REVIEW OF HYDROGEOLOGY AND GROUNDWATER RESOURCE STUDIES IN THE SUDAN (WITH BIBLIOGRAPHY)

by

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ERRATA

Pg 2, sect. 1.1.4		line 13	for "removable" read "controlled"
		line 18	for "publication, DECARP (1976)" read "1976) publication, DECARP." This ref. is listed under Sudan Govt/UN.
Pg 4, sect 1.3		line 6	for "Nuwaba" read "Ruwaba"
Pg 5, sect 2.1		line 7 & 8	for "the Red Sea Hills formed the margin of a tectonic plate of that time" read "the Red Sea Hills once formed the margin of a tectonic plate".
Pg 6, sect 2.3.1		line 3	insert closing bracket after "Intercalary".
Pg 14		line 2	for "which soon evaporate" read "and soon evaporates".
Pg 17		line 5	for "higher maximum limits of dissolved solids" read "higher maximum limits of dissolved solids compared to International and European Standards".
		line 7 & 8	for "standards and sulphates" read "standards. Sulphates".
		line 8 & 9	for "nitrates are often as high" read "nitrates are often high".
Pg 18		line 13	for "water" read "the water supply".
	par 2	line 1 & 3	for "Basin" read "Basins".
Pg 20 sect 3.2		line 8	for "elastic" read "clastic", for "knors" read "khors".
Pg 22	par 1	line 3	for "Shell (1965)" read "by Shell-BP (Wedmann, et al., 1965)".
	par 2	line 3	for "25 $m^3/d/m$" read "25 $m^3/d/m$ to 30 $m^3/d/m$".
		line 4	for "IOH (1978)" read "IOH (1978 c)".
	par 5	line 2	for "IOH (1978)" read "IOH (1978 c)".
		line 6	insert "This estimate of recharge is based on a highly empirical value for the specific yield of the upper part of the aquifer".
Pg 23		line 4	for "cannot" read "probably cannot".
Pg 24 sect 3.2.2.1		line 8	for "Geol. Surv. Dept. Sudan)" read "(Geological and Mineral Resources Dept. 1977)".
		line 11	add "Unfortunately the project report had not been completed at the time of writing and the results can therefore not be given here."

Pg 25	sect 3.2.2.6	par 1	line 6	for "support this area" read "support the agriculture in this area".
Pg 26	sect 3.2.2.7	par 1	line 3	for "extreme" read "extremely good".
Pg 27	sect 3.2.3.1		line 1	for "El Tayeb (1969,1972)" read "Saeed (1969 b, 1972)".
	sect 3.2.3.4		line 2	for "(El Tayeb, 1969)" read "(Saeed, 1969 b)".
Pg 28	sect 3.2.3.6	par 1	line 1	for "Groundater" read "Groundwater".
		par 2	line 1	for "El Tayeb (1969)" read "Saeed (1969 b)".
Pg 29		par 1	line 3	for "El Tayeb" read "Saeed".
	sect 3.2.4	par 1	line 3	for "Hable" read "Habl".
		par 2	line 4	for "runoff" read "runoff and".
Pg 31			line 3	for "transmissibility" read "transmissivity".
Pg 33	sect 3.2.8.1		line 4	for "from seismic profile" read "than those computed from seismic profiles".
	sect 3.2.8.2		line 5	for "conductivity ratio" read "ratio of hydraulic conductivity".
Pg 35		par 3	line 14	for "is" read "it".
Pg 37	sect 3.3.1		line 6	for "sandstone" read "Sandstone"
	sect 3.3.1.2	par 2	line 2	for "sandstone" read "Sandstone"
Pg 38	sect 3.3.1.3		line 8	for "(1967)" read "(1976)"
	sect 3.3.1.4		line 7	for "Basins" read "basins"
	sect 3.3.1.5		line 7	for "sandstone" read "Sandstone"
	sect 3.3.1.7		line 4	for "sandstone" read "Sandstone"
Pg 40	sect 3.3.2.2		line 11	for "sandstone" read "Sandstone"
	sect 3.3.2.3		line 10	for "appear" read "appears"
Pg 41	sect 3.3.2.6		line 4	for "sandstone" read "Sandstone"
Pg 42		par 1	line 7	for "sandstone" read "Sandstone"
Pg 43	sect 3.3.3.1		line 6	for "sandstone" read "Sandstone"
Pg 46			line 4	for "forseable" read "foreseeable"
Pg 47			line 2	for "less" read "shallower"
Pg 48	sect 3.3.4.6	par 1	line 6	insert opening bracket before "Hunting", delete opening bracket before "1976".
Pg 50			line 2	delete closing bracket after "1974".
			line 3	for "1978 c" read "1978 a".
Pg 51	sect 3.3.5.4	par 1	line 4	for "1978 c" read "1978 a".
Pg 55		par 2	line 3	for "flow, there" read "flow. There"
Pg 57			line 2	for "for well abstraction" read "for abstraction".

