 1986)

River Basin	Surface Area (km²)		Hydrometrical Station					Estimated Discharge (10^9 m³/yr)			Run-off coeff. Moz.
	Total	part in country	N°	Area (km²)	Discharge (m³/s) max	min	mean	Border	Moz.	Mouth	(%)
Maputo	29 800	1 570	E6	28 500	> 824	0.7	92	2.8	0.1	2.9	9.4
Umbeluzi	5 600	2 356	E8	5 400	1 990	0.2	16	0.4	0.17	0.5	9.5
Incomati	46 246	14 925	E23	21 200	2 500	0	65	3.1	0.13	3.2	1.4
Limpopo	412 000	79 600	E35	342 000	7 880	0	175	4.8	0.8	5.6	1.5
Save	106 420	22 575	E47	100 885	13 800	0	226	6.0	1.6	7.5	10.1
Buzi	28 800	25 600	E188	26 374	6 590	11.8	215	0.8	6.3	7.1	22.0
Pungoe	29 500	28 000	E66	15 046	3 440	4.6	108	0.4	6.3	6.7	20.5
Zambeze	1 200 000	140 000	E285	1 193 000	116 000	374	3 353	88	18.0	106	13.0
Licungo	27 726	27 726	E91	20 400	12 500	1.3	207	—	8.9	8.9	26.6
Ligonha	16 299	16 299	E132	5 410	457	0	27	—	2.6	2.6	11.2
Lurio	60 800	60 800	E128	56 200	4 420	0	235	—	8.0	8.0	13.3
Messalo	24 000	24 000	E147	10 000	1 386	0	48	—	3.0	3.0	10.6
Rovuma	155 400	101 160	E202	42 400	> 3 100	6.4	356	10	18	28	14.8
Lugenda	—	—	E202	—	—	—	—	—	—	—	12.0
Others	235 389	235 389	—	—	—	—	—	—	23	23	—
Country	2 377 980	780 000						116	97	213	12.8

Table 4: Main dams and reservoirs (after DNA/UNESCO 1986)

Name	River	Type a)	Year	Height wall (m)	Available storage (10^6 m³)	Annual Discharge (10^6 m³)	Purpose b)	Installed generating cap. (MW)	Potent. irr.area (ha)
Constructed									
Cahora Bassa	Zambeze	BA	1974	171	39,200	76,900	E	2060 c)	—
Massingir	R. d.Elefantes	T	1976	48	2,256	1,800	R+E	45	70,000
Chicamba Real	Revue	BA	1959	75	1,536	700	E	36	—
Pequenos Libombos	Umbeluzi	T	1987	36	357	305	R+A	—	15,700
Nacala	Moecula	T	1971	17.4	4.4	16.4	A	—	—
Nampula	Monapo	BG	1960	17.5	4.0	2,353	A	—	—
Locumue/Lichinga	Luchiringo	T	1970	17.5	1.7	2.5	A	—	—
Mavuzi	Revue	PA	1953	8.0	1.2	1,400	E	46	—
Chimoio	Mezingaze	T	1959	15.0	0.27	—	A	—	—
Ulongue	Muae	T		3.4	0.18	—	A+E	0.2	—
Macarretane	Limpopo	PA	1956	12.0	0	5,510	R+A	—	20,000
Under Construction									
Corumane	Sabie	T	(1987)	45	1,273	644	R+E	15.0	36,000
Chipembe	Montepuez	T		15.6	24.2	115	R	—	2,000
Proposed									
Moamba-Major	Incomati	T		40	900	2,150	R+E	26.8	110,000
Bue-Maria	Pungoe	T		70	871	3,233	A+R	40.0	62,500
Montepuez	Montepuez	T		15	74	105	A+R	—	1,500

a) BA = Concrete arch; BG = Concrete gravity; PA = Weir gates; T = Earth
b) E = Hydro power; R = Irrigation; A = Urban water supply
c) in the second phase to be extended with 1548 MW

as an underground drain. The ephemeral streams have only water during and immediately after heavy rains.

Many **dams** have been constructed in order to guarantee the water supply to urban centers and to irrigation schemes, to produce energy or to regulate the torrential regime (Table 4). The Cahora Bassa dam in the Zambeze is one of the world's ten largest dams. In 1971, 583 small dams were registered as having an estimated total volume of 60 million m³ (DPSH 1974). More than 90% was in use for agricultural purposes or livestock watering.

Mozambique has about 13 000 km² of inland water. The largest **natural lakes** are located along the Malawian border. The Mozambican part of lake Niassa has a surface area of 7 000 km². Some smaller lakes and ponds can be found in the north-east, but the majority are situated in the south on the inland plains, in local depressions in the inland dune area and behind the recent dunes in the littoral zone.

2.5 Springs

Springs in Mozambique are traditionally classified, in accordance with their temperature, as "warm" and "cold". The water of **"warm"** springs is of deeper origin and generally has a temperature of above 40°C. Fifteen "warm" springs have been recorded in Manica and Sofala, five in the Zambeze Intracratonal Basin and ten in the south of the Zambezia Province. They occur in the marginal zone of the Zimbabwe craton, in the Zambeze Intracratonic Basin and ten in the Zambeze Intracratonic Belt, along the East African Rift System and along the contact between the Basement Complex and the Sedi-

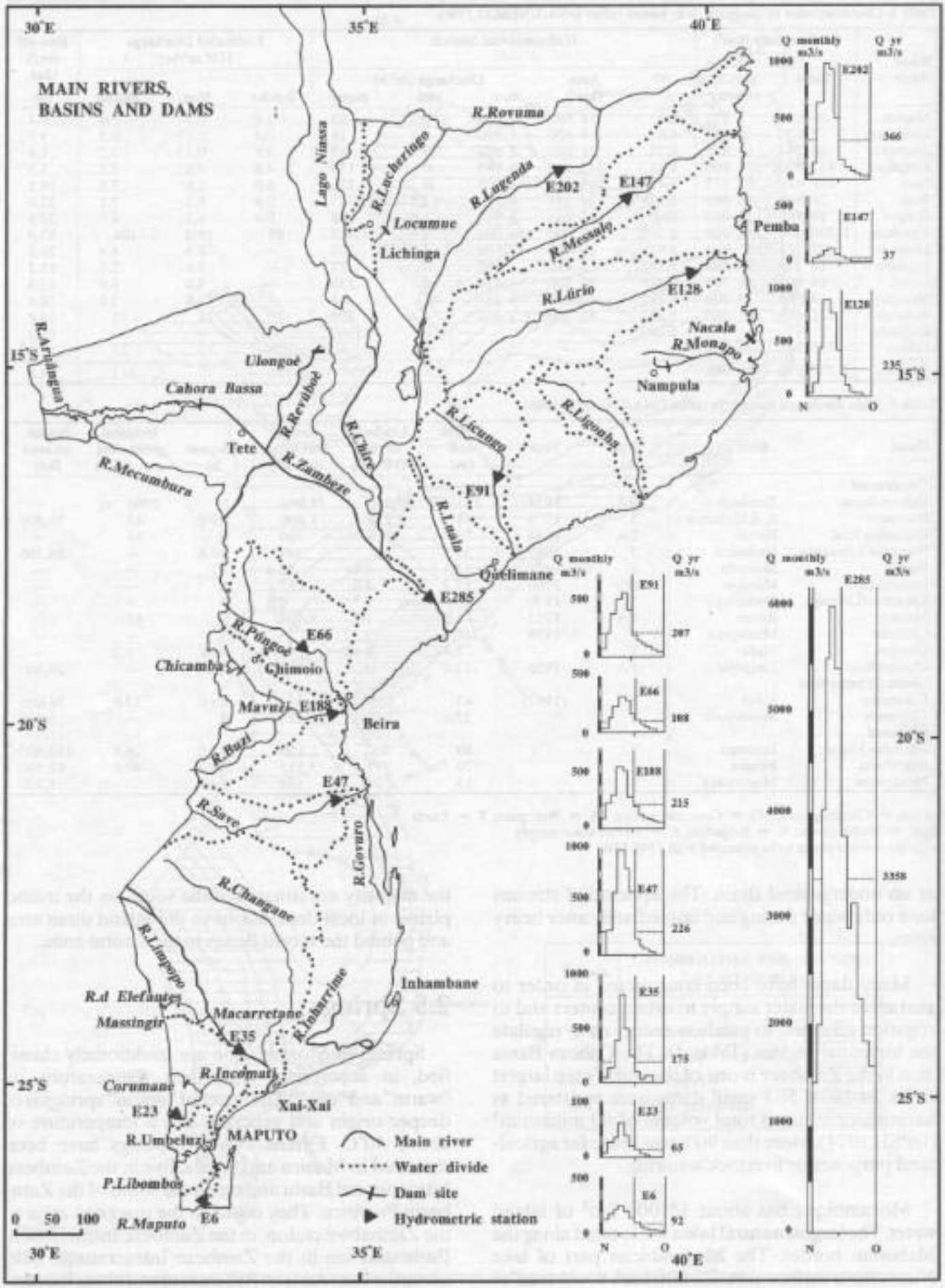


Figure 6: Main rivers, basins and dams

mentary Basins. The warmest springs are found in Zambezia (Maganja da Costa 82°C, Morrumbala 78°C, Chirombe 76°C, and Namacurra 73°C) and near Tete city (Boroma 80°C) (Freitas 1959).

Concentrations of **"cold"** springs (20 to 25°C) are found in the Libombos, along the margins of the Mueda Plateau and the Serra da Mesa (Nacala), and in the coastal belt in the south, at the contact between dunes and alluvium.

Most of the springs are **used** by the local population, but only a few are protected. The main water supply system using spring water is on the Mueda Plateau and serves about 150.000 people.

Water of three springs is bottled as table water: two springs rising from rhyolite near Namaacha (Namaacha and Montemor) and one spring from granites, south of Vila Manica (Vumba).

2.6 Natural Recharge

Natural recharge is defined as the quantity of rainwater that reaches the groundwater table by infiltration. In tropical and subtropical countries, recharge is linked to heavy storms, as water from milder rains directly evaporates or is absorbed by the soil from where it is returned to the atmosphere by transpiration. In the sandy dune soils around Maputo, IWACO (1985) found a direct **relation** between the accumulated rainfall of storms over 30 mm/day (P_{30},mm) and the annual recharge (R,mm) calculated by an adopted Thornthwaite and Mather soil water balance method:

$$R = 0.77 \times P_{30} - 83$$

Reliable **calculations** of the natural recharge are scarce in Mozambique. Best studied is the recharge in the sandy soils around Maputo with an estimated value of 140-185 mm/yr or 17-23% of the annual rainfall (IWACO 1985). Recharge estimations of the sandy soils of the Mueda Plateau and the littoral Cajueiros Plateau near Pemba give values of 350 and 210 mm or 33 and 30% of the annual rainfall respectively (DNA 1985a, 1986). A recharge of less than 10 mm/yr was found in the clayey soils of the semi-arid Chitima region near Tete, using the Thornthwaite and Mather soil water balance method (DNA 1987b).

The Map-inset, entitled "Indicadores da recarga" (**recharge index**, see Annex 1), is a qualitative tentative to define the recharge conditions in the country. It is based on the annual rainfall (isohyetes and colors) and on the recharge capacity of the terrain (tone). The recharge capacity is high, if the actual evapotranspiration and the run-off coefficient, or if the water storage capacity of the soil and slope of the terrain, are small. The last two parameters have been used to define the recharge index (Table 5). They are derived from the soil map of Mozambique (INIA/FAO 1982) and from a publication of Reddy and Vermeer (1984).

Table 5: Determination of the Qualitative Recharge Index

terrain slope / Soil water Storage Capacity	0-8%	0-30%	8-30%	8->30%	>30%
0 — 50 mm	A	A	B	B	C
50 — 100 mm	A	B	B	C	C
100 — 150 mm	B	B	C	C	
150 — 200 mm	B	C	C		
200 — 250 mm	C	C			

A = high (10-30%); B = medium (5-10%); C = low (< 5% of the annual rainfall)

The Map-inset shows that most of the Basement Complex is situated in areas with medium to high rainfall and a medium recharge index. Most of the sedimentary terrains have a low rainfall, but medium to high recharge capacities of the terrain.

2.7 Water Consumption

The total water consumption in 1985 was estimated at 1612 million m^3, of which only 4% derived from groundwater resources (Table 6). More than 90% of the total consumption was used in agriculture, 7.4% for domestic use, and 1.7% in industry.

Most of the **urban centers,** including smaller towns and villages with a developed infrastructure, have some system of water distribution. The census of 1980 indicated that 20% of the urban population had a house connection and 23% a public tap. The rest mainly used ground water from shallow wells and boreholes. The water distribution systems in the provincial capitals are principally based on surface water (96.4%), except in Tete, Pemba and Xai-Xai (3.6%). Of the 112 smaller centers 30% relies on groundwater. Although new well fields have been installed around Maputo, Pemba, Tete and Ilha de Mozambique, the contribution of ground water for urban domestic use will not change in the near future, as there will be a substantial increase in the proportion of the population that will make use of the central distribution systems, predominantly relying on surface water.

It is estimated that only 20% of the present systems functions properly (DNA/UNESCO 1986). Consumption figures calculate with a use of 100 to

Table 6: Recent and future water consumption (partly after DNA/UNESCO 1986)

Users Group			1985				2000			
			Users (10^6)	Total use (10^6 m³/yr)	Groundwater component (10^6 m³/yr)	(%)	Users (10^6)	Total use (10^6 m³/yr)	Groundwater component (10^6 m³/yr)	(%)
URBAN	Provincial Capitals 10	Public distrib. System	0.6	33	1	3.6	5.4	141	14	15
		Other water points	1.3	12	10	80				
	Centres 112	Public distrib. system	0.6	11	3	30				
RURAL	Protected source		1.1	10	10	100	15.2	153	138	90
	Unprotected source		10.4	37	30	80	1.7	6	5	80
	Industrial		—	27	8	30	—	188	38	20
	Irrigation schemes		—	1472	29	2	—	3132	63	2
	Livestock		—	10	3	30	—	20	6	30
TOTAL AVERAGE			14.0	1612 100%	94	— 6%	22.3	3640 100%	264	— 7%

150 l/cap/day for house connections, 60 to 80 l/cap/day for yard connections and 30 l/cap/day for public taps.

About 80% of the **rural** population uses ground water as the principle source, as can be concluded from the census of 1980. The Map-inset "Abastecimento de Agua" (water supply type, see Annex 1) shows, at district level, the proportion of the population that uses ground water as the principle source. Most of these sources, however, do not have any protection and can be considered contaminated because of poor sanitary conditions around the source.

Only 12.9% of the present rural population has a protected water source in the vicinity of the home. Most of these protected sources supply communal villages (900.000 inhabitants), the large villages around Chokwe (30.000 inhabitants) and the villages on the Mueda Plateau (150.000 inhabitants). But the majority of the population still has to walk long distances to fetch water. In Cabo Delgado, the average distance from the house to a water source is 1.6 km. But in semi-arid areas like the interior of Inhambane, distances of 30 km are not uncommon during the dry season (DNA/UNESCO 1986). Water consumption in the rural areas will be at maximum 30 l/cap/day. Consumption of 12 l/cap/day is regarded as the absolute minimum.

The **target** of the National Programme on Rural Water Supply, PRONAR, is that by the year 2000, 90% of the rural population should have a protected water source within 500 m of their home. Assuming that one source could supply 500 people, about 25.500 water points would have to be constructed, a figure difficult to attain.

The present water consumption of the **industrial sector** is about 27 million m³/yr. The industries in Maputo account for 60% of this total. Most of the water used by industries in the main industrial centers Maputo, Beira and Nampula comes from the city's public distribution system. The industrial water consumption will probably show an increase of 700% by the year 2000, mainly because of the projected metallurgical industries in the Tete-Matundo-Moatize area. These will use 60% of the total.

Irrigation schemes have the largest water consumption, but mainly rely on surface water. Agricultural consumption will more than double by the year 2000, when it will account for some 85% of the total.

The water consumption figures of cattle and other **livestock** in Table 6 are very uncertain. They are based on the following assumptions: 700.000 head of cattle, using 30 l/head/day; 500.000 goats, using 5 l/head/day; 200.000 pigs, using 10 l/head/day and 100.000 sheep, using 5 l/head/day.

3. THE MAP

3.1 Methodology

The Hydrogeological Map of Mozambique, scale 1:1, 000, 000, is the result of the analysis of all the relevant **information available.** This information consists of previous hydrogeological and geophysical surveys, borehole records, geological maps, satellite images and other, more indirect data.

Table 7 gives a summary of the previous regional **hydrogeological studies**. Most of them can be classified as simple groundwater inventories, accompanied by thematic maps, based on data already collated. Only a few studies are of cartographical interest, such as the study of the Lugenda Basin, that uses a classification comparable with the one used in the present Map to make a hydrogeological differentiation within the Basement Complex.

About 2 800 **borehole files** have been consulted from the Groundwater Data Bank of DNA and the archives of GEOMOC. They included old drilling reports of companies and institutes like DSGM, GEOTECNICA E MINAS and SOSOMOC. It is estimated, that about 7 000 boreholes have been drilled for hydrogeological purposes in the past. But only 40% had reliable records with technical data and a site indication. Data about water level and (specific) yield were registered in 95% of the consulted records, but less than half had a borehole log or additional chemical information.

The Map-inset, called "Distribuição de furos com dados" (Distribution of boreholes; see Annex I), shows the uneven distribution of the consulted tube wells over the country. The Map-inset gives the number of tube wells per 1:50 000 topographical mapsheet, which represents an area of 15' by 15' geographical minutes or about 700 km^2. Only in 7% of the maps, is the borehole density over 1 per 100 km^2 (or 1 per 1 cm^2 on the Map), whereas 63% of the maps have no boreholes at all. Half of the consulted tube wells are located south of the Save. Other privileged areas are the Buzi Plateau, the Chimoio Plateau, the coastal belts of Nampula and Cabo Delgado and the Montepuez area.

The lack of basic data and their uneven distribution made it necessary to use and analyze more **indirect information,** in order to fill the gaps and to obtain a well balanced and reliable result. The approach used to limit and to define the hydrogeological units of the Map consisted of four successive stages:

In the first stage, an analysis was made of existing **geological and lithological maps,** in order to produce a hydrogeologically relevant division into geological units, capable of being distinguished on the Map.

In the second stage, an interpretation was made of 37 series of 3 or 4 false color **satellite images,** to divide the Basement Complex into three relevant hydrogeological units (see section 3.2). The images were also used to solve certain problems concerning previous geological interpretations and to define the marine flood plains with mangrove.

The results were **checked** in the third stage, using existing well data and borehole logs. As a result of a visit to the Beira Corridor, together with the consultant Albert Mente, the geomorphological division of the Basement Complex was validated to be hydrogeologically relevant.

The fourth stage can be characterized as the **synthesis** of the collected material, in order to establish the hydrogeological units of the Legend and to define their limits on the Map.

3.2 The Legend

The Legend of the Map is in accordance with the UNESCO "International Legend for Hydrogeological Maps", published in 1970 and revised in 1983.

The main **items** of the Legend are Groundwater Occurrence (I), Topography (II), Geology (III), Surface water (IV), Ground water (V), Water Quality (VI) and Man-made features (VII). An English translation of the Legend is given in Annex 1.

Map-units of groundwater occurrence

The groundwater occurrence is the Legend's dominant item, hierarchically divided into 3 Classes, 9 Groups and 32 Units. The Classes are represented by their color and the Groups by the tone of the respective color (Table 8). The Units are depicted by lithological ornaments and stratigraphic symbols.

The division into 3 **Classes** (A,B,C) is based on the dominant porosity type, the extent of the aquifers and the productivity of the formations.

The **blue** colored **Class A** represents aquifers, in which the water predominantly circulates through

Table 7: Previous hydrogeological studies

AREA	AUTHORS	YR	SCALE	SURVEYS	MAPS
NORTH OF THE ZAMBEZE					
1 MONTEPUEZ	DSGM	74	500 000	Water samples	Thematic: hydrochemical
2 MUEDA PLATEAU	ITALTECHNO	78	250 000	Aerial Ph.; springs	Thematic
3 LUGENDA BASIN	TECHNOSYNESIS	80	500 000	Aerial Ph.; sat.im	Groundwater Potential
CENTER					
4 PUNGOE BASIN	GEOT&M/COBA	72	500 000	Desk study	Geology
5 ZONA "K", MANICA	GEOT&M	73	500 000/100 000?	Aerial Ph.	Groundwater Potential
6 BUZI BASIN	COBA	80	500 000	Desk study	Groundw. Pot.; Contam. Risk
7 ZAMBEZE BASIN	LUXTON&HUNT.	74	100 000	Aerial Ph.	Groundw. pot. (physiogr.)
SOUTH OF THE SAVE					
8 SOUTH OF THE SAVE	BURGEAP	61	500 000/1 000 000	Test Drill., Field	Thematic+General
9 GAZA/ALT.CHANG.	BR. AGUA DOCE	73	(250 000)	Test Drill., Geoph	Prob.fresh water areas
10 GAZA-LIMPOPO-INCOM	SELKHOZPROM	84	250 000/500.000	Test Drill	Thematic+Exploitation
11 INHAMBANE	AQUATER	80	250 000/(50 000)	Field; Desk	Thematic
12 INHAMBANE	DNA	87	500 000	Desk., summary	Thematic; dug. wells
13 SABIE-MASSINTONTO	BONIFICA	81	50 000	Aerial Ph.; Geoph.	Thematic
14 LOWER INCOMATI	DNA	85	100 000	Desk study	Thematic
15 GREAT MAPUTO	IWACO	86	100 000	Test Drill., Geoph.	Thematic

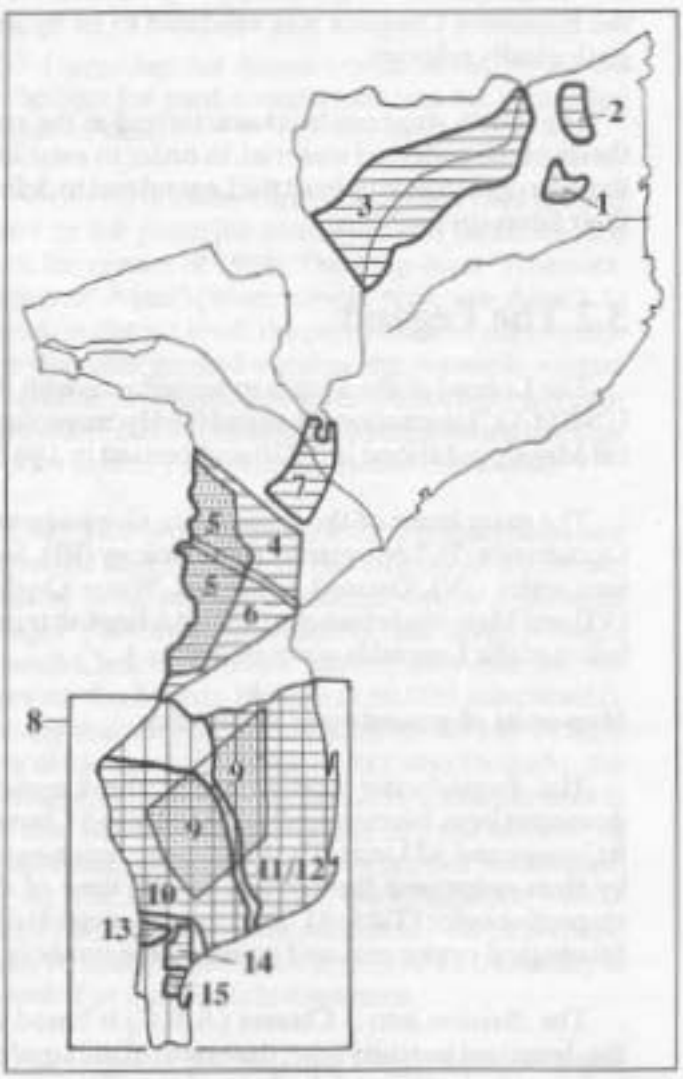


Table 8: Classes and Groups of groundwater occurrence and characteristics for groundwater development

	CLASSES AND GROUPS OF GROUNDWATER OCC		GROUNDWATER DEVELOPMENT CHARACTERISTICS			
	Intergranular formation	Fissured formation	Average yield (m^3/h)	Maximum pumping period (h/day)	Possible Water Supply Capacity	Recommended aim of surveys
	Class A	Class B				
PRODUCTIVE AQUIFERS Class A,B	dark blue (A1)	dark green (B1)	>50	24	Large cities, industries and irrigation schemes	Determination of Safe Yield
	medium blue (A2)	medium green (B2)	10-50	24	Towns (>5000 inh), medium sized industries and irrigation schemes	Determination of Safe Yield
	light blue (A3)	light green (B3)	3-10	16	Villages (2000-5000 inh) small sized industries and irrigation schemes	Determination of Safe Yield + well sites
	Class C					
AREAS WITH LIMITED OR NO GROUNDWATER RESOURCES Class C	light brown (C1)		<5	8	Villages (1000-2000 inh). cattle (<2000 head)	Determination aq. dimensions + well siting
		medium brown (C2)	<3	8	Small villages (<1500 inh). cattle (<1500 head)	Determination aq. dimensions + detailed siting
		dark brown (C3)	<1	6	Groups of houses (<250 inh) cattle (<250 head)	Det. of aq. dim. + very detailed well siting

intergranular pores. Generally, they are continuous and consist of unconsolidated or semi-consolidated material. Yield prospects range from 3 to over 50 m^3/h.

The **green** colored **Class B** represents aquifers, in which the water predominantly circulates through fractures and fissures. Usually they are discontinuous and consist of consolidated rocks. Yield prospects range from 3 to over 50 m^3/h. Class B also includes karstic rocks, in which the fissures might be widened by chemical solution.

The **brown** colored **Class C** comprises areas with limited or local groundwater occurrences and areas without any groundwater resources. The porosity can be intergranular or fissured. Yield prospects generally range from less than 1 m^3/h to 5 m^3/h.

The subdivision of each Class into 3 respective **Groups** (A1-A3, B1-B3, C1-C3) is principally based on yield prospects of tube wells, indicated in Table 8, assuming a standard drawdown of 10 metres. The classification of a water-bearing formation is based on a statistical analysis of observed specific yields (yield per meter of drawdown also denominated as "specific capacity"), using a log-normal distribution. Where insufficient data was available, the classification has been made on the basis of comparison with known formations with similar geology and morphology.

In addition to the productivity criterium, the **subdivision of Class C** is based on geological and morphological characteristics. Group C1 (light brown) consists of areas with local continuous or discontinuous aquifers, that are unconsolidated towards the surface. Yield prospects are generally below 5 m^3/h. Group C2 (medium brown) comprises areas with fissured formations of very low productivity and yield prospects below 3 m^3/h. Group C3 (dark brown) represents areas with hardly any groundwater resources and is morphologically defined as mountainous.

For the **sedimentary formations**, Group C1 consists of unconsolidated sediments of low permeability, like clay, silt or clayey sand, whereas Group C2 consists of low productive consolidated rocks, like arkosic sandstone, marl or shale.

For **crystalline rocks**, the subdivision of Class C is principally morphologically defined. It is based on the experience that the thickness, degree and texture of weathering is a determinant factor for the productivity prospects of wells in a certain area.

The areas of Group C1 have a well developed weathering mantle, which can reach a thickness of 20 to 50 m. These areas are geomorphologically defined as flat areas with hardly any rock outcrops or lineaments. The groundwater occurrence in these areas is related to the deeply developed weathering mantle

and/or to the associated fracture zones. The distribution of the water within the weathering profile is rather complex, but the main circulation is related to the more permeable transition zone from the weathering mantle to the parent rock. Normally the aquifers are of a local character and of limited extent. In the crystalline rocks, Group C1 can be considered as a complex unit with local aquifers and adjacent areas with limited or without any groundwater resources.

The areas of Group C2 have a less developed weathering mantle with a thickness that only rarely reaches to 20 m. Geomorphologically, they are characterized by undulating to flat areas with common rock outcrops or lineaments. Usually, groundwater resources in these areas are restricted to the secondary openings in the lower parts of the weathered rocks. Group C2 can be considered a complex unit with areas of very limited groundwater resources and some local linear aquifers.

The areas of Group C3 are mountainous and have no significant weathering mantle or groundwater resources. They are geomorphologically distinguished by their relief and by dominant rock outcrops. The only possibility of finding groundwater in these regions is along fault and fracture zones, often associated with springs and seepage zones.

The classification and extent of units on the Basement Complex and in the Volcanic Terrains are mainly based on satellite images, checked by available borehole records. The most relevant terrain characteristics were considered to be the existence of rock outcrops and lineaments, general relief, drainage network, vegetation, soils and geological, lithological and structural phenomena.

The subdivision of the 9 Groups into 32 hydrogeological Units, distinguished on the Map, is principally based on lithostratigraphic criteria. On the Map, they are represented by different ornaments and symbols, respectively indicating their lithology and lithostratigraphy or age.

Signs, symbols and additional information

In addition to the classification of the water-bearing formations, described in the previous section, the Map provides a variety of other information concerning groundwater occurrence. Most of the symbols can be readily interpreted by reference to the Legend, but some require further explanation.

The **stratigraphical columns** and hydrogeological **cross-sections** are intended to give information about the deeper formations, normally not represented on then map. They are schematic, especially at deeper levels. In the cross-sections caution must be used when considering the unrealistic dip of the strata, caused by the 25 fold exaggeration of the vertical scale. For example, a true dip of 2° has a projected inclination of 42° in the cross-section.

Groundwater divides are considered to coincide with surfacewater divides. This rule does not hold for the deeper aquifers in the south and for the upper aquifer in the Mazimechopes area, south of the Rio dos Elefantes.

Instead of groundwater table contours, the Map gives the **depth of the groundwater table** from the surface, in order to facilitate practical applications: 20 m corresponds to the maximum limit of dug wells in Mozambique; the 50 m depth is used as an indicative limit for the application of hand pumps and wind pumps; and above 100 m depth, simple lifting techniques and percussion drilling are difficult to apply.

The representation of **springs** is not systematic, because of the absence of a country-wide inventory. The springs, classified on the Map as "Thermal and/or mineral" may not meet modern international diagnostic criteria, as bacteriological purity, invariability of composition and temperature and therapeutic properties are often unknown.

The **"mineralization"**, represented by iso-lines of "Dry Residue", is the only indication of groundwater quality, shown on the Map. The indicated limits more or less coincide with the maximum tolerability for certain purposes:

500 mg/l: limit of good quality water for all purposes;
1000 mg/l: limit for irrigation of most plants and crops;
1500 mg/l: limit of acceptable water for domestic use;
3000 mg/l: limit of tolerable water for domestic use in semi-arid areas;
5000 mg/l: limit for livestock in semi-arid areas.

Orange hatching indicates the existence of mineralized aquifers. Inclined lines mark the probable existence of local fresh water in the vertical section. The mineralization of deep aquifers, however, is not represented.

3.3 Use of the Map

The Map has been designed for groundwater specialists, but it may also be used by people with a more general background, provided that the Legend is studied. It should be capable of providing consider-

able assistance to planners and organizations, involved in the development of the country and the management of natural resources with special reference to water.

First, the Map gives much information on the quality and the availability of water resources in a certain area. As such, it can indicate the **feasibility of certain projects** in defined areas from the hydrogeological/hydrological point of view. If, for example, water consuming activities like large irrigation schemes, certain industries or urban centers are projected in areas with limited yield prospects, one has to discount the use of groundwater and to rely on surface water.

Secondly, the Map can be used in regional development projects, in order **to identify areas** that have strong possibilities but need further hydrogeological investigation.

Thirdly, **regional water supply projects** can use the Map for their proper **planning** and for the selection of appropriate drilling equipment, construction techniques, lifting devices and materials. Based on the Map, one can make an estimation of the proportional contribution of dug wells, common tube wells or deep tube wells. The Map can also be used to select appropriate techniques for the siting of wells, like the use of aerial photographs, the type of geophysical surveys or the necessity for making test drillings or observation wells.

Fourthly, the Map can serve as an **educational appliance** for intermediate to high-level students, in order to illustrate the availability and occurrence of ground water in the country, and to create a wider awareness of water related problems.

It is **not advisable** to use the Map directly for the solution of local technical problems as the siting of new wells. One has to consider, that the information on the Map is generalized, commonly based on extrapolations or on deductions of indirect characteristics. Furthermore, the scale is a limiting factor. As an example, it has to be realized that Map-units with an area of less than 4 mm^2 (or 4 km^2 in reality) cannot be represented, being too small. In addition, small alluvial valleys have often been exaggerated in size, in order to include them on the Map. Another factor is that units are often very complex and show a high degree of internal variability.

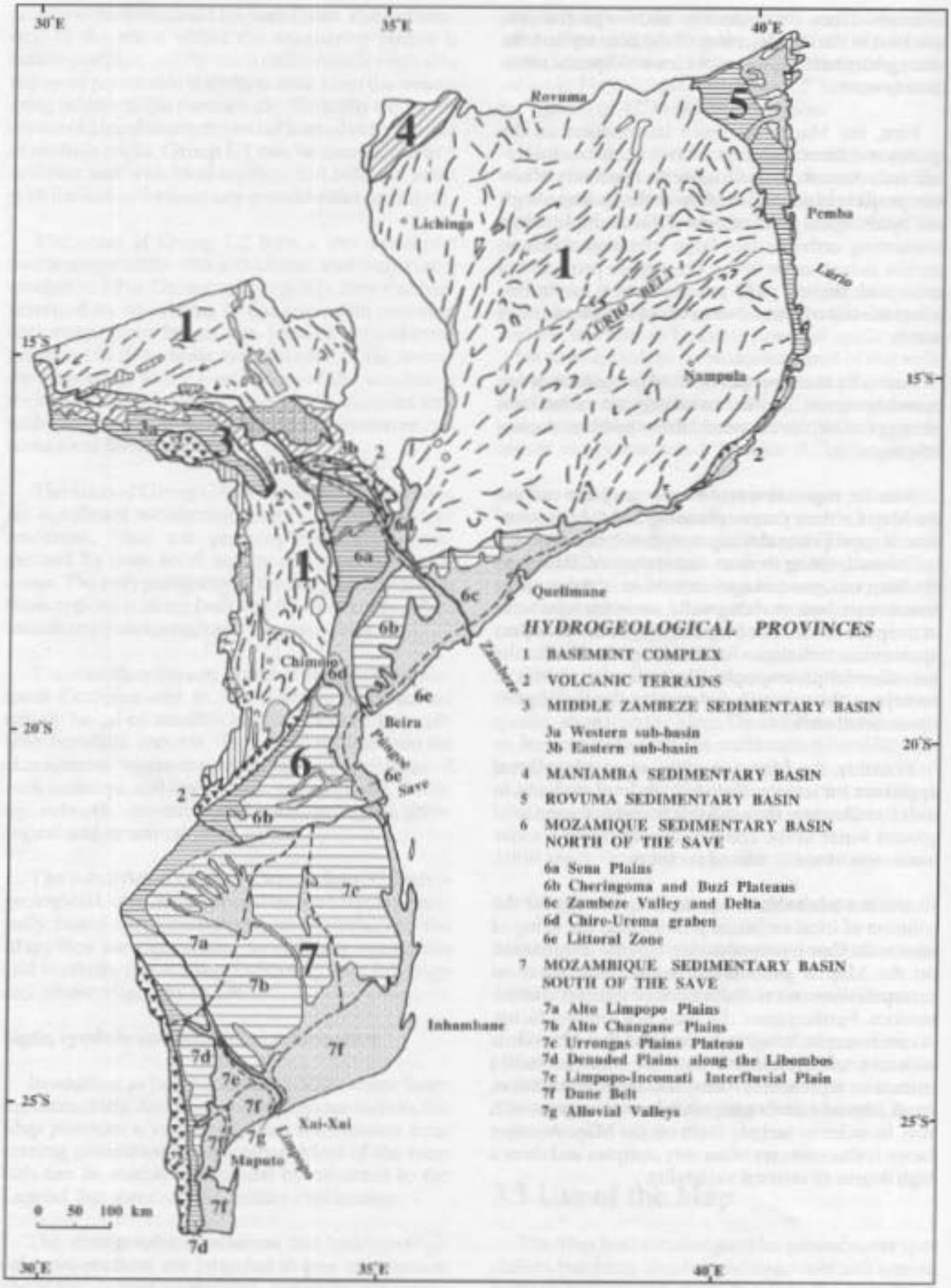


Figure 7: Hydrogeological Provinces

4. HYDROGEOLOGY OF MOZAMBIQUE

4.1 General Considerations

Summary

The Hydrogeological Map of Mozambique gives a rather pessimistic impression of the groundwater occurrence in the country. On the Map, about 75% of the area is brown colored (Class C), being almost the entire part of the Basement Complex, the Volcanic Terrains and 40% of the Sedimentary Basins. Taking into account that still 40% of the more productive aquifers in the Sedimentary Basins contain brackish water, one can conclude that only 17% of the country has groundwater resources with yield prospects over 3 m^3/h and a mineralization below 1500 mg/l.

Some comments have to be made on these figures. On the one hand, most of the large to medium scale groundwater extractions for urban, industrial and agricultural water supplies require well yields over 10 m^3/h, good recharge conditions and a mineralization of less than 1000 mg/l or even 500 mg/l. Such conditions are very rare in Mozambique and can only be found in some alluvial valleys and fans and in some sandstone and limestone formations, covering less than 2% of the country area. On the other hand, rural water supplies require a minimum well yield of only 0.8 m^3/h, whereas water with a mineralization up to 3000 mg/l is still acceptable under semi-arid conditions. Hence the brown coloured Class C, especially the light brown Group C1, is still suitable for this type of small scale extractions. But the possibility of a higher percentage of unsuccessful drillings must be taken into account.