Pg 64		par 1	line 5	for "1978" read "1978 a".
Pg 65	sect 3.3.8.6	par 2	line 16	for "recharge" read "recharged"
Pg 66		par 3	line 3	for "1978" read "1978 a"
		par 4	line 3	for "recharge" read "recharged"
Pg 67		par 2	line 4	for "1978" read "1978 b"
		par 3	line 9	for "metres" read "meters"
	sect 3.3.9		line 4	for "taken to" read "taken as"
Pg 68	sect 3.3.9.1	par 1	line 5	for "project early early" read "project early".
	sect 3.3.9.2	par 2	line 3	for "level" read "levels"
Pg 72		par 1	line 8	for "enriched in isotopes" read "enriched in stable heavy isotopes"
Pg 74	sect 3.3.10.2	par 1	line 2	for "Atbara, Nile" read "Atbara and Nile"
		par 2	line 1	for "Permeanent" read "Permanent"
			line 3	for "deep" read "below surface"
Pg 76	sect 3.3.11.1		line 6	for "Wadi" read "Wad"
Pg 80	sect 3.3.12.3	par 1	line 4	for "directions, the" read "directions. The"
Pg 82	sect 3.3.12.6	par 3	line 5	for "have" read "has"
Pg 83		par 1	line 6	for "well" read "wells"
Pg 87	sect vii a)		line 1 & 2	for "programmes underway" read "pro-grammes underway"
Pg 89		par 2	line 2	for "department" read "departments"
Pg 90			line 2	delete "its"
Pg 92	10th Ref			for "Salicify Changes" read "Salinity Changes"
Pg 97	4th Ref			for "El Sheiich" read "El Sheikh"
Pg 109	10th Ref			for "post 1975" read "1976"

CONTENTS

PREFACE

This desk study was undertaken to review the available literature on groundwater resources in Sudan and to discuss related development options. In view of the number of groundwater studies planned and underway it must be expected that this work will soon be out of date but hopefully it will be of value to the government of Sudan and other organisations in improving groundwater policy and locating new projects.

Computer searches were used at the outset according to the system described by Grey (1978) : Techsearch, Geoarchive and Georef all provided valuable references. Several British consulting companies and government organisations which had carried out groundwater resource studies gave access to their reports. The author spent 11 days in Sudan meeting representatives of government departments and foreign aid organisations who were also extremely helpful in providing information.

Due to the large amount of literature available, efforts were concentrated on post-1970 work and due to the number of projects planned and government reorganisation, the treatment of groundwater management and development options is more restricted than originally envisaged.

I am much indebted to many people, too numerous to mention individually, both in Britain and Sudan for their assistance in preparation of this report.

1. INTRODUCTION

The Democratic Republic of the Sudan is one of the largest countries in the African continent. It is located between latitudes 6^o and 22^o N and longitudes 22^o and 38^o E, covering an area of almost 2,500,000 km^2

1.1 Climate.

The climate of Sudan is determined by its position between the Equator and the Tropic of Cancer, and varies from hot, tropical, continental in the south to hot desert in the north according to Miller's (1947) classification.