Hydrogeological Provinces

Although the Map shows aquifers, divided into Classes, Groups and Units, the authors find it more convenient to describe the hydrogeology of Mozambique through geologically and geographically defined Hydrogeological Provinces (Figure 7), being:

* the Basement Complex (Precambrian)
* the Volcanic Terrains (Post-Cambrian)
* the Middle Zambeze Sedimentary Basin (Karoo)
* the Maniamba Sedimentary Basin (Karoo)
* the Rovuma Sedimentary Basin (Meso-Kenozoicum)
* the Mozambique Sedimentary Basin north of the Save (Meso-Kenozoicum)
* the Mozambique Sedimentary Basin south of the Save (Meso-Kenozoicum)

In spite of the fact that some Hydrogeological Provinces are rather comparable, they are distinguished from each other by their geological structure, age and geographical position. As such, they have distinct geological, physiographical, climatological and hydrogeological characteristics.

In the next sections, the description of the Hydrogeological Provinces starts with their respective physiography and geology, followed by their groundwater resources. Accompanying tables give the result of statistical analyses of several characteristics of the Map-units. In these tables, the productivity of the aquifers is characterized by a statistically defined interval q20-q80, and by the average value q50 of the specific yields. The 20% extreme minimum values (below q20) and the 20% extreme maximum values (above q80) are considered to be exceptional and not representative of the characterization of the Map-units.

The water quality in this chapter is normally described in terms of "mineralization", pH, hardness (ppm $CaCO_3$) and major ions. The "mineralization" is usually measured as "Dry Residue".

4.2 Basement Complex

Physiography

The Basement Complex covers 57% of the country, occupying the western part of the central region and almost the entire region north of the Zambeze. The area consists of mountains, upland and middle plateaus and an eastern strip of lowlands. The last unit has an accumulating relief, whereas the other parts are characterized by erosive-denudative landforms. Most of the plateaus have an inselberg-landscape.

On the plateaus, the rocks can be deeply **weathered,** especially if the weathering prolonged over millions of years, while the loose material is not removed by erosion processes. An exceptional thickness of more than 50 m is observed to the east of Chimoio (Gondola) and 50 to 80 km to the east of Montepuez (Nivaco, Megama, Nangimbue).

A typical weathering profile on acid rocks like granites and gneisses is shown in Figure 8. The degree of weathering diminishes from the top-soil to the parent rock at the base. The profile is more clayey developed on basic rocks containing ferromagnesian

minerals. Lateritic soils are common in some parts of Manica, Zambezia and Cabo Delgado.

Rainfall is high in the mountainous areas (1200-2000 mm/yr) and medium on the plateaus (800-1200 mm/yr). Therefore recharge is reasonable, in spite of less favourable soil terrain conditions. River flow is mainly permanent in the rainy areas, but seasonal or ephemeral in drier zones.

Geology

Geologically, the Basement Complex is divided into the Early Precambrian formations of the Zimbabwe Craton and the Later Precambrian formations of the Mozambique Metamorphic Belt. The oldest formations mainly consist of greenschists with interstratified quartzites, limestones, grauwackes and conglomerates. The **Zimbabwe Craton s.s.** has a very limited extent in Mozambique. It is found in the frontier area of Manica, to the west of Nhamatanda and in the Munhinga-Bonde and Mavita areas (Figure 2).

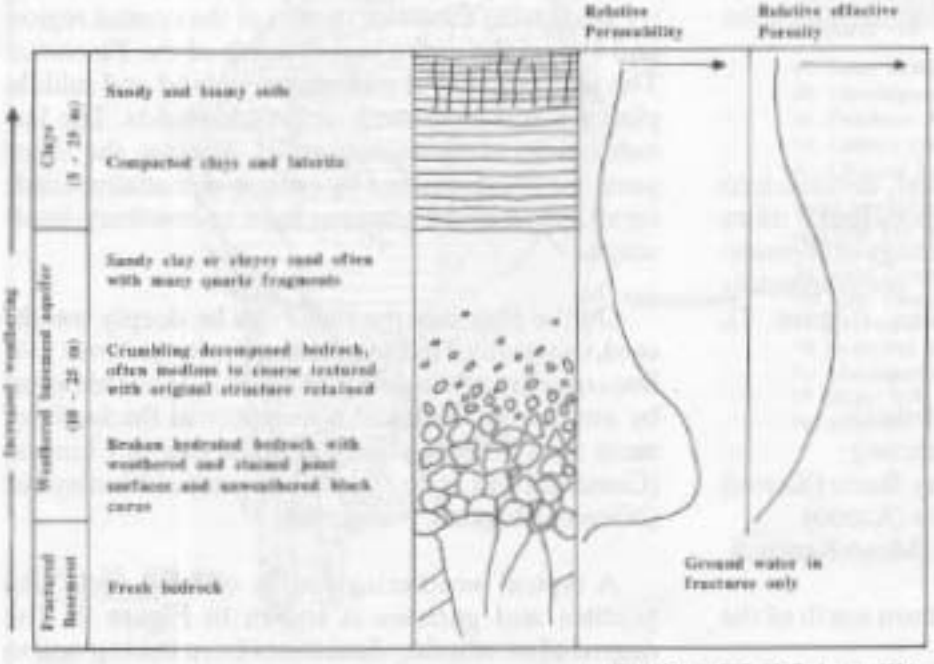
The major part of the Basement Complex is included in the high-grade **Mozambique Metamorphic Belt,** which is dominated by the Gneiss Granite Migmatite Complex, alternated with metasediments (e.g. marbles) and charnockites. In the mountainous western part of Manica and in the north of Tete, remnants of less metamorphized metasediments, covering the older complexes, are united in the Umkondo Group (Figure 2). This Group is divided into the low-grade metamorphic Umkondo and Fingoe Formations, respectively in Manica and Tete, consisting of slates, quartzites and some carbonate rocks, and into the medium-grade metamorphic Fronteira Formation, Manica, with quartzites and schists.

In the central part of Tete province, a **Gabbro-Anorthosite Complex** is distinguished, consisting of numerous intrusions of various sizes of intermediate, basic and ultra-basic rocks. Small pegmatite intrusions found in Nampula and Zambezia are thought to be formed in the same orogenic phase.

The dominant **structural orientation** in the Mozambique Metamorphic Belt is N-S, whereas several secondary orientations are distinguished in different parts of the country: NE-SW in the north-east, ENE-WSW and NE-SW in the north-west and NW-SE in the centre.

Ground water

In general, the water-bearing formations of the Basement Complex are low productive, discontinuous and of a limited extent. The productivity principally depends on the thickness and texture of the weathering mantle. The groundwater occurrences are associated with geologically weak zones, easily disintegrated into individual blocks, bounded by fractures and joints. These zones are associated with particular geological structures, like folds, faults and fractures, displaying relatively high permeability. Furthermore, the occurrence of coarse grained or heterogeneous rocks as well as soluble marbles, or the existence of contacts between rock types of different nature, facilitate weathering. These give rise to more or less limited aquifers. The aquifers are predominantly linear in shape, with an average length of



(After Chilton & Smith-Carington 1984)

Figure 8: Typical weathering profile in acid crystalline rocks

Table 9: Hydrogeological characteristics of some areas on the Basement Complex and Volcanic Terrains

Area		N° of wells	Average depth water level (m)	Average thickness weathering (m)				Specific yields ($m^3/h/m$)			Failures and unprod. wells (%)	Sites suitable for dug wells (%)	Productive wells in fault zones with spec. yields ($m^3/h/m$) not included in statistics
				completely weathered	total depth	saturated layer: completely weathered	saturated layer: total depth	q^{20}	q^{50}	q^{80}			
		a	b	c	d	e	f	g	h	i	j	k	l
GROUP C1													
Montepuez	CD	81	13	19	27	8	15	0.09	0.26	0.74	25	35	–
Meza-Ancuabe	CD	21	19	18	28	4	12	0.08	0.19	0.48	25	30	–
Namuno	CD	16	19	18	21	6	8	0.05	0.14	0.37	50	25	–
Balama-Namuno	CD	39	15	19	26	7	13	0.13	0.32	0.75	20	40	–
Montepo	NAM	11	15	18	–	5	–	0.10	0.27	0.77	20	15	4 wells; q=3-10
Meeia/Angoche	NAM	41	5	18	–	13	–	0.18	0.44	1.1	5	90	6 wells; q=3-10
Mandimba	NIA	7	10	22	28	12	18	0.15	0.70	1.8	15	70	–
Gondola	MAN	15	15	20	37	7	23	0.04	0.12	0.27	30	45	–
Chimoio	MAN	43	9	11	23	4	16	0.07	0.20	0.60	20	45	–
Zembe/Tembe	MAN	36	10	12	25	5	17	0.11	0.24	0.54	10	50	–
Chibata	MAN	19	9	11	30	4	20	0.13	0.37	1.04	15	40	4 wells; q=3-10
Vanduzi	MAN	7	8	12	31	4	23	0.09	0.20	0.46	0	45	–
		338	12	16	27	7	16	0.09	0.26	0.68	20	50	
GROUP C2													
Meluco	CD	18	14	18	–	8	–	0.06	0.15	0.38	40	50	–
Lurio Belt	CD/NAM	40	9	14	–	6	–	0.06	0.17	0.43	20	55	–
Nampula	NAM	10	10	12	17	7	12	0.03	0.07	0.16	70	30	–
Changara/Guro	TT/MAN	41	10	3	24	0	14	0.04	0.14	0.43	75	0	–
Sussundenga	MAN	26	9	7	22	0	8	0.06	0.15	0.37	40	0	–
		144	12	10	22	4	12	0.05	0.15	0.38	45	25	
OTHERS													
Rhyolites Lib. (C3)	MAP	13	14	2	6	0	0	0.03	0.08	0.18	75	0	3 wells q=8-19
Basalts Lib. (C1,C2)	MAP	74	19	3	16	0	2	0.04	0.13	0.45	50	10	–
Bas. Angoche (B3,C2)	NAM	11	4	15	25	11	21	0.45	0.85	1.6	0	100	Note: tap a fault
Anorthosites Tete (B3)	TT	31	11	4	12	0	4	0.09	0.31	1.1	20	0	1 well: q=36

Explanation:

* Column (a) gives the number of wells used in the statistical analyses of the specific yields. The number of wells used in the other columns is different. Therefore there may be discrepancies between the values in column (b) and the difference between columns (c) and (e) or (d) and (f).
* Columns (c) and (e) give the thickness of the completely alterated bedrock, whereas columns (d) and (f) include the partly weathered bedrock up to the top of the fresh rock.
* The specific yields of columns (g), (h) and (i) represent the probabilities of non-exceedence of 20, 50 and 80%, using the log-normal distribution.
* Column (j) gives the percentage of failures and unproductive wells ($Q<0.8\ m^3/h$). Note that the figures of different areas are not comparable, for in some areas, e.g. in the Lurio Belt, the use of geophysical siting techniques was more common practice than in others.
* Column (k) gives the percentage of well sites where shallow dug wells could have been constructed. Criteria are the existence of a water level within 15 m from the surface and the existence of an unconsolidated layer of at least 5 m below the water table.

1 to 2 km, a width of 40 to 100 m and a thickness of 25 to 40 m.

The typical **weathering profile** of Figure 8 gives the hydrogeological characteristics of the different horizons. The groundwater table is usually located near the base of the clayey-sand/sandy-clay layer. The next saturated horizon is very clayey, and therefore porous, but impermeable. The most permeable horizon is found in the transition zone to the unweathered parent rock and has an average thickness of 3 to 5m. It consists of coarse-textured material and blocks, without a significant clay component. Drillings are commonly made as far as the hard rock, to intersect this permeable layer that acts as a drain, which is replenished from the upper horizons that act as a storage reservoir. Dug wells generally do not reach into this more permeable horizon. Occasionally, they take advantage of a suspended aquifer on top of a lateritic layer, which may run dry after the wet season.

The best studied areas on the Basement Complex are located in the eastern parts of Cabo Delgado and Nampula provinces, in the area around Tete city and in the area around Chimoio. The hydrogeological characteristics are summarized in Table 9. It shows that the well yields in areas of Group C1 are twice as productive as in areas of Group C2. It also shows that the percentage of failures in Group C1 is half that of Group C2, and that Group C1 is much more suitable for the construction of dug wells.

The relation between the average thickness of the saturated weathering mantle and the range of specific yields in a particular area is shown in Figure 9. The figure is a good validation for the hypothesis underlaying the subdivision of Class C, stating that the productivity prospects increase with the thickness of the weathering mantle. The statement does not hold for individual boreholes, since the yield is very dependent on local factors, related to geology and the quality of the well construction.

Table 10: Hydrogeological potential of the most common hard rocks in Mozambique

Rock type	Fracture and joint development	Weathering characteristics	Hydrogeological characteristics	Groundwater potential	Occurence
Marble	very good	Dissolution of $CaCO_3$	Coarse textured: sec. porosity	very high (B1)	Montepuez and elsewhere
Anorthosite	good to very good	Mechanical disintegration; thin	Coarse textured with integranular porosity	very high (B3)	Gabbro Anorthosite Complex of Tete
Mylonite	good	Mechanical disintegration: thick transition zone	Deformation in small blocks (Microbreccia)	high	W of Cabo Delgado, Niassa, North of Zambeze Valley, Tete
Pegmatite	good to moderate	Kaolinitic weathering: thick	Coarse textured with sec. porosity; impermeable if kaolinitic	high to low	Zambezia, Nampula, Tete Cabo Delgado, Niassa
Dolerite, Porphyry and Quartz-breccia	good	Mechanical disintegration in small blocks (spheroidal)	Fractured in contact zone; groundwater barrier in center	high on contact	Tete, Manica, Sofala, Zambezia
Quartzite	good	Mechanical disintegration; hardly any weathering	If fractured deformation in small blocks	high to moderate	N of the Serra da Gorongosa, E of Montepuez
Gneiss, Granite	moderate	Clays with residual mica and quartz; moderate to thick	Best along contact between different rock types	moderate to low	Principal rock type
Amphybolite and Pyroxenite	moderate	Thick clayey weathering	Very low permeability; often brackish	low to zero	Morrola, Cabo Delgado
Charnockite	moderate to poor	Thin	Groundwater almost absent	low to zero	Manica, Tete, Zambezia, Niassa
Schist	poor to very poor	Thin clayey weathering	Impermeable	low to zero	Manica, Tete

The degree of disintegration and the formation of a weathering mantle depend greatly on the **rock type,** as is illustrated in Table 10. The most productive aquifers are related to marbles and anorthosites, that are respectively classified as Group B1 and B3. All the other crystalline rocks are included in the low productive Class C.

The marbles appear as elongated bands, up to 30 km long and 200 or 300 m wide, in several parts of the country. The hydrogeological characteristics of the marble outcrops are unknown, except for the one between Montepuez and Balama. This outcrop has a length of 30 km, is medium textured, karstified and fractured up to a depth of 60 m. Well yields are between 40 and 70 m^3/h and aquifer tests indicate a high storage volume. Other marble outcrops are even coarser textured, but the high topographical position of most of them might hinder the replenishment of the aquifers.

The wells in the Gabbro-Anorthosite Complex of Tete are moderately productive (Table 9). This might be due to the coarse textured minerals and the friable structure of the anorthosites, or due to the intensive faulting and fracturing in this part of the Intracratonal Basin of the Middle Zambeze. Intensely brecciated rocks, called mylonites, occur in the same zone and give rise to specific yields of up to 36 $m^3/h/m$. Another mylonite zone is found along the border between Cabo Delgado and Niassa, which hydrogeological characteristics are unknown.

Other rocks of the Basement Complex show low productivity prospects. Positive exceptions may be found along dikes, where aquifers can develop in the fracture zone on the contact between the intrusive body and the adjacent rocks. The main aquifer will develop in the formation most susceptible for weathering. The unfractured parts of the dike often form impermeable barriers. An example of productive wells along a group of dikes is found between Cambulatsitsi and Necungas in the south-east of Tete province.

The **quality** of the ground water in the Basement Complex is generally good, with a total mineralization below 600 mg/l. Higher salt concentrations are found in areas with a relatively high evaporation, as in the coastal belt of the northern provinces (500-1000 mg/l) and in the depression along the Zambeze. Other anomalies are related to the mineralogical composition of the parent rock. Dark coloured ferromagnesian rocks, such as amphybolites, contain hard water with mineralizations of up to 4000 mg/l. (e.g. in the Montepuez area). Basic rocks with predominant calcic plagioclase, such as gabbros and anorthosites, also contain hard groundwater with mineralizations of between 400 and 1600 mg/l.

The total hardness of the water is very variable, but normally medium to high. Of 84 samples, 36% had soft water (>150 ppm $CaCO_3$), 45% medium hard water (150-300 ppm $CaCO_3$), 6% hard water (300-450 ppm $CaCO_3$) and 13% very hard water (>450 ppm $CaCO_3$). The ground water in marbles is also very hard (>600 ppm $CaCO_3$).

Bicarbonate water is the dominant type in the Basement Complex. But in the coastal zone of Cabo Delgado, half of the samples had chloride water.

The pH of the groundwater generally varies from 7.0 to 8.3. The water in the northern part of Tete is

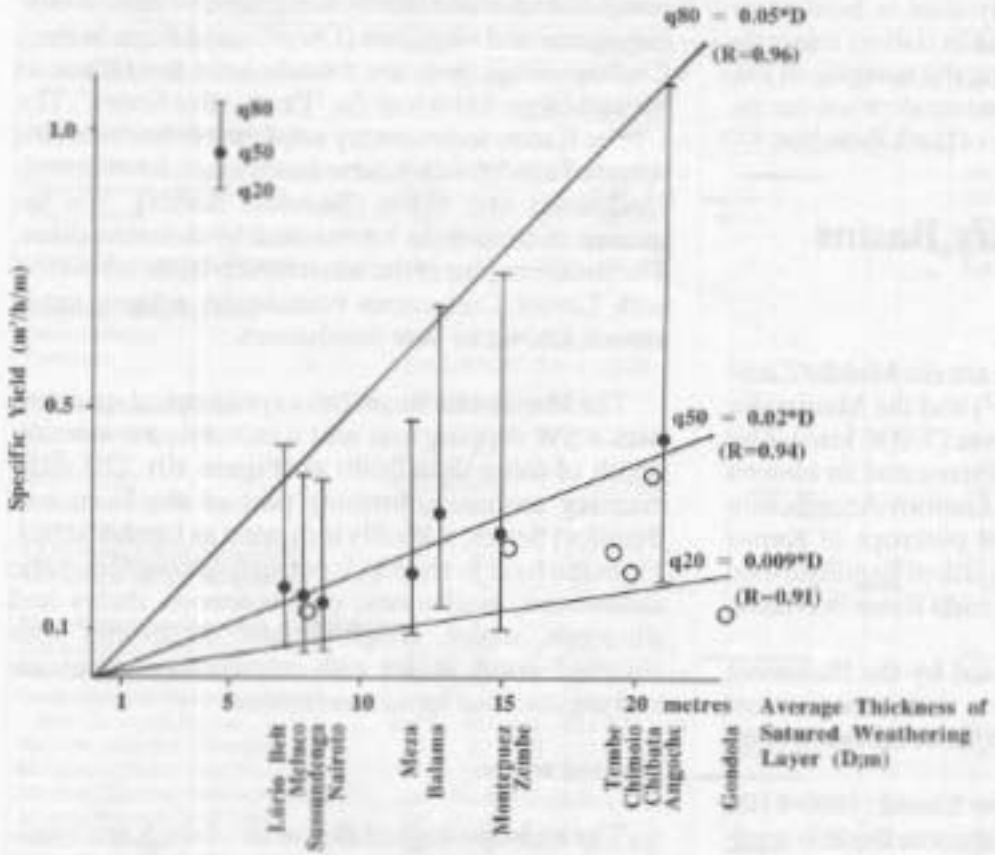


Figure 9: Relation between the average thickness of the satured weathering layer and specific yields (Cabo Delgado and Nampula (●), Manica (○)).

more acid. Here the only three samples had a pH of 5.4 to 6.4. Together with a low hardness of 80 to 130 ppm $CaCO_3$, the water can be considered to be rather aggressive in this area.

4.3 Volcanic Terrains

Physiography and Geology

The volcanic Terrains are developed along the margins of the Sedimentary Basins and the Basement Complex, especially along the Kaapvaal Craton (the Libombos) and along the Zimbabwe Craton. They mainly consist of basalts, rhyolites and alkaline rocks, most of them originating from fissure eruptions. Outcrops of rhyolites and alkaline rocks form ridges and mountains, like the Libombo Range and the mountains around Lupata. Basalts are more susceptible to weathering and commonly form plains with dark clayey soils.

Ground Water

Hydrogeologically, the Volcanic Terrains are quite similar to the Basement Complex. Primary and secondary fractures are the most important water-bearing features in these rocks. The weathering mantle is generally less developed than on the Basement Complex and rarely exceeds 10 m. It may be more developed in basaltic terrains, but since the material is very clayey, it is almost impermeable. The stratigraphical sequence may include ash layers and weathered layers between the brittle rock, due to ancient weathering between two eruption phases. Contact metamorphism rendered adjacent sedimentary rocks impermeable, as occurred with the Lupata Sandstones.

Basalts are considered the most productive volcanic rocks, but well yields are still very low (Table 9). The wells, drilled in the basalts in Angoche are more productive, for they intersect a fault zone, defined by geophysical surveys. Rhyolites have poor hydrogeological characteristics, but existing fractures and faults might be more productive than in basalts, clayey weathering products being absent. The hydrogeological characteristics of the alkaline rocks is not known, because of absence of borehole data.

The **quality** of ground water in rhyolites is very good. It has a mineralization of less than 500 mg/l, a low hardness (< 10 ppm $CaCO_3$) and a sodium chloride to sodium bicarbonate composition. Near Na-

maacha, spring water from rhyolites is bottled as table water. Ground water in basalts is more mineralized and harder, especially along the margins of the Sedimentary Basins, where the mineralization can be up to 8500 mg/l, as at the edge of the Libombos.

4.4 Karoo Sedimentary Basins

Physiography

The two main Karoo Basins are the Middle Zambeze Basin in Tete (35 000 km^2) and the Maniamba Basin in the north-west of Niassa (7 000 km^2). The former can be divided into a western and an eastern sub-basin, separated by the Gabbro-Anorthosite Complex. Other, more isolated outcrops of Karoo sediments can be found to the south of Espungabera, around Canxixe and in the Lugenda Basin in Niassa.

The main Basins are enclosed by the Basement Complex and form depressions with rare residual hills and terraces, remnants of former erosion cycles.

The Maniamba Basin is quite humid (1100-1400 mm/yr), whereas the Middle Zambeze Basin is semi-arid (500-700 mm/yr). Recharge is high in the former, but low in the latter. Streams are seasonal to ephemeral.

Geology

The **Middle Zambeze Basin** has an asymmetrical synclinal structure, bordered by faults (Figure 10). It is composed of several inclined blocks, in which the sedimentary sequence can be over 3000 m thick. In this Basin, the Lower Karoo commences with basal conglomerates and tillites, succeeded by mudstones, claystones and siltstones (Dwycka and Ecca Series). Carbonaceous beds are found above the tillites, in Mozambique known as the "Productive Series". The Upper Karoo sedimentary sequence consists of fine textured sandstones, coarse sandstones, fossiliferous sandstones and marls (Beaufort Series). The sequence is frequently intersected by doleritic dikes. The southern part of the western sub-basin is covered with Lower Cretaceous continental arkosic sandstones, known as Tete Sandstones.

The **Maniamba Basin** has a symmetrical structure with a SW dipping axis and a calculated maximum depth of more than 2000 m (Figure 10). The sedimentary sequence, forming part of the Ecca and Beaufort Series, is locally indicated as Lunho Series. From the base to the top, it consists of conglomeratic sandstones, mudstones, carbonaceous shales and siltstones, shales, conglomeratic sandstones with silicified wood, shales with calcareous concretions and argillaceous loose sandstones.

Ground water

The hydrogeological character of the Karoo sedimentary rocks is known only from a few limited areas around Zumbo, Chitima, Boroma and Changara. Only one well has been drilled in the Karoo of the Maniamba Basin.

The sedimentary sequence is dominated by low productive fine textured rocks. Contact areas near volcanic rocks and areas with many rock outcrops are also considered to have poor yield prospects (group C2 and even C3). For example in the Changara region, 50% of the wells is unsuccessful,

FORMATION		HYDROGEOLOGICAL GROUP
Qal,Qt,Qc,Qp	Quaternary	A123,C1
Ks	Tete Sandstones	C2
(JKß,JKp)	Stormberg Volcanic rocks	C123
Rs	Karoo sandstones	B3,C23
Ri	Karoo mudstones and sandstones	B3,C2
x	Precambrian crystalline rocks	B3,C123
Qal,Qc,Qp	Quaternary	A3, C1
Ri	Lunho Series (mudst&sandst)	C2
x	Precambrian crystalline rocks	C123

Figure 10: Schematic geological sections across the two Karoo Sedimentary Basins

Table 11: Aquifers of the sedimentary basins in the north and center of Mozambique

SEDIMENTARY BASIN & WATER BEARING FORMATION	AGE	SPECIFIC YIELDS ($m^3/h/m$) group	N° wells	q^{25}	q^{50}	q^{75}	0.1 0.3 1.0 5 10 100	WATER QUALITY Dry Residue (mg/l)	pH	REMARKS
Middle Zambeze Sedimentary Basin							C321 AB3 AB2 AB1			
Karoo sandstones	Ro,Ri	B3	29	0.15	0.42	1.2		400 - 800	7.3-8.1	coarse texture; friable
Karoo mudstones and shales	Ro,Ri	C2	–	(0.04 - 0.4)				400 - 2500	–	fine texture; dikes
Tete sandstones	Ks	C2	1	(0.08)				brackish	–	best prospects along valleys
Alluvium, Nhartanda Valley (Zambeze)	Qal	A3	6	(130 - 480)				400 - 600	–	120 to 200 m^3/h; old valley
Alluvium, Revubue Valley (Matundo)	Qal	A1	3	(48 - 71)				500 - 1600	6.9-8.6	brackish at the base (Karoo)
Maniamba Sedimentary Basin										
Karoo sandstones	Ro,Ri	C2	1	(0.6)				–	–	1 well in sandstones
Loose cover	Qp,c,al	A3,C1	1	(0.8)				–	–	1 well in cover
Rovuma Sedimentary Basin										
Macondo sandstones NW	Ki	B3	4	(0.13 - 1.1)				80 - 200	5.2-5.7	deep water level; aggressive
Mocis - center	Ki,Ks	C2	–	–				(4800)	–	brackish, low potential
Sandstones NE	TI\,TIs	C2,B3	4	(0.2 - 0.8)				100 - 300	–	sand cover with water
Littoral limestones/calcarenites	TIs	B2	63	0.53	1.3	3.3		400 - 3300	7.6-8.6	salt intrusion
Littoral sand cover	Qd	A3	–	(0.2 - 0.4)				(600)	–	local
Alluvium near Bilibiza (Muaguide N)	Qal	A3	5	0.21	0.73	2.5		200 - 3000	–	salty flow from marls
Alluvium near Metuge (Muaguide S)	Qal	A1	7	3.0	5.6	10.3		fresh	–	well field Metuge
Mozambique Sedimentary Basin, north of the Save										
Sena sandstones - Sena Plains	Ks	C2	26	0.06	0.26	1.2		400 -8500	7.4-8.8	data of productive wells only
Sena sandstones - Buzi valley	Ks	C2	6	0.04	0.07	0.12		1500 -2600	–	
Grudja marls, Cheringoma limestones – Buzi/Cheringoma Plateaus	Ks,TIs	B3?	18	0.15	0.30	0.60		400 -2500	–	no separation
Mazamba sandstones - Cheringoma Plateau	TIs	B3	16	0.13	0.39	1.2		350 -2500	–	eastward more productive
Mazamba sandstones - Buzi Plateau	TIs	B3??	14	0.05	0.20	0.62		30 - 400	–	eastward more productive
Alluvium of Zambeze (Marromeu/Luabo)	Qal	A1-A2	15	0.50	1.2	2.9		fresh	–	wells with deficiencies
Alluvium W-margin Urema Graben	Qal	A1-A3	–	–				fresh	–	alluvial fans
Littoral beach ridges	Qd	C1	6	(0.1 - 0.4)				1400 - 3800	–	top less brackish, Q=1-2.4

whereas the other part has yields below 3 m^3/h. Better prospects may be encountered in fracture zones, in coarse textured sandstones, in fault-breccias and along dolerite intrusions. Such aquifers are common near Zumbo and Boroma (Table 11, Group B3).

Water quality in the Karoo formations is variable. Most of the wells have a mineralization of 400 to 800 mg/l, but high concentrations of 1400 to 2500 mg/l are common in the Changara and Moatize regions. Values up to 7000 mg/l have been found in the Lower Karoo sequence near Chitima (DNA, 1987b).

The arkosic **Tete Sandstones** that cover the major part of the area south of Lake Cahora Bassa are impermeable. There is a lack of borehole information, but the Sandstones probably contain brackish water.

Thin **Quaternary sand covers** are common on the plains of the Middle Zambeze Basin and along the eastern and southern margins of the Maniamba Basin. They represent colluvium, alluvial terraces, eluvium and possibly eolian sands. They may contain local aquifers, that can be tapped by dug wells.

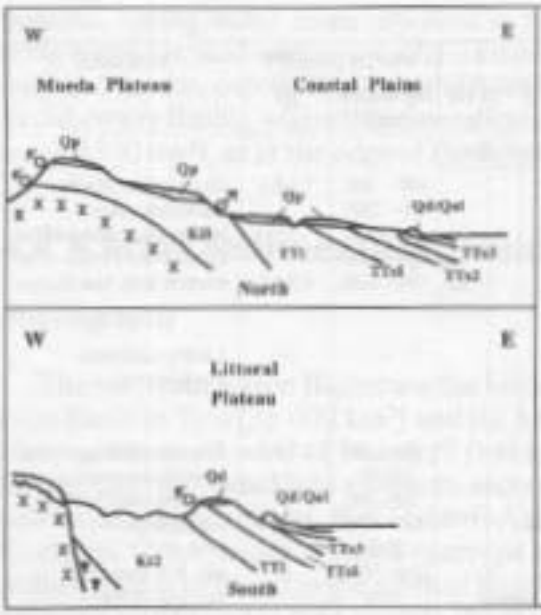
The best aquifers are found in the **alluvial valleys,** especially along the Arangua, Panhame and Mucumbura in the west of Tete and along the Zambeze, downstream of Boroma. Very illustrative examples with yields over 200 m^3/h and hardly any drawdown can be found in the Nhartanda well field in an old branch of the Zambeze near Tete and in the Matundo well field in the Revubue valley near the confluence with the Zambeze (Table 11). The water quality in these well fields is good, but deteriorates with depth.

4.5 Rovuma Sedimentary Basin

Physiography and geology

The Rovuma Sedimentary Basin in the north-east of the country covers an area of about 25 000 km^2 (on-shore). It widens from Ilha de Moçambique in the south to the Rovuma in the north, where it is 120 km wide. It mainly consists of slightly undulating plains and low plateaus. In the north, the coastal plain is dissected by river valleys. It rises inland, where it culminates in the outstanding Mueda Plateau with a maximum altitude of about 1000 m and the remnants of the Macomia Plateau.

Rainfall varies between 800 mm/yr at the Pemba coast to over 1200 mm/yr on the Mueda Plateau. The recharge capacity is medium to high in the north to low in the southern part of the Basin, where soils are more clayey. Rivers are seasonal to ephemeral.



FORMATION		HYDROGEOLOGICAL GROUP
Qal	Quaternary	A123,C1
Qal,Qd,Qp	Quaternary	A3,C1
TTs3	Littoral limestones	B3
TTs2	Mikindani Beds (Sandstones)	B3
TTs1	Sandstones and calcarenites	B3
TTi	Sandstones and marlstones	C2
Ks,K12	Marlstones	C2
K11	Maconde Sandstones	B3
▼	Angoche Basalts	(B3),C12
x	Precambrian crystalline rocks	C123

Figure 11: Schematic geological sections across the Rovuma Sedimentary Basin

The **lithological sequence** is summarized in Figure 3 and 11. The geology is dominated by Cretaceous marlstones. The plateaus in the north-west are underlain by the Cretaceous continental Maconde Sandstones, covered with a 20 to 40 metres thick sand layer. Coastward, the Maconde Sandstones are succeeded by fine textured marine sandstones (Tertiary) and fluvial sandstones of the Mikindani Beds (Upper Tertiary), that reach a thickness of 30 to 60 m near Mocimboa da Praia. Along the entire coast, one finds Pliocene to recent calcarenites and reef limestones, covered with eolian or marine sands. The extensive plains in the north are covered with Quaternary sands. Alluvium is little developed, except along the rivers Rovuma, Messalo, Muaguide (Montepuez), Muaguide (Metuge), Lurio and Monapo.

Ground water

The hydrogeology of the Rovuma Sedimentary Basin is little known from boreholes, except in the littoral zone around the main towns and cities. Groundwater prospects are limited by the dominance of impermeable marlstones with brackish ground water. In the more productive aquifers of the littoral zone, there is a serious salinization risk. The most favourable areas are found in the north and along the main alluvial valleys, especially at the contact with the Basement Complex.

The **Mueda and Macomia Plateaus** are underlain by the continental Maconde Formation, consisting of kaolinitic quartz-feldspatic sandstones with interbedded conglomerates at the base. The upper part is considered to be rather productive with a permeability of 3 or 4m/d (DNA 1985a). The depth to the groundwater table is the main restraint of the aquifer, commonly being deeper than 100 m. On the plateaus, the Maconde Sandstones have a 20 to 40 m thick sand cover. It may contain some local suspended lenses, but the base normally lies above the regional groundwater table. Numerous springs with discharges of up to 30 l/s appear at the margins of the plateaus. The spring water is very pure with a chloride content of between 15 and 45 ppm. The water is acid (pH of 5.2 to 5.7) and soft (20 to 130 ppm $CaCO_3$), and therefore aggressive and corrosive to concrete constructions.

The wells in the **Tertiary formations** east of the Maconde Sandstones have moderate yields (Table 11). To the north of the Messalo, the groundwater is of good quality with a mineralization between 100 and 300 mg/l.

To the south of the Messalo, the **Cretaceous marlstones** form the dominant formation. The few existing boreholes indicate a very low productivity and brackish water.

The most productive consolidated formations are found in the littoral zone with **Miocene to Pliocene calcarenites and coral limestones.** Specific yields are generally moderate to high. The main problem is the salinity of the aquifer or the high risk of sea-water intrusion as a result of over-exploitation. This has already occurred in the well fields on the peninsulas of Pemba and Nacala. In these littoral aquifers, the water can be very hard (up to 1500 ppm $CaCO_3$).

To the north of the Messalo, most of the plains are covered with a 10 to 30 m thick **eluvial cover,** in

which many wells have been dug. Other sand covers are found on some littoral plateaus between Pemba and Moma, commonly with a coarse textured base. The productivity is not very high with specific yields below 0.4 $m^3/h/m$, but the water quality is generally good with a mineralization below 600 mg/l. On the Peninsula of Nacala, more than 60 springs originate at the base of the sand cover, but their discharges are small.

The **alluvium** along the main rivers, crossing the sedimentary terrains, includes the most productive aquifers of the Basin. The Metuge well field for the future water supply of Pemba along the Muaguide, is installed in a 40 m thick alluvial fill. Specific yields range from 1.2 to 12 $m^3/h/m$. Other promising alluvial zones can be found at the contact with the Basement Complex. Wells in the Monapo valley have yields of between 40 and 60 m^3/h. The alluvium of the Messalo seems to be the best developed. The ground water quality in the alluvial aquifers is generally good, but may be poor if the water originates from adjacent plains with mineralized ground water, as is the case in the Muaguide valley near Bilibiza. The alluvium in the littoral zone is of little hydrogeological importance, being impermeable and containing brackish water. Small recent dunes can form positive exceptions, but ground water can still be rather brackish.

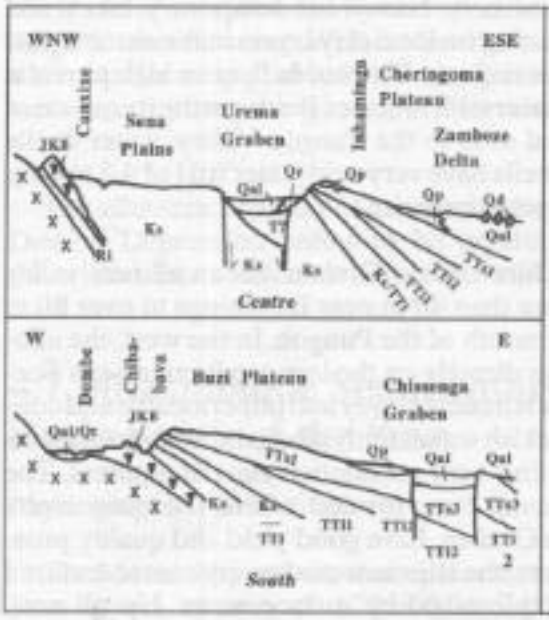
4.6 Mozambique Sedimentary Basin North of the Save

Physiography and geology

The Mozambique Sedimentary Basin north of the Save covers an area of 80 000 km^2. As is shown in Figure 7, the Basin can be geomorphologically divided into the inland Sena Plains, the Cheringoma Plateau between the Zambeze and Pungoe valleys, the Buzi Plateau between the Buzi and Save valleys, the valley and delta of the Zambeze and the littoral zone. The northern part of the Basin is split by the N-S oriented Chire-Urema Graben, a continuation of the East African Rift System.

Rainfall varies from 1400 mm/yr along the coast and 900 mm/yr more inland to less than 700 mm/yr on the Sena Plains. Except for the last mentioned area, the recharge conditions are quite good. Streams are perennial in the littoral zone, but seasonal to ephemeral further inland.

The **sedimentary sequence** is summarized in Figure 3. Figure 12 and the cross-section on the northern Map-sheet show the geological structure of the northern part of the Mozambique Sedimentary Basin. West of the Urema Graben and along the western margins of the Cheringoma and Buzi Plateaus, the geology is dominated by the Cretaceous continental arkosic Sena Sandstones, which can attain a thickness of more than 2500 m.