1.1.1 Rainfall (Figure 1)

Rainfall generally occurs between May and October and is brought by southwesterly winds which follow the northward movement of the inter-tropical convergence zone (ITCZ). During the second part of the year rains cease as the ITCZ moves southwards again, the accompanying northeasterly winds being dry. In the south of the country the climate is humid with an average annual rainfall often more than 1,000 mm. The length of the wet season and total rainfall decrease with latitude: in South Kordofan the long term annual averages are 150 rainy days and rainfall of 850 mm while in North Kordofan there are 120 rainy days and 450 mm of rain. The ITCZ reaches about 18^oN which determines the effective limit of rainfall: north of this only occasional desert storms occur. The variability of rainfall from year to year increases with latitude due to fluctuations in the limit reached by the ITCZ, and the predictability of rainfall north of the 400 mm isohyet is poor.

A secondary source of rainfall, from winds circulating the anticyclone over the Arabian peninsula, affects the eastern part of the Red Sea Hills during October to December. Rain from the southwest monsoon generally falls in afternoon storms of 2 to 3 days duration while rain from the Red Sea usually occurs in early morning storms. The southwest winds in summer are often strong, causing intense dust storms (Haboob) and low visibility.

1.1.2 Temperature

Temperatures are high, with a mean daily winter temperature of 16°C in the north and 29°C for the south. The maximum is reached in late spring or early summer before the rains start, and a second peak occurs after the rains. At Khartoum it is often 47°C during the hot season. The diurnal fluctuation of temperature increases with aridity and in the desert often reaches 22°C.

1.1.3 Evaporation

Potential evapotranspiration is everywhere more than 1,000 mm, and over 2,000 mm in the north. On an annual basis it greatly exceeds rainfall, but on a monthly basis it may occasionally be less than rainfall.

1.1.4 Desertification

South of the true desert, the savannah belt between latitudes 12°N and 18°N is highly sensitive to minor changes in climate and land use. Droughts often occur when the ITCZ does not reach as far north as usual and the effects on vegetation are exacerbated by over-grazing and burning. Rainfall of 300 mm to 400 mm is generally thought necessary for stabilisation of sand-dunes, but since the early 1960's there have been many consecutive years of lower than average rainfall: between 1965 and 1974 it was 10% less than the average for the previous 30 years with a southward shift of isohyets by 75 to 100 km (Adams and Hales, 1977). This caused more pressure on restricted grazing land, and although rainfall has been recovering in recent years the degradation of pasture and mobilisation of sand-dunes are not easily controlled. Tinker (1977) stated that desert conditions were advancing southwards at the rate of 5 to 10 km a year, due as much to poor land management as to the drier climate. The processes involved in desertification, and steps proposed to halt it and restabilise the dunes are set out in the Sudan Government/UN (1976) publication, DECARP. This ref. is listed under Sudan Govt. UN.

1.1.5 Past Climates

Although the recent drought has brought much suffering, particularly to nomads in the savannah belt, it was by no means a rare occurrence. Droughts have frequently happened in the past, and cycles of 7 to 8 years and 30 to 100 years have been noted. Quaternary studies (e.g. Grove and Warren, 1968; Street and Grove, 1976) indicate that the present is a period of slowing increasing aridity with increasingly restricted humid interruptions.

During the last 2,000 years humid periods occurred in 1950-1965, 1870-1895 and before that at intervals of about every 100 years. Ferguson (1970) quotes evidence from early explorers that 400 years ago the area south of Khartoum was well wooded resulting in a temperature some 5^{o}C lower than present. Another important period of high runoff occurred between 3,500 and 3,000 BP. Street and Grove have presented a generalised sequence of climatic events from 21,000 BP to the present day as summarised below:

(a) Apart from geological evidence, little is known about climatic fluctuations before 21,000 BP. Dating of groundwater however indicates an important humid and more temperate period around 30,000 to 20,000 BP.

(b) 21,000 to 12,500 BP: greater and more widespread aridity than at present with rainfall possibly only 20% of that of today. The most intense arid conditions were experienced from about 18,000 BP corresponding to glacial conditions in higher latitudes. The seasonal migration of the ITCZ was much reduced and the desert limit was 450 km further south.

(c) 12,500 to 10,000 BP: increasing humidity corresponding to late glacial conditions. Restoration of vegetation with lowland forest species about 300 km north of their present limits.

(d) 10,000 to 5,000 BP: highest recorded lake levels indicating a rainfall 200% to 400% higher to those of today corresponding to interglacial conditions. The increase in rainfall coincided with the onset of warming of the western Indian ocean at ca. 10,000 BP.

e) 5,000 BP to present: decline from full interglacial conditions.