FORMATION		HYDROGEOLOGICAL GROUP
Qal,Qt	Alluvium	A123,C1
Qc	Colluvium	A3
Qd	Dunes/beach ridges	C1
Qp	Eluvium	C1
TTs3	Divinhe Fm (arg. sandst.)	B3
TTs1	Mazamba Fm (cont. sandst.)	B3?
TTi2	Buzi Fm (arg. sundst.)	B3/C2?
TTi1	Cheringoma Fm (limest. ,marls)	B3
Ks/TTi	Grudja Fm (glauc. sandst.,marls)	C2
Ks	Sena Fm (cont. sandst.)	C2
JKβ	Karoo basalts and rhyolites	C123
Ri	Karoo sandstones	C2
x	Precambrian crystalline rocks	C123

Figure 12: Schematic geological sections across the Mozambique Sedimentary Basin north of the Save

The Cheringoma and Buzi Plateaus are mainly underlain by the Miocene continental arkosic Mazamba Sandstones. They consist of a fine textured, silty micaceous member, with a characteristic purplish-violet color and an upper coarse textured member. They are underlain by marine sandstones of the Buzi Formation (not in outcrop, up to 700 m thick), limestones and calcarenites of the Cheringoma Formation (up to 450 m thick) and the Cretaceous glauconitic sandstones and marls of the Grudja Formation (up to 1500 m thick). The last two formations have 60 to 90 m thick outcrops along the western escarpment of the Cheringoma and Buzi Plateaus.

The central and eastern parts of the plateaus are covered with a thin eluvial layer. Alluvium is well developed in the valleys of the Zambeze and Buzi, in the Chire-Urema Graben, in the Zambeze delta and in the Dombe depression, north-west of Chibabava. To the south of the Zambeze delta, the thickness of the littoral alluvium decreases and sandstone outcrops can be found in a small strip to the north of the mouth of the Save. Old beach ridges form a system of parallel low sand ridges in the swampy littoral zone.

Ground water

Concentrations of boreholes are found on the Sena Plains, around Inhaminga and in the north-west of the Buzi Plateau. But the hydrogeology of the other areas had to be interpreted from indirect data or by analogy, because of lack of borehole data.

The Mozambique Sedimentary Basin north of the Save is not very favourable for groundwater development, except in the main alluvial valleys and in the Zambeze delta. Yield and quality prospects improve coastward.

The coarse textured arkosic **Sena Sandstones** have a low permeability and may contain brackish water with a mineralization up to 8500 mg/l. The percentage of unproductive drillings is over 60%. Of the productive boreholes only 40% contains fresh water. On the Sena Plains, best prospects are found in the river valleys, where well yields are higher and water quality can be good, due to the infiltration of river water. The valley of the Sangadeze river, however, contains highly mineralized water.

The characteristic dense dentritic drainage pattern of the Sena Formation is absent in some areas to the north of the Zambeze and west of the Urema Graben. These areas may have more permeable rocks and are classified as Group B3, but there is no confirmation from borehole data. Another possibility is, that these more permeable areas represent old terraces of the Zambeze, as can be found upstream of Chemba.

The marine **Grudja and Cheringoma Formations**, that are overlain by the Mazamba Formation on the Buzi and Cheringoma Plateaus, are low to moderately productive (Table 11). The calcarenous Cheringoma Formation is assumed to be more productive and to contain less mineralized water than the argillaceous sandstones of the Grudja Formation. The water quality is variable and affected by the highly mineralized water of the Sena Sandstones.

The continental **Mazamba Sandstones** are comparable to the Sena Sandstones and only slightly more productive (Table 11). The permeability probably increases coastward, but the classification as Group B3 is suspect. On the Cheringoma Plateau the most productive wells intersect a thin permeable layer at the transition from an upper argillaceous to a lower carbonatic-argillaceous sandstone. This aquifer has a thickness of a few metres only, and is found at a depth of 50 to 100 m.

On the Cheringoma Plateau, the water quality of the Mazamba Formation is acceptable. The mineralization decreases coastward from 1500 mg/l near Inhaminga and 1000 mg/l near Dondo, to 350 mg/l in some wells directly north of Beira. On the Buzi Plateau, the Mazamba Formation contains very good water with chloride concentrations of less than 50 ppm and a hardness of less than 100 ppm $CaCO_3$.

Extensive areas of the Buzi and Cheringoma Plateaus have an eluvial **sand cover** that may contain shallow ground water along the main valleys and in the coastal belt. Numerous temporary lakes and ponds, resting on local clay layers in the eastern part of the Cheringoma Plateau, indicate a high phreatic groundwater table. West of Beira, on the transition of the eluvial soils to the Pungoe Valley, water in the shallow wells have very acid water (pH of 4.5 to 6.5), which is very corrosive.

The **Chire-Urema Graben** has an alluvial valley fill of more than 40 m near Inhaminga to over 80 m near the mouth of the Pungoe. In the west, the alluvium rests directly on the low productive Sena Formation. It is mainly clayey and impermeable and contains brackish water. Only along the western margins can one find very productive alluvial aquifers. The large alluvial fans, formed where the main rivers enter the Graben, have good yield and quality prospects. Here, the alluvium can be very coarse textured and be replenished by surface water. Up till now, good prospects have been verified only along the Metuchira river, 12 km north of Nhamatanda, where

wells are very productive, even though they were not sited as a result of geophysical surveys.

Boreholes and shallow wells in the Chire and Urema valleys show a sharp increase in mineralization towards the centre. The colluvial cover along the eastern margins may contain fresh groundwater, but this has not been confirmed.

The productivity prospects for the alluvium in the Zambeze Valley may be very good, but there is hardly any data available. Some shallow wells indicate that the water quality along the edge of the valley may deteriorate under the influence of brackish ground water in the adjacent Sena Sandstones.

Boreholes around Marromeu and Luabo in the centre of the **Zambeze Delta** are moderately productive (Table 11). It is assumed that new wells in this central part may be even more productive, as the older wells were shallow and show many construction deficiencies. The oil test well Micaune 1 intersects more than 300 m of sands before it strikes more clayey formations. Buried river channels and levees are most promising. They can be pinpointed by geophysical surveys and aerial photographs. The water quality is assumed to be good in the interior of the delta, except in water-logged areas. The mineralization increases coastward. The brackish water limit on the Map is verifiable only from a soil map at the mouth of the Zambeze and by a geomorphological interpretation of former marine flood plains around Quelimane.

In the **littoral zone,** the low sandy beach ridges form one of the few sources for domestic water supply. The sand bodies are often less than 10 or 15 m thick and are surrounded by clayey sediments with saline formation water. Wells in Quelimane indicate a low productivity (Table 11). In the first metres the water quality may be good, but deteriorates with depth.

The alluvium of a part of the **Buzi valley** and the Dombe Depression seems to be productive, but there is no data available.

4.7 Mozambique Sedimentary Basin South of the Save

Physiography

The Mozambique Sedimentary Basin south of the Save covers an area of 170.000 km^2 (Figure 7). Inland its morphology is characterized by extensive erosion plains, gently dipping coastward. They are intersected by the valleys of the Save and Limpopo and by smaller rivers originating from the Libombos. In the north-east the structural Urrongas Plateau is underlain by limestones. It is separated from the inland plains by the Mazunga Graben, of which the Funhalouro-Mabote Graben is a subsystem. The coastal belt is characterized by a dune area with an average width of 30 km. The Incomati and Limpopo have built an extensive alluvial plain, inland from the dune belt.

Rainfall varies from 700 to 1000 mm/yr along the coast to 350 mm/yr in the most inland part of the Alto Limpopo Plains. Recharge is moderate to high in the coastal dune belt, but low in the inland areas, despite the favourable terrain conditions.

The main rivers are the Maputo, Umbeluzi, Incomati, Limpopo and Save. In general they have a permanent character, but the last three rivers frequently have no flow at the end of the dry season. Smaller streams are ephemeral to the north of the Limpopo, seasonal to the south of the Limpopo and permanent or semi-permanent in the dune belt. Numerous lakes are found in the area. On the inland erosion plains, BURGEAP (1961) registered over 700 small lakes and ponds, but only 8% had a permanent or semi-permanent character. Many of them may contain brackish water.

Geology

The **lithological sequence** is summarized in Figure 3, whereas Figure 13 and the cross-section of the southern Map-sheet show the geological structure. The gently eastward dipping strata are interrupted by block-faulting along N-S oriented Graben systems. The age of the rocks increases from the coast inland.

The main part of the inland area is dominated by **continental formations,** consisting of coarse textured arkosic sandstones. At the Zimbabwean border one finds outcrops of the Cretaceous Sena Formation, which is succeeded by the Lower Tertiary Elefantes Formation and the Miocene Mazamba Formation.

The coastal belt and almost the entire area south of the Rio dos Elefantes are dominated by **marine and transitional formations.**

The **Cretaceous** formations are fine textured, dominated by shales, marls and glauconitic sandstones. The Maputo Formation is the oldest one (Aptian/Albian). It consists of argillaceous glauconitic sandstones and outcrops in the extreme south along the Libombos. The succeeding shaly Domo

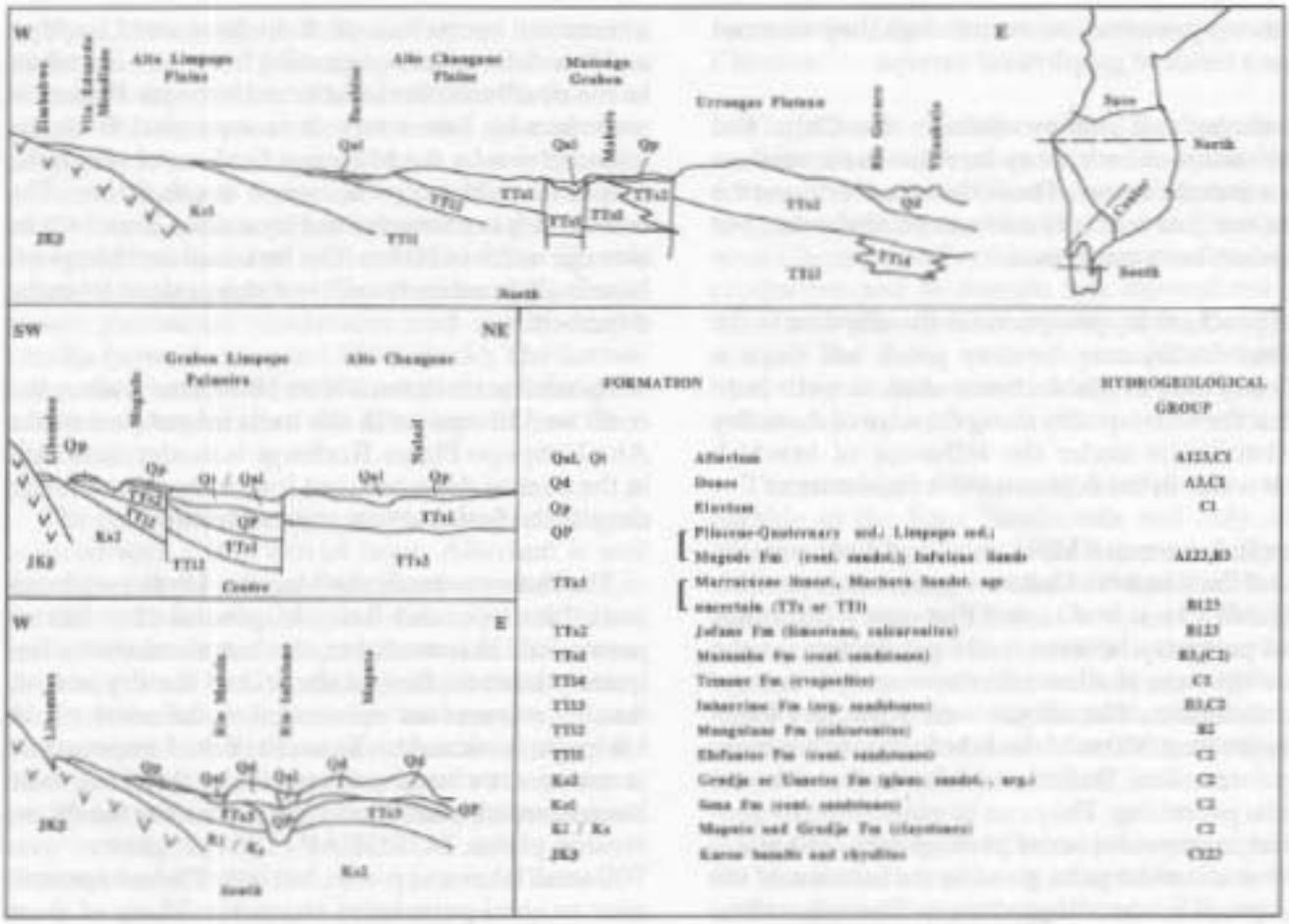


Figure 13: Schematic geological sections across the Mozambique Sedimentary Basin south of the Save

formation is only found at depth to the north of 25°S latitude. The upper Cretaceous marine Grudja Formation is the most developed and can attain a thickness of over 1500 m in the subsurface of Inhambane. It consists of glauconitic sandstones, marls and calcarenites. It is found in outcrop in the west of Maputo province, where it is locally known as the Uanetze Formation.

The **Tertiary** marine sequence is dominated by calcarenous and medium textured sandstones. The sequence starts with the calcarenous Eocene Cheringoma Formation also denominated as the Mangulane Formation and the Salamanga Formation in the north and the south of Maputo province, respectively. It is found in outcrop between Magude and the Rio dos Elefantes and along the Maputo river. Probably it has an extension to the north of the Limpopo along the 32°30'E meridian, where many boreholes intersect a calcarenous formation between the Elefantes and Mazamba Sandstones.

The Oligocene Inharrime Formation is found in the entire Inhambane province. It directly underlies the dunes along the south coast between Zandamela and Jangamo on the so-called Zandamela High (Flores 1973). It consists of argillaceous sandstones. Just south of the mouth of the Save, this formation is covered with the evaporitic Temane Formation, consisting of dark claystones with intercalated gypsum and anhydritic beds. This formation occupies an area of 37,500 km^2 and attains a maximum thickness of 173 m. The top is found at a depth of 140 to 370 m.

In the major part of the coastal belt, the Inharrime Formation is overlain by the Miocene Jofane Formation, consisting of limestones and dolomites, commonly with oolites and coral fragments. It oucrops on the Urrongas Plateau and in Maputo province, where it is denominated as the Tembe-Santaca or Santiago Formation. Furthermore it underlies most of the dunes in the coastal belt.

The Jofane Formation marks the end of the regional marine transgressions, but some local transgressions continued during Pliocene and Quaternary. An up to 180 m thick deltaic to lacustrine sequence is found below the Limpopo-Incomati Interfluvial Plain, recently recognized as the Palmeira Limpopo Graben (Figure 13). Probably com-

parable in age and genesis, but less developed, are the Infulene Sands, just west of Maputo city with a thickness of 50 m (IWACO 1986).

In Maputo province, the Miocene rocks are covered with a discontinuous continental reddish conglomeratic sandstone, denominated as the Magude Formation. This **Pliocene** formation may reach a thickness of 30 m in the outmost south and east of Moamba.

Almost 70% of the Basin is covered with **Quaternary** sediments. Most of the inland plains have a clayey to sandy eluvial cover, with an average thickness of only 5 to 10 m. On the Hydrogeological Map and in Figure 2 it is only indicated, if it is assumed to reach a considerable thickness. A recent study in the area between Maputo city and Moamba classified the 'eluvial' cover to be of colluvial origin (Beernaerts, in preparation).

The coastal dune belt consist of a narrow strip of recent dunes and an up to 100 km wide area of inland ancient dunes. The ancient dunes were formed in inter-pluvial periods during Pleistocene glaciations. They consist of orange-brown to reddish colored clayey sands of fine to medium texture. Exceptionally, they may reach a thickness of more than 100 m, as they do in the south of Gaza and Inhambane provinces. The recent littoral dunes consist of clean, medium to coarse textured sands.

Alluvial deposits are well developed along downstream courses of the major rivers and below the Limpopo-Incomati Interfluvial Plain. Frequently the alluvium can reach a thickness of over 60 m.

Indurated Quaternary rocks can be found in local badly drained alluvial depressions, where they can be classified as calcretes or lacustrine limestones, and along the coastline, where they are know as "beach rocks" or "gres costeiros".

Table 12: Aquifers of the Mozambique Sedimentary Basin south of the Save

SUB-REGION / WATER BEARING FORMATION	AGE	group	N° wells	q^{20}	q^{24}	q^{48}	0.1 0.3 1.0 5 10 100	Dry Residue (mg/l)	pH	REMARKS
Alto Limpopo Plains							C321 AB3 AB2 AB1			
Sena sandstones	Ks	C2	11	–				400- 900	7.4-8.4	40% failures, Q=0.1-6 m³/h
Elephants sandstones	TTi	C2	4	(0.05 - 0.33)				300-6000	7.3-8.3	Brackish around depressions
Alto Changane Plains										
Mangalane calcarenites (W)	TTi	B2	11	0.55	2.6	12.7		200-21000	7.8-8.3	Margin Alto Limpopo Plain
Mazamba sandstones (N)	TTs	B3	20	0.27	0.70	1.9		1100-21000	7.6-8.4	Eluvium with fresh water
Mazamba sandstones (Center)	TTs	B3?	55	0.11	0.29	0.76		1800-30000	6.9-8.4	Eluvium can contain fresh w.
Mazamba sandstones (extreme S)	TTs	B3	29	0.36	0.89	2.2		1200-15000	7.6-8.3	Eluvium can contain fresh w.
Old alluvium Bala Bala (S)	Qal	A3	17	0.23	0.66	1.9		900-11000	6.7-8.3	20 tot 60 m thick cover
Eluvial covers	Qp,Qtl	C1	–	–	–	–		200-33000	6.9-8.4	60% shallow wells with fresh w
Limpopo/Incomati interfluvial Plain										
Old terrace (W)	Qt	C1	12	0.11	0.23	0.48		salty	–	Limit based on well yields
Old alluvium (center)	Qal	A2	12	0.96	2.9	8.7		3000-16000	5.7-8.3	Depth to 80m (see deep aquif.)
Denuded plains along the Libombos										
Maputo and Grudja marine formations	Ks,TTi	C2	46	0.09	0.24	0.71		3000-38000	7.2-8.9	Water level can be very deep
Mangalane and Santaca Calcarenites	TTi,TTs	B2	31	0.54	1.3	3.0		400-24000	7.4-8.1	idem, less product.in extr. NE
Old terraces of Moamba (Magude Fm?)	Qt	C1	8	0.07	0.27	1.1		1200-41000	–	Marine terrace?
Umongas Plateau										
Jofane limestones (karstified, E)	TTs	B1	40	1.6	7.1	31		900-2800	7.1-8.3	Coastal zone (Govuro)
Jofane limestones (center and W)	TTs	B3	26	0.23	0.58	1.5		1100-7200	7.7-8.5	Not karstified, salty in center
Dune Belt										
Recent littoral dunes (P. Ouro, Toko)	Qd	A3(A2)	10	1.7	4.0	9.3		100- 800	7.2-8.6	Risk of salt intrusion
Old dunes, coastal zone Inhambane/Gaza	Qd	A3	120	0.33	0.80	1.9		100-1300	6.5-8.4	Water level can be deep
Old dunes along Incomati valley	Qd	A3	23	0.16	0.35	0.77		200- 900	6.5-8.4	k = 1-9 m/d
Eolian valley fill Machava	Qd	A3(A2)	11	1.3	2.1	3.4		400-1400	6.9-8.2	Exceptional N-S buried valley
Old dunes coastal zone Matutuine	Qd	A3	6	0.23	0.57	1.4		300- 850	6.0-?	East of Maputo valley
Old dunes, inland zone Inhambane/Gaza	Qd	C1	24	0.11	0.18	0.30		300-1200	7.0-8.0	Limit based on yields only
Alluvial Valleys										
Limpopo (Middle); Paluri-Chibuto	Qal	A2	19	0.66	3.2	15.8		200- 1300	–	Yields variable, may be salty
Limpopo (Lower); Chibuto-mouth	Qal	A3	6	0.20	0.34	0.58		300-10000	–	Center salty, margins fresh
R. d. Elefantes	Qal	A2	4	(0.6-1.3)				400- 1300	–	Salty seepage from margins
Incomati (Middle); Magude-Manhiça	Qal	A1	52	1.8	5.5	17.0		400- 8000	–	Salt wedge 5 of L. Chuali
Incomati (Lower); Manhiça-mouth	Qal	A2	20	0.47	1.3	3.7		400-30000	–	Salt wedge at the mouth
Umbeluzi Well Field	Qal	A2	12	0.66	3.3	16.0		300-10000	–	Limited area with fresh water
Calcretes in Inharrime valley	Qal	A3?	7	1.7	3.7	8.0		1100- 3100	7.6-8.4	Salt enrichment

Ground water

The Mozambique Sedimentary Basin south of the Save is the best studied Hydrogeological Province of Mozambique (Table 7 and the central Map-inset). The hydrogeological characteristics are not very favourable for ground water development, except in some alluvial valleys, in the dune area and in deeper aquifers. More than half of the area has serious problems with saline ground water, especially in a central strip from the Save to the Maputo river. The high salt concentrations originate from saline formation water, semi-arid conditions and marine inundations during Pleistocene transgressions. The productivity of the consolidated aquifers and the importance of the loose cover increase coastward (see Table 12 and the Map).

The hydrogeological description of the Basin, given below, follows a division into subprovinces, based on water quality and on geological and geomorphological characteristics (Figure 7).

The **Alto Limpopo Plains** (Figure 7, unit 7a), stretching from the Rio dos Elefantes up to the Save, is dominated by low productive arkosic sandstones of the Cretaceous Sena Formation and Lower Tertiary Elefantes Formation. Conglomeratic beds and local calcarenous facies (near Combomune) form the main water bearing strata, but yields over 3 m^3/h are exceptional. The depth of the water table and very poor recharge conditions limit the groundwater development. In general, the water quality is acceptable. The mineralization increases eastward from 700 to 1300 mg/l, but can be worse around local depressions. The Banhine Depression in the centre of the plains has a thin alluvial cover with shallow groundwater, that can be brackish to saline (up to 33, 000 mg/l).

The **Alto Changane Plains** (Figure 7, unit 7b) are situated between the Alto Limpopo Plains in the west, the Urrongas in the east, the Limpopo in the south and the Save in the north. They are underlain by the continental arkosic to argillaceous sandstones of the Miocene Mazamba Formation. The productivity of the wells is moderate to low (Table 12). The less productive part is enclosed by the Changane and Limpopo rivers, where the sandstones are very clayey. A positive exception is found at the transition to the Alto Limpopo Plains, along the 32°30'E meridian. Here, wells intersect a calcarenous formation, that probably forms part of the Mangulane Formation (Table 12). This formation may form the more productive deeper aquifer below the Alto Changane Plains (Figure 13).

The Quaternary cover above the Mazamba Sandstones is generally thinly developed. It can be more pronounced in local depressions, in the Funhalouro-Mabote Graben, along the Changane river and in the Bala-Bala area between Mabalane and Changane-Maqueze. In the last area the sediments can be up to 60 m thick with moderate well yields, but with brackish to saline water.

The aquifers, underlying the Alto Changane Plains, have very saline ground water, which is major restraint for their development. The mineralization is generally over 3 000 mg/l but can be up 30 000 mg/l. Locally, the quality of the main aquifer is better, as it is along the Chigombe valley, west of Dindiza, and below the plains the Changane river and the Funhalouro-Mabote Graben.

In the early seventies, a regional geophysical survey discovered the existence of more resistant layers, that proved to represent less mineralized aquifers (Brigada de Agua Doce/DSGM 1970-73, Serafino and Garcia 1977, SELKOZPROMEXPORT 1983-84). Local shallow aquifers with fresh ground water can be found in areas with a relatively high recharge, like areas with sandy topsoils and local depressions with replenishment form surface water. They are often too small to be depicted on the Map, but form the principal source for the present rural water supply. Large fluctuations of the water table and poor recharge conditions form the main restraints for the development of these shallow aquifers.

Almost all the electrical soundings showed a deep layer with a relatively high resistivity. Four test drillings in the early eighties verified the existence of a regional fresh water aquifer at depth. The mineralization varied from 800 to 1200 mg/l (SELKOZ-PROMEXPORT 1983-84). Cross-sections, published by the Brigada de Agua Doce, show that the top of the deep fresh water aquifer varies from less than 50 m along the Limpopo, Changane and Chigombe valleys, to over 200 m in the areas west of Nalazi, north-west of Dindiza in the northern part of Funhalouro-Mabote Graben and in other subsystems of the Mazunga Graben (Ferro, Bouman 1987).

In the region between the Incomati and Save, the deeper aquifer with fresh water is generally refered to as the "Limpopo aquifer" (Table 13). North of the Limpopo it is low productive with a permeability of only 0.5 to 1.4 m/d. In this part, the renewable resources are calculated to be about 3 million m^3/yr or 360 m^3/h only (Ferro, Bouman 1987). Hence over-exploitation is a serious risk.

The Urrongas Plateau (Figure 7, unit 7c), situated in the north-east of Inhambane province, is under-

Table 13: Deeper aquifers of the Mozambique Sedimentary Basin south of the Save

WATER BEARING FORMATION		AGE	SPECIFIC YIELDS (m³/h/m)					WATER QUALITY		REMARKS
			group	N° wells	q²⁴	q¹⁰⁰	q⁴⁰⁰	0.1 0.3 1.0 5 10 100	Dry Residue (mg/l)	pH	
								CI21 ARI ARI2 AR1			
Limpopo Aq., Alto Changane	150-300 m	TTs	C2	3	(0.14 - 0.36)				800 - 1200	7.2-8.2	k=1.2-2.4 m/d
Limpopo Aq., Interfluvial Plain	80-150 m	Qal.TTs	A2	5	(0.18 - 18)				1000- 2600	7.8-8.3	k=0.8-5.4-19 m/d
Limpopo Aq., Interfluvial Plain	150-300 m	TTs	B2	7	0.56 1.6		2.6		500- 2000	7.8-8.3	k=1.1-2.4-15 m/d
Limpopo Aq., Incomati Valley	80-120 m	Qal	A1	4	(8 - 24)						Deltaic sediments
Limpopo Aq., Macia Dune area	180-300 m	TTs	C2	5	0.06 0.19		0.67		440- 1100	7.8-8.4	Prod. exception near Macia
Inhame Sands	20- 60 m	TTs	A2	14	1.8 3.8		7.9		200- 3000	6.3-7.4	Brackish at the base
Jofane Limestones, Inhamban	70-150 m	TTs	B2	13	0.67 1.6		3.9		1000- 3000	7.8-8.6	
Marracuene Limestones	30-120 m	TT	B1	10	3.9 7.6		14.8		600- 900	7.9-8.2	Karstified, Incomati Valley
Marracuene-Maputo calcarenites	<70 m	TT	B2	31	1.0 2.7		7.0		200- 800	7.9-8.2	facies change of Marr.Limest.
Matola/Machava calcarenites	<80 m	TT	B2	71	0.6 1.5		3.6				
Matola/Machava sandstones	<50 m	TT	B2	65	0.42 1.0		2.6		600- 4000		salty along valleys
Matola/Machava arg. sandstones	<200 m	TT	B3	52	0.25 0.58		1.4				
Salamanga limestones (Maciaaloe)	<80 m	TT	B2	18	0.39 1.2		3.9		750-14500		salty along Maputo valley
Maragueta aq. (marly sandstones)	120-200 m	Ks?	B3	7	(0.41 - 0.61)				1200- 5000	6.8-7.3	kD = 19-39 m²/d

lain by limestones of the Jofane Formation. These are extremely productive in a 20 km wide strip along the eastern margin of the outcrop area, where they are karstified. Westward, the productivities are comparable to the ones of the Mazamba Formation (Table 12). The ground water is brackish, especially in the centre of the Plateau. The western part is less mineralized with salt concentrations of between 1000 and 1800 mg/l. In the karstified coastal zone the mineralization is between 1000 and 3000 mg/l. Poor quality, depth to aquifer, large groundwater table fluctuations and variable productivities are the major restraints for groundwater development.

The **"denuded plains along the margins of the Libombos"** (Figure 7, unit 7d), situated between Catuane and the Rio dos Elefantes, are also underlain by mineralized aquifers. Along the Libombos, the fine textured marine Cretaceous and Lower Tertiary formations are low productive and highly mineralized. Eastward, the calcarenites and limestones of the Lower Tertiary Mangulane Formation and the Miocene Santaca Formation are much more productive (Table 12). The water quality, however is very variable, but mostly poor. Additionally, depth to groundwater table and poor recharge conditions are limiting factors for groundwater development.

The Pliocene-Quaternary deposits cover the remnants of the plateaus, but lie far above the regional-groundwater table. As an exception, the well developed cover of the plains between Magude and Boane, west of the Matola river, contains ground water, but this is highly mineralized.

The **Limpopo-Incomati Interfluvial Plain** (Figure 7, unit 7e) is developed in the Palmeira-Limpopo Graben. It is underlain by a more than 100 m thick deltaic to fluvio-lacustrine sedimentary sequence. Wells have moderate to high yields, but the sediments contain very saline formation water (Table 12). Test drillings show that the water turns less mineralized with depth (SELKOZPROMEXPORT 1983-84). An intermediate aquifer is distinguished at a depth of 80 to 180 m. It is moderately to high productive, and contains fresh to slightly brackish ground water (Table 13). The groundwater development, however, is restricted by a hydraulic connection with the upper saline aquifer.

A deep aquifer is distinguished at a depth of 180 to 300 m. It is separated from the intermediate aquifer by an up to 60 m thick clay layer. The deep aquifer is only productive in a 20 km wide NW-SE oriented strip. Just south of the Limpopo, with an average permeability of 2.4 m/d (Table 13). The median mineralization is 1000 mg/l. Productivity and quality deteriorate outside the mentioned band. The development of the intermediate and deep aquifers (Limpopo aquifer) is limited by their depth, the uncertainty about the water quality and the available renewable resources, that are calculated to be 3.5 million m^3/yr or 400 m^3/h (Ferro, Bouman 1987).

The **Dune Belt** (Figure 7, unit 7f) is developed along the entire coast south of the Save. The porous eolian sands form a regional phreatic aquifer with fresh ground water. The permeability decreases from the coast inland, as a consequence of the increase in clay content.

The narrow strip of recent dunes along the present coastline can be very productive, as the wells at Ponto do Ouro and Tofo show. But the small distance from the sea and from lagoonal inland depres-

sions, often containing brackish to saline water, is a limiting factor for groundwater extractions. Hence the recent dunes are included in Group A3, despite of the high well yields.

For the inland dunes, the Map shows a limit, separating a coastal part with yield prospects over 3 m^3/h, from an inland part with lower yield prospects. This division is supported by permeability studies, that indicate values between 4 to 8 m/d and 0.5 to 3 m/d for the respective units (IWACO 1986, SELKO-PROMEXPORT 1983).

The factors that may inhibit groundwater development include the depth to water table in steeply uprising dunes, and poor water quality, associated with local clay lenses (Homoine) or with ancient marine inundations (Matola).

The **Alluvial Valleys**, developed along the main rivers (Figure 7, unit 7g), may contain productive stratified aquifers of good quality. The central reaches of the Limpopo and Incomati have especially high-yield prospects with specific yields of up to 20 $m^3/h/m$. In the centre of the Incomati valley, between Lago Chuali and Palmeira, the good prospects are offset by the existence of highly mineralized groundwater, draining from the adjacent Interfluvial Plain (DNA 1985b). Yield prospects in the lower reaches of these main valleys are limited, whereas the mineralization increases as a consequence of ancient marine inundations or the existence of a sea-water intrusion near the river mouth.

The alluvium of the Save and the Rio dos Elefantes is relatively poorly developed, as is the alluvium in the valleys of the Changane, Matola, Movene and Tembe. The latter valleys contain brackish to saline groundwater. Better developed is the alluvium of the Maputo and Umbeluzi valleys, but the water is often saline. Geo-electrical surveys can outline local fresh aquifers,as has been done with the Umbeluzi well field, south-east of Boane.

Available groundwater resources in the alluvial aquifers should not be overestimated. As an example, the renewable resources in the central reach of the Incomati valley are estimated at 150 million m^3/yr, but only 40% can be used to avoid salinization problems (DNA 1985b).

The unconsolidated sediments in the coastal belt are frequently underlain by more productive **deeper aquifers**, indicated on the Map by violet asterisks. A summary of these aquifers is given in Table 13.

The dunes along the Inhambane coast cover the very productive limestones of the Jofane Formation, except in the area around Inharrime, where the dunes cover the low productive argillaceous sandstones of the Inharrime Formation. In most areas, the water is slightly brackish, but fresh between Homoine and Massinga.

The dunes in the Gaza province cover the coastward extension of the Limpopo Aquifer previously mentioned. In this area, however, the aquifer is unproductive, except in one well near Macia.

The lower reach of the Incomati valley and the dunes between Maputo and Manhiça cover a limestone formation, that grades westward into calcarenites, sandstones and argillaceous sandstones (respectively indicated as Marracuene limestones, Marracuene-Maputo calcarenites and Matola/Machava calcarenites, sandstones and argillaceous sandstones). The productivity of the wells is related to the lithology, as is shown in Table 13. The limestones are very productive, but have a high salinization risk.

Two other aquifers are distinguished in the Maputo area: the Maxaquene aquifer and the Infulene Sands. The first one is found at a depth of 120 to 200 m below the city. It consists of marly sandstones, interbedded in a more than 300 m thick series of marls. The productivity is low and the water is slightly brackish. The more productive Infulene Sands have a limited extent, directly west of Maputo and is exploited for the city's water supply. Good management is required in these two aquifers to avoid overexploitation.

South of the Bay of Maputo, the dunes cover limestones and calcarenites of the Salamanga Formation, that outcrops along the Maputo river. It is locally productive, but may contain saline water in the vicinity of the river.

In conclusion, the deeper aquifers in the Mozambique Sedimentary Basin south of the Save may form an alternative to solve local water problems. But water quality and poor recharge conditions may limit their exploitation.

5. GROUNDWATER DEVELOPMENT — BASIC GUIDELINES

5.1 General Observations

Future development plans indicate that groundwater use will increase from 95 million m^3/yr in 1985 to 264 million m^3/yr in the year 2000 (Table 6). New constructions have to reach a capacity of at least 200 million m^3/yr, whereas rehabilitation programmes have to be developed for a larger part of the remaining 64 million m^3/yr. The improvement of the rural water supply will add 128 million m^3/yr. Hence small scale extractions will receive major attention in future plans, although larger scale extractions and the rehabilitation of existing systems cannot be neglected, nor the maintenance of the existing and future constructions.

The Hydrogeological Map indicates the suitability for groundwater development, giving yield prospects, depth to water and water quality. Table 8 gives a summary of the groundwater development characteristics of the different Classes and Groups. Class A and B are suitable for medium to large scale extractions, on condition that the quality is good and replenishment is guaranteed. Small scale extraction can be planned in almost every area with fresh ground water, but in Class C it will be more difficult to find suitable well sites, especially in the medium and dark brown Group C2 and C3.

The Map does not give an indication about the availability of groundwater resources, as there is no accurate data about transmissivities, storage coefficients or recharge. Hence sizable extractions have to be accompanied by previous hydrogeological studies to determine the safe yield of the aquifer and to define the measures for an appropriate management.

This chapter is meant to give some basic guidelines about the different methods of groundwater exploration to assist decisions on the suitable siting of wells (section 5.2), about the choice of different means of groundwater withdrawal (section 5.3) and about the different well designs, which are suitable for use in the country (section 5.4).

5.2 Groundwater Exploration

Groundwater surveys for defining sites of boreholes or to plan new well fields may include a desk study of existing data, previous studies and maps, a field inventory of existing water resources, simple geological surveys, interpretation of aerial photographs or satellite images, geophysical surveys, test drillings and even well and aquifer tests. The complexity of terrain, distribution of aquifers, required well yield, recharge and available funds, time, personnel, equipment and know-how are important factors that determine the selection of the most appropriate survey.

It is essential to collect and study the relevant information available. The characteristics of individual boreholes are stored in the computerized Groundwater Data Base of DNA, whereas the original borehole files and drilling reports may be consulted at GEOMOC or ING. Geological maps may be consulted at ING. Published and unpublished geological maps, scale 1:250,000, exist for the whole country, except for the north-western part of Gaza. A photo-geological map of the Quaternary cover of the Sedimentary Basins, scale 1:50 000 and 1:250 000, is in preparation. Detailed soil and land classification maps of selected areas may be found at INIA. Hydrological and meteorological data may be collected from a data base at DNA. Aerial photographs and topographical maps may be ordered from DINAGECA. The whole country is covered by topographical maps, scale 1:50 000, 1:250 000 and 1:500 000, but most of them require updating.

The use of aerial photographs is essential in **unweathered hard rock areas.** In **weathered hard rock areas,** geo-electrical surveys are particularly appropriate. Together with geomagnetical surveys, they were introduced in Mozambique by GEOTECNICA E MINAS in the early sixties. Experience in the Basement Complex shows, that the use of adequate geophysical siting techniques can result in an increase of the success rate from 30 to 80% in the weathered hard-rock areas. As an example, resistivity values of less than 30 Ohm.m generally correspond to almost impermeable clayey weathering layers or layers with brackish water; values between 30 and 60 Ohm.m often correspond to the more productive sandy weathering layers with fresh water, and values over 60 Ohm.m correspond to dry sand layers or slightly weathered rocks. As a rule, zones with a weathering thickness of 30 or 40 m are considered to be suitable for the construction of boreholes, provided that the weathering layer is not completely or predominantly clayey.

In **stratified sedimentary formations** with brack-

Table 14: Legend of the map 'Carta das captações mais adaptadas . . .'