1.2 Physiography.

The physiography of Sudan is described in Vail (1978).

The country as a whole consists of a planated surface dropping gradually from 800 m above sea level in the far south and west to 300 m above sea level in the north along the Egyptian border. Inselbergs of harder rocks form the most striking feature of the scenery and sand dunes also provide some topographical relief in the north. Except in the north the plain is bound by higher land often reaching more than 3,000 m above sea level.

In the far west there is some surface drainage westwards into Chad and in the east to the Red Sea, but most of the country forms part of the Nile drainage system. The evolution of the Nile, which originally consisted of several separate rivers which have only relatively recently joined up, and its terraces are described in Rzoska (1976).

Apart from the Nile and its major tributaries, the While and Blue Niles, surface flow in streams is largely seasonal, the duration of flow depending mainly on the length of the rainy season, amount of rainfall and size of catchment. Most of the major streams such as the Atbara River flow for 4 months of the year, but the Bahr el Arab in the west sometimes continues into December.

1.3 Vegetation and Soils.

The 'natural' vegetation of Sudan ranges from desert north of 18^{O}N through acacia desert grass and scrub to savannah of mainly acacia trees. Soils are generally clayey over the south of the country and along the rivers and sandy in the north. The sandy soils are mainly derived from the Nubian Sandstone Formation while clay soils are derived from the finer grained Umm Ruwaba Formation, the Basement Complex and alluvium from river floods. Due to the flatness of the country large areas are inundated in the summer by waters from the White Nile.

2. GEOLOGY

Due to the vast amount of literature, including two recent and fairly comprehensive publications (Whiteman,1971; Vail, 1978), only a brief summary of the geology of Sudan is given here.

The stratigraphic column (Table 1) is relatively simple owing to the absence or limited preservation of Phanerozoic deposits. A generalised map of the more extensive formations is shown in Figure 2). The availability of geological maps is listed in Vail (1978): mapping at the scale of 1 : 250,000 by the Geological Survey Department is nearing completion. Also in Vail's work is a photogeological map at the scale of 1 : 2 M which shows the distribution of superficial deposits. Due to the vast size and flatness of the country and extensive cover of superficial deposits outcrops are few and the contacts between different formations obscured: geological mapping and interpretation have therefore relied heavily upon the use of aerial photographs, borehole logs and geophysical surveys. The lack of fossils in the sedimentary formations has also made identification and subdivision of formations a formidable task.

2.1 Basment Complex.

This comprises the oldest and most widespread groups of rocks, is mainly PreCambrian and consists mainly of schists and gneisses. Marbles, pelites and quartzites also occur but are of limited extent. The group also includes granitic emplacements, basic and ultrabasic bodies and some younger intrusives such as ring structures and dyke swarms. Basalts, rhyolites and andesites form younger units of the Basement Complex in eastern Sudan, implying that the Red Sea Hills once formed the margin of a tectonic plate. Structural features are described by Whiteman (1971). The whole complex underwent several periods of pediplanation lasting until Carboniferous or Jurassic time, and several periods of faulting. The general slope of the surface, disregarding undulations, is about 10 to 20 m/km in a northerly direction.

2.2 Palaeozoic Formations.

2.2.1 Cambro-Ordovician Sandstones

In the far northwest of the country on the border with Libya and Chad, Cambro-Ordovician sandstones are found overlying the Basement Complex with marked unconformity.

2.2.2 Nawa Formation

The Nawa Formation has been preserved in a few localities near Nawa village (approx. 30°E; 12°N) in down-faulted blocks in the Basement Complex. No fossils have been found, and the sediments are therefore considered to be of undifferentiated Palaeozoic-Mesozoic age. They consist of well compacted purple-green mudstones and arkosic grits, containing much fresh detrital mica, feldspar and thin limestones. Due to the cover of superficial deposits the formation is only known from boreholes and geophysical surveys: the greatest known thickness is about 285 m.

2.3 Mesozoic Formations.

2.3.1 Nubian Sandstone Formation

Of the Mesozoic formations, the Nubian Sandstone Formation is by far the most significant: it covers a third of the country and is also extensive