GROUNDWATER DEVELOPMENT MAP, SCALE 1:2 000 000

		REMARKS
DUG WELLS (< 20 m in unconsolidated aquifers)		
●	Area generally suitable for dug wells (70-100%)	Areas without any of the 3 respective symbols for dug wells are generally unsuitable for this means of groundwater withdrawal. Exceptions can be found in areas with suspended lenses or in narrow alluvial valleys, too small to be represented. (0-30%)
◒	Area locally suitable for dug wells (30-70%)	
◒	Area with brackish or saline water in the upper aquifer, limiting the suitability for dug wells (10-30%)	
COMMON BOREHOLES (< 100 m)		
▲	Area generally suitable for boreholes (70-100%)	Areas without any of the 3 respective symbols for common boreholes (or tube wells) are generally unsuitable for this means of groundwater withdrawal. Exceptions can be found in fracture zones and along alluvial valleys (0-30%)
◭	Area locally suitable for boreholes, or area with low yield prospects or high risk of failure (30-70%)	
△	Area with brackish or saline ground water, limiting the suitability for common boreholes (10-30%)	
DEEP BOREHOLES (> 100 m)		
▼	Area with deep aquifers of moderate to high productivity and acceptable quality	The symbol for deep boreholes (or tube wells) is only depicted on the map, if a more shallow alternative is absent. The lack of a symbol does not implicate the absence of deep aquifers
▼	Area with deep aquifers with low yield prospects or brackish water; or area in which the existence of deep aquifers is expected but not yet verified	
SPRING PROTECTION		
■	Areas with springs that can be protected	The existence of springs is unknown in many parts of the country
AREAS WITH VERY LIMITED GROUNDWATER POTENTIAL		
▨	Mountainous areas	Exceptions can be found in spring and seepage zones, fracture zones, alluvial valleys and talus slopes. Surface water and rainwater harvesting can be an alternative
▤	Area with brackish or saline ground water	Exceptions can be found in recharge areas like areas covered with sandy soils or depressions along river valleys. Rainwater harvesting can be an alternative

ish and fresh aquifers, geo-electrical soundings have proved to be very useful. Geo-electrical surveys by the Brigada de Agua Doce in the Limpopo Basin show that the saline aquifers have resistivities between 1 and 7 Ohm.m, whereas the less mineralized aquifers have resistivities of 7 to 40 Ohm.m. Interpretation of vertical electrical soundings need to be checked by existing well records, by test-wells or by geophysical borehole loggings in wells with a known stratigraphy.

Other successful **geo-electrical** surveys have been made to study the seawater intrusion near the cities Maputo and Pemba and to determine the groundwater table on the Mueda Plateau (Smidt, Lopes 1986).

The more qualitative **electromagnetic** technique has been applied around Maputo (IWACO 1986) and is suitable for the determination of the deepest parts of a loose cover above consolidated rock. The **seismic refraction** method has been recently introduced by DNA, but is commoly applied in hard rock areas in Zimbabwe.

In the past, the siting of dug wells was simply based on topographical positions. Test drilling with hand augers has been successfully introduced in Cabo Delgado by UDAAS and HELVETAS. This low-cost siting technique can easily be used to select the most favourable aquifer, preferably sealed with a clay layer. Such drillings can be made in one or two days, whereas the digging of shallow wells takes almost one month. Hence test drilling by hand may save man-power and money, especially in areas with variable conditions.

5.3 Means of Groundwater Exploitation

The most common means of groundwater withdrawal are dug wells, tube wells, spring capture and infiltration galleries. The hydrogeological parameters that determine the choice of a certain construction are the depth to groundwater table, depth to water bearing formation, thickness and extent of aquifer, maximum acceptable drawdown and the potential of the water-bearing formation.

The National Programme for Rural Water Supply, PRONAR, gives priority to the construction of **dug wells**, lined with concrete rings, protected by concrete slabs and equipped with hand pumps. Dug wells are relatively cheap and easy to construct, provided that the water-bearing formations are unconsolidated and not deeper than 15 m. In Mozambique, dug wells of 20 m depth are very exceptional. They are rarely constructed in solid rock that needs sophisticated equipment like pneumatic hammers or dynamite. In almost impermeable formations, wide diameter wells can be very useful, as the well can function as a storage reservoir.

Dug wells, equipped with hand pumps have a low productivity of about 5 to 10 m^3/day. In isolated areas and near a small group of houses, dug wells can be equipped with buckets and ropes.

In relation to boreholes, dug wells have some disadvantages. Dug wells generally have poorer sanitary conditions. Inadequate construction techniques can result in injuries to workers from cave-ins. Unsealed wells can give rise to falls. Furthermore, the period of construction is often limited to the dry season when the water table is deepest.

Tube wells have to be chosen when the water table or the water-bearing formation is deeper than 10 or 20 m or located in solid rock. They are prefered if the source has to supply over 500 persons or if a motor pump is used in combination with a water tank at the surface.

Spring protection can be a cheap and reliable alternative to well construction in areas with springs or seepage zones. It is particularly appropriate if the water can be transmitted by gravity to the site where it is required. In relation to dug wells, the construction is often more simple and the contamination risk is smaller. Spring capture can be simple if there is a single outflow point. In case of less defined seepage zones, infiltration wells or galleries have to be constructed. The most complex system is found at the Mueda Plateau.

Infiltration galleries can also be adapted to areas with subsuperficial groundwater flow, as in valleys of seasonal and semi-permanent rivers. Examples are found in the valleys of the Licuare and Monapo rivers. In areas with shallow fresh water overlying brackish water, galleries can be the only solution to avoid the deterioration of water quality. They are especially appropriate on the sandy ridges along the Zambezia and Sofala coast. An example installed by Geotecnica & Minas, is found at the prison on Xefina island.

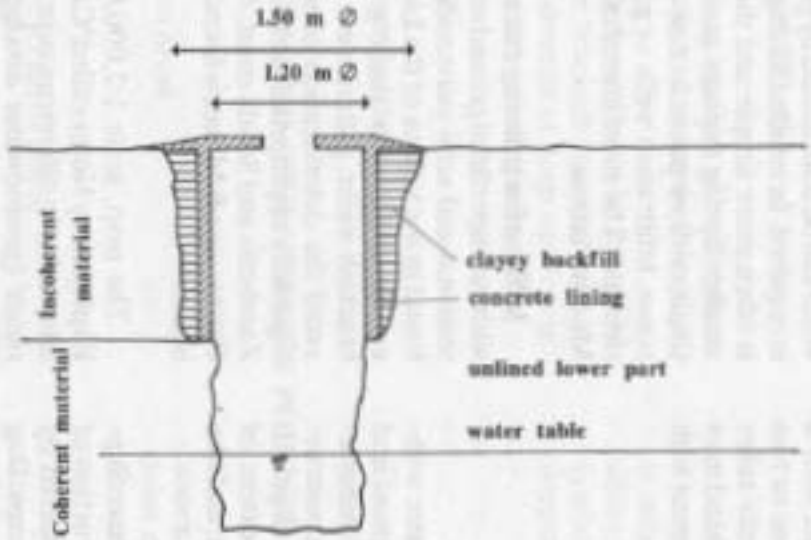
The map, scale 1:2,000,000, attached to these Explanatory Notes called 'Carta das captações mais adaptadas às diferentes ocorrências de água subterrânea' (**groundwater development map**; Table 14) gives the suitability for the construction of dug wells, boreholes or spring captures. The suitability for deep wells is only shown in the event of shallow aquifers being unfavourable.

Figure 14: Dug well designs

DUG WELL DESIGN I

IN PARTLY COHERENT MATERIAL;

SOLID ROCK, COVERED WITH WEATHERING LAYER



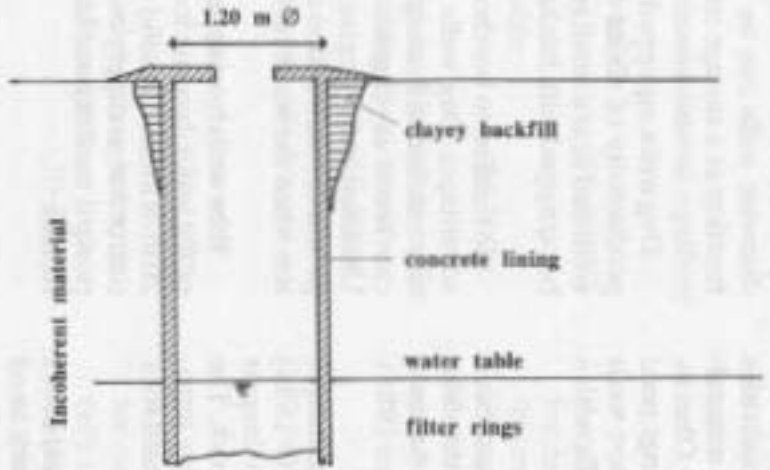
Maximum depth:
* 15 or 20 m; 3 to 4 m below water table at the end of the dry season

Diameter:
* 1.2 to 1.5 m in permeable aquifers
* up to 5 m in impermeable formations

Finishing:
* lining with concrete rings, of which the last two are filter rings (only in design II)
* concrete slab with manhole if equipped with hand pump, wind mill or motor pump. If equipped with buckets and ropes the upper ring must stand at least 0.7 m above the soil
* good drain for spilled water
* clayey backfill in first metres

DUG WELL DESIGN II

IN INCOHERENT MATERIAL



Lifting device:
* preferably a hand pump
* bucket and rope if used by a small group of people or if the well is located far from a service/maintenance centre
* motor pump (and reservoir) if more than 500 persons have to be served and fuel or electricity are available and the well is located near a service/maintenance centre
* from the sanitary point of view preference is given to an aquifer that is sealed by a clayey layer on top
* take care of polluting sources

The map can be used for the planning of future projects. Counting the population per map unit, one can make an estimate of the rural population that may be supplied by different means of groundwater withdrawal. A first calculation on national level, giving priority to the construction of dug wells, indicates that only 40% of the rural population can be supplied by dug wells and 1 or 2% by spring protection. Another 40% can rely on common tube wells, whereas for 5% deep tube wells are the only solution. For 13% one has to find an alternative solution (Bouman 1987). This type of calculations may underestimate the contribution of dug wells, as the suitability for this type of construction is very dependent on local conditions rather than the more general conditions, indicated on the map.

5.4 Well Design

Figures 14 to 17 show several examples of well designs, common in Mozambique. They can not be treated as 'standard designs', yet, but may be regarded as recommendations. Care must be taken not to copy the designs too strictly, as the hydrogeological conditions may require adaptations.

For **sanitary reasons**, it is recommended that boreholes and dug wells for domestic use are not constructed within 20 m from a road or main track, within 50 m from a latrine or corral and within 100 m from a cemetery or permanent refuse dump. For the same reason, wells have to be sealed with a concrete slab. In addition, boreholes need a cement grout along the first 5 or 10 m along the well casing and 2 m blank casing sump below the final screen.

Borehole records have to be made, containing information about the site, drilling methods, lithology etc. In order to standardize and computerize the information, a visit to DNA is advisable. Also, for dug wells, a short description of the characteristics of the well and its construction is recommended.

In boreholes, gamma-ray logging and electric logging, comprising Spontaneous Potential and the resistivity arrangements Short Normal and Long Normal, are recommended to determine the optimum location of the **filters** and the blank casing, especially if mud was used during the drilling. The diameter of the casing depends on the well yield, being at least 4" for yields up to 25 m^3/h, 6" for yields between 25 and 40 m^3/h, 8" for yields between 40 and 80 m^3/h and 10" for yields between 80 and 160 m^3/h. If the installation of a gravel pack is foreseen, the borehole diametre will be:

- for boreholes deeper than 50m or with yields higher than 3 m^3/h, at least 152mm (6") and the maximum 304 mm (12") wider than the diameter of the foreseen screens.
- for boreholes with a depth up to 50 m and a yield less than or equal to 3 m^3/h, at least 102 mm (4"), and at maximum 254 mm (10") wider than the diameter of the foreseen screens.

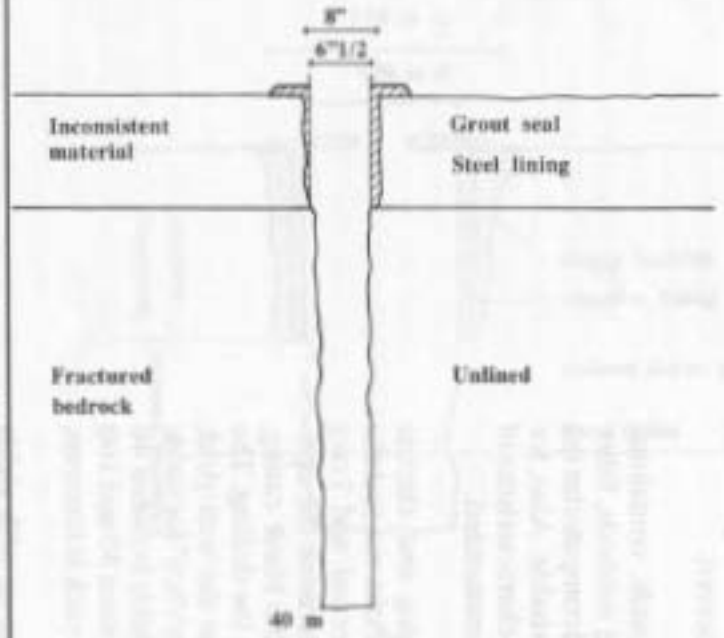
The slot-size of the screens is expressed in thousandths of an inch and depends on the grain size of the waterbearing formation.

Generally in tube-well designs, the use of PVC-casing and screens is recommended, because of their low cost and their durability (if well treated). The use of PVC is strongly recommended in areas with aggressive and brackish water. Johnson screens or other prefabricated screens of galvanized iron are recommended for tube wells with a depth greater than 120 m and in cases where the thickness of the aquifer or the dynamic water level doesn't permit the use of PVC.

Figure 15: Borehole designs in decomposed and consolidated formations of Class C (and B)

BOREHOLE DESIGN I

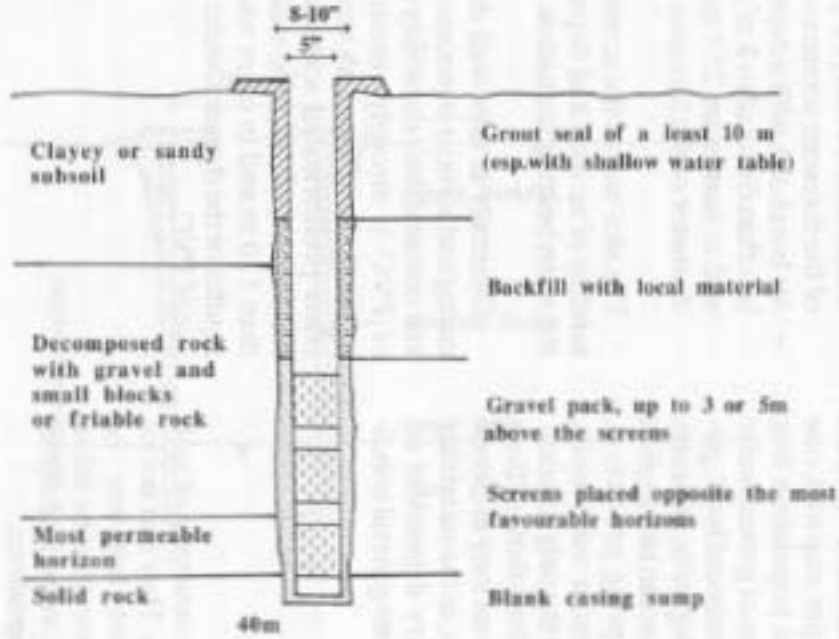
SOLID ROCK WITHOUT LOOSE MATERIAL



* Down the hole hammer rig
* Steel or PVC casing, diameter depending on drilling diameter
* Design also applicable to karstic limestones without weathering material in the fractures but diameter depending on well yield

BOREHOLE DESIGN II

WEATHERED LAYER OVER DECOMPOSED ROCK

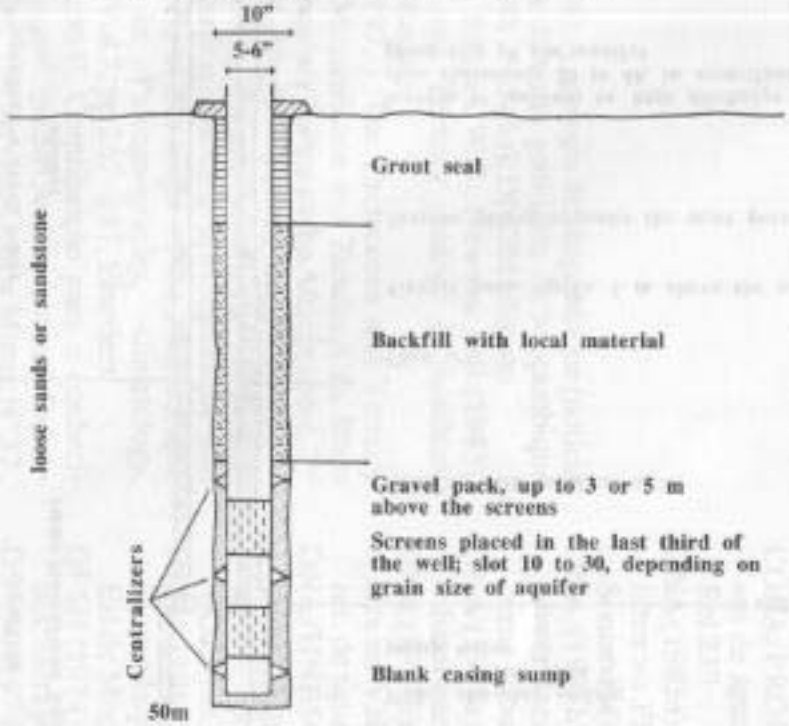


* Percussion rig
* Steel or PVC casing (5" or 4")
* Screens with discharge capacity of 1 m³/h/m, except if yield is over 6 or 10 m³/h
* Grain size of gravel pack in accordance with texture of weathered material; generally 2 or 5 mm
* Design also applicable to sedimentary rocks, but diameter depending on well yield

Figure 16: Borehole designs in unconsolidated aquifers of Class A and semi-consolidated aquifers of class B

BOREHOLE DESIGN III

MODERATELY PRODUCTIVE SANDS AND SANDSTONES (unconfined aquifers)

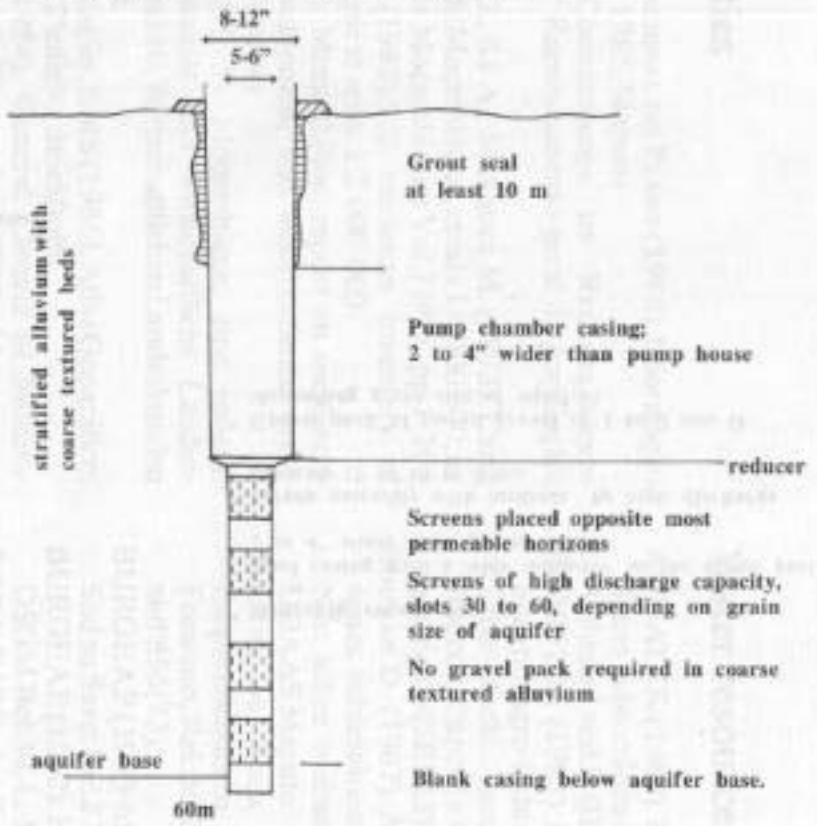


* Percussion or hydraulic rotary rig
* PVC or steel casing of 5 or 6", respectively for yields of less than 20 m³/h and 20 to 40 m³/h
* Screens with discharge capacity of 2 to 5 m³/h/m with slot 10 to 30 (depending on yield and grain size)
* Gravel pack of sieved gravel of 1 to 3 mm diameter (depending on grain size of aquifer)

BOREHOLE DESIGN IV

HIGHLY PRODUCTIVE ALLUVIUM

(unconfined to semi-confined aquifers)

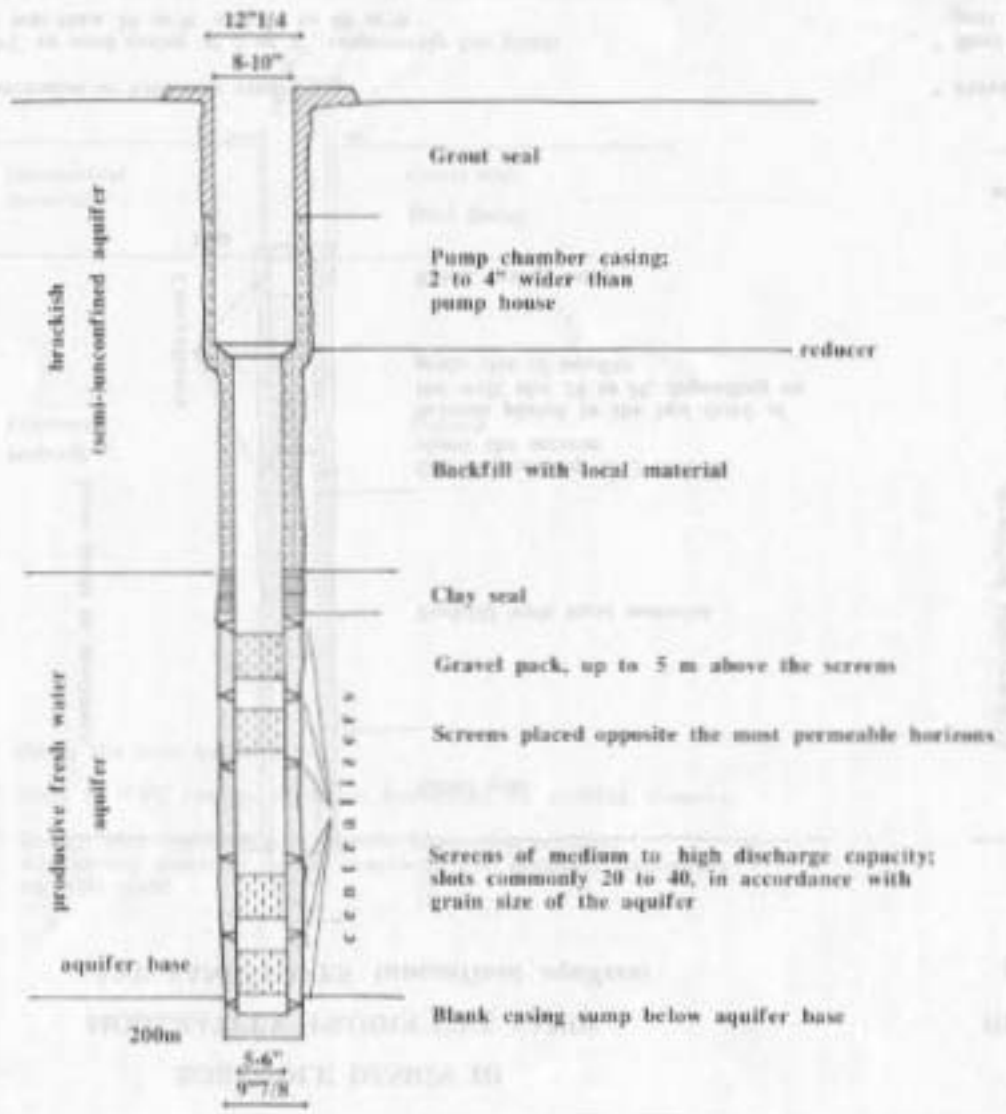


* Percussion or hydraulic rotary rig
* Steel or PVC casing with a wide diameter of 8 to 12" in upper part
* Screen with high discharge capacity (10 to 20 m3/h/m), e.g. Johnson type, specifications depending grain size of aquifer.
* Artificial gravel pack is not required in sandy alluvium without clay lenses

BOREHOLE DESIGN V

MODERATELY PRODUCTIVE (SEMI-) CONSOLIDATED SEDIMENTARY FORMATIONS WITH SHALLOW WATER TABLE (confined aquifers)

(e.g. the Limpopo Aquifer)



* Hydraulic rotary rigs.
* Steel casing with a wide diameter in the upper part, 2 to 4" wider than pump house.
* Screen assembly with medium to high discharge capacity (5 to 10 m³/h/m).
* Gravel pack of sieved gravel of 1 to 3 mm Ø (depending grain size of aquifer).

Figure 17: Borehole design in deep confined aquifer of Class B

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Annex 1
LEGEND TO THE HYDROGEOLOGICAL MAP OF MOZAMBIQUE, SCALE 1 : 1,000,000

I. GROUNDWATER OCCURRENCE

A. INTERGRANULAR AQUIFERS (CONTINUOUS, COMMONLY UNCONSOLIDATED)

permeability

generally high — A.1 Highly productive aquifers ($Q > 50\ m^3/h$)

Qal — Sandy alluvium, including gravel, silt and clay layers

medium or variable — A.2 Productive aquifers ($Q = 10 - 50\ m^3/h$)

Qal, Qr — Sandy alluvium, including gravel, silt an clay layers

low — A.3 Moderately productive aquifers ($Q = 3 - 10\ m^3/h$)

Qal, Qr — Clayey alluvium with interstratified sandy layers, locally including calcretes

Qd — Fine to medium textured sands of eolian and/or marine origin

Qc — Colluvium, associated to mountainous areas and escarpments

B. FISSURED AQUIFERS (DISCONTINUOUS AND CONSOLIDATED)

permeability

frequently high but variable — B.1 Highly productive karstified aquifers ($Q > 50\ m^3/h$)

TTi — Karstified limestones and calcarenites - Jofane Formation

peG — Partially karstified marbles of the Basement Complex; hydrogeology known in the Montepuez area only

medium or variable — B.2 Productive aquifers ($Q = 10 - 50\ m^3/h$)

TTs, TTi — Limestones and calcarenites, often with some intergranular porosity — Jofane Formation (TTs); Cheringoma Formation (TTi); Mangalane Formation (TTi); Salamanga Formation (TTi)

low — B.3 Moderately productive aquifers ($Q = 3 - 10\ m^3/h$)

TTs, TTi Ks — Limestones and calcarenites — Jofane Formation (TTs), Cheringoma Formation (TTi), Grudja Formation (TTi,Ks)

TTs Ks, Ki — Sandstones and conglomerates Mazamba Formation (TTs), Mikindani Beds (TTs), Sena Formation (Ks), Maconde Formation (Ki)

Qp/Ki — Conglomeratic sandstones — Maconde Formation (Ki), covered with Pliocene-Quaternary sands (Qp) 20-40 m thick, normally without any ground water

Rs, Ri — Coarse to medium textured sandstones, compact, foliated fine textured sandstones, marlstones, mudstones and carbonaceous shales including coal beds and diorite intrusions (Karoo)

peθ — Gabbro Anorthosite Complex of Tete

C. AREAS WITH LOCAL AQUIFERS (INTERGRANULAR OR FISSURED) OF LIMITED PRODUCTIVITY OR AREAS WITHOUT SIGNIFICANT GROUNDWATER RESOURCES

permeability

low to very low — C.1 Areas with continuous or discontinuous local aquifers of limited productivity (generally $Q < 5\ m^3/h$). On the Basement Complex the groundwater occurrence is related to the weathering mantle or to fracture zones (medium weathering thickness 20-50 m)

Qal, Qr — Clayey alluvium including sand layers

Qd — Loamy silty to medium textured sands of eolian and/or marine origin

Qp — Loose, fine textured clayey sands or sandy clays over sedimentary rocks

Qli, Qr — Eluvial cover over extrusive rocks

Qpe — Eluvial cover over crystalline rocks of the Basement Complex

very low — C.2 Areas with limited groundwater occurrence (generally $Q < 3\ m^3/h$). On the Basement Complex the existence of outcrops and a poorly developed weathering mantle are limiting factors for groundwater occurrence (weathering thickness generally less than 20 m). Positive exceptions can be found in fault zones and alluvial valleys.

TTi, Ks — Sandstones and conglomerates - Elefantes Formation (TTi) Sena Formation (Ks)

TTi, Ks, Ki — Glauconitic sandstones, marlstones, calcarenites and claystones - Grudja Formation (Ks),and marlstones, marly limestones and siltstones of the Rovuma Basin (TTi, Ks, Ki)

JKα,JKβ — Extrusive rocks: rhyolites (α), basalts (β)

Rs, Ri — Compact schistose sandstones, marlstones, mudstones and carbonaceous shales, including coal beds and diorite intrusions

peU — Slates, schists, quartzites and carbonate rocks of the Umkondo Formation and quartzites, micaschists and schistose gneisses of the Fronteira Formation

peG — Crystalline rocks of the Gneiss Migmatite Complex, including metasediments, charnockites and granites

peZ — Green schists, serpentinites, banded quartzites, conglomerates, grauwackes and the Granite Gneiss Complex of the Zimbabwe Craton

very low to zero — C.3 Mountainous areas without a significant weathering mantle and almost without any groundwater resources (generally Q < 1 m³/h). Ground water frequently appears in spring zones. More productive exceptions can be found along fault zones and talus slopes.

Ka, Ky, Kθ — Intrusive rocks: syenites (*a*), granites and similar rocks (*y*) gabbros and similar rocks (*θ*)

JKτ, JKρ, JKβ — Extrusive rocks: phonolites, trachytes and similar rocks (*τ*) rhyolites (*ρ*) and basalts (*B*)

Rs — Compact siliceous sandstones of the Upper Karoo and the Carumacufac sandstones

peU — Slates, schists, quartzites and carbonate rocks of the Umkondo Formation and quartzites, micaschists and schistose gneisses of the Fronteira Formation

peθ — Diorites, gabbros and anorthosites of the Gabbro-anorthositic Complex of Tete

peG — Crystalline rocks of the Gneiss Migmatite Complex, including metasediments, charnockites and granites

peZ — Green schists, serpentinites, banded quartzites, conglomerates, graywackes and the Granite Gneiss Complex of the Zimbabwe Craton

LITHOSTRATIGRAPHIC INDICATIONS ON THE MAP

Qal, Qt	Quarternary: Recent alluvium and terraces
Qc	Quarternary: Colluvium
Qd	Quarternary: Coastal dunes, inland dunes and marine sands
Qp	Quarternary: Eluvium; weathering products of sedimentary rocks (clayey-sand and sandy-clay plains)
Qo, Q8	Quarternary: Eluvium; weathering products of volcanic rocks
Qpe	Quarternary: Eluvium; weathering products of the crystalline rocks of the Basement Complex
TTs	Upper Tertiary: sedimentary
TTi	Lower Tertiary: sedimentary
Ks	Upper Cretaceous: sedimentary
Ki	Lower Cretaceous: sedimentary
Ka, Ky, Kθ	Lower Cretaceous: igneous
JKp, JKß, JKτ	Cretaceous and Jurassic: volcanic
Rs	Upper Karoo: sedimentary
Ri	Lower Karoo: sedimentary
peU	Upper Precambrian: metasediments
peG	Upper to Middle Precambrian: igneous-metamorphic
peθ	Upper to Middle Precambrian: igneous Gabbro Anorthosite Complex of Tete
peZ	Lower Precambrian: igneous-metamorphic

II. TOPOGRAPHY (grey)

- Capital of the country
- Province capital
- District centre
- Local centre
- Tarred road
- Projected tarred road
- Earth or gravel road of regional importance
- Railway
- Prominent power line: a-existing b-projected
- International boundary
- 753 Summit with altitude in metres

III. GEOLOGY (black)

- Geological boundary
- Important fault or lineament
- Foliation in the Basement Complex
- Dike intrusion
- Volcanic neck
- Mine or quarry
- Oil test well

Qal 15 / TTs 60 / Ks 320 / JKβ >80 — Representative stratigraphic column (lithostratigraphic unit at the left side and formation thickness at the right side).

The represented lithostratigraphical units in the columns generally have the same symbols as the hydrogeological Units with the following additions:

- Completely weathered layer (Qpe, Q8)
- Calcretes (Q)
- Claystones and mudstones (TTs, TTi, Ks, Ki)
- Evaporites (TTi)

A— —A' Hydrogeological cross section

IV. SURFACE WATER (blue)

- Perennial stream
- Seasonal stream
- Ephemeral stream
- Marsh or swamp
- Lake

V. GROUND WATER (violet)

- Spring
- (Ground) water divide
- 20 — Line of equal depth to the groundwater table in metres (if known); this is not equivalent to the depth of the aquifer
- Direction of groundwater flow
- Direction of deep groundwater flow
- Boundary of area with artesian conditions
- Deep regional aquifer

VI. WATER QUALITY (orange)

- Thermal and/or mineral spring
- 1500 — Line of equal dissolved solids content (Dry Residue) in mg/l
- Well with salty water (DR > 3000 mg/l)
- Lake with salty water (DR > 3000 mg/l)
- Marine flood area, commonly with mangrove
- Areas with brackish to salty ground water (DR > 1500 mg/l); exceptions may occur in small pockets of fresh ground water
- Areas with brackish to salty ground water (DR > 1500 mg/l) over fresh ground water
- Areas with fresh ground water over brackish to salty ground water (DR > 1500 mg/l)
- Areas with local occurrence of brackish to salty ground water (DR > 1500 mg/l)

VII. CONSTRUCTION AND WORKS (red)

- Shallow hand dug well
- Ks — Well with indication of penetrated formation and yields (m^3/h):
  ◇ not known; ◈ 0-3 m^3/h; ◈ 3-10 m^3/h; ◈ 10-50 m^3/h
  ◆ > 50 m^3/h
- 12 — Well field with abstraction capacity (10^3 m^3/day)
- Protected spring
- Dam and reservoir with maximum storage capacity (10^6 m^3)
- Proposed dam site and future limit of reservoir
- 50.000 / 108 — Hydrometrical information: upper part: area of the catchment in km^2; lower part: average annual run-off in m^3/s

REMARKS

The hydrogeological units, represented on the Map, generally refer to the upper geological strata, which are not necessarily the most productive ones. Only when the upper layer is very thin and situated above the groundwater table, the second layer is represented. This frequently happens to the thin eluvial covers. In the case of the Mueda Plateau two superimposed Units (Qp and Ki) are represented: the light green shading, corresponding to the most important deeper aquifer (Ki) and the light brown vertical stripes, indicating the existence of an upper layer of considerable thickness (Qp) but normally without groundwater. Where little productive or highly mineralized aquifers are underlain by more productive or less mineralized aquifers of regional importance, the last ones are represented by violet asterisks (*). The hydrogeological Units are characterized by the type of porosity and by their productivity; the latter being defined as the medium yield with a standard drawndown of 10 metres. In the areas with aquifers of limited productivity caution must be taken with the daily pumping time, which may not exceed the limit of 8 hours.

THIS HYDROGEOLOGICAL MAP HAS BEEN DEVELOPED BY THE NATIONAL DIRECTORATE FOR WATER AFFAIRS (D.N.A.) WITH UNICEF SUPPORT; THE LEGEND IS IN ACCORDANCE WITH THE UNESCO INTERNATIONAL LEGEND FOR HYDROGEOLOGICAL MAPS

Conformal Conical Projection of Lambert

Topographical base: Geological Map of ING 1:1,000,000 (in prep.); Operational Navigation Charts, N-5 (1976), P- 5 (1981) and Q-5 (1983), of D.M.A.A.C. 1:1,000,000; Atlas of Mozambique 1:1,000,000 of the Land Survey Department (1960); Road Map of Mozambique 1:2,000,000 of D.N.T.C. (1983); Hydrological Basin Map 1:2,000,000 of the Hydraulic Department (1972) and topographical maps 1:250,000.

Geological base : Interpretation of satellite images by the authors (1:250,000); Geological map 1:1,000,000 of ING (in prep.); Geological map 1:2,000,000 of DSGM (1976, 2nd edition); Lithological map 1:1,000,000 of ING (1983); Geological maps, edited and not-edited, by DNGM, IHG, Hunting Geology and Geophysics Ltd and BRGM.

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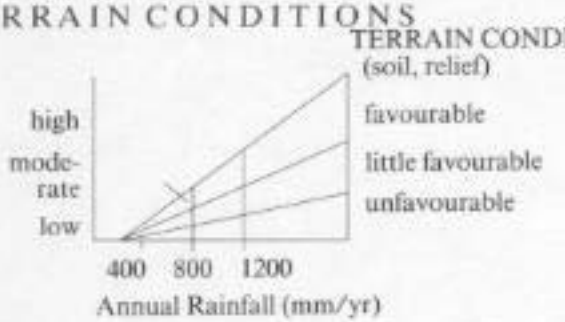
MAP INSETS

Left Map Inset: *INDICADORES DA RECARGA/RECHARGE INDEX*

RAINFALL

~1000~ Isohyetes of the average annual rainfall (mm/yr)

TERRAIN CONDITIONS



Middle Map Inset: *DISTRBUIÇÃO DE FUROS COM DADOS/CONSULTED BOREHOLES*

INFORMATION DENSITY

Number of boreholes per map sheet 1:50 000 (15'×15')	Qualification of information
0	Zero
1 and 2	Nihil
2 - 5	Moderate
6 - 10	Reasonable
11 - 20	Good
> 20	Very good

All the consulted boreholes could be localized and have information about well yield, water quality and/or lithology

Right Map Inset: *ABASTECIMENTO DE ÁGUA/TYPE OF WATER SUPPLY*

WATER SUPPLY SYSTEMS

- Water supply systems in cities with more than 20 000 inhabitants
- Existing systems in other cities, towns and villages
- ○ Distribution system of the Mueda Plateau

RURAL WATER SUPPLY

- 0- 24% ground water
- 25- 49% ground water
- 50- 74% ground water
- 75-100% ground water

The percentage indicates the part of the rural population per district that answered during the census of 1980 to use ground water as the principal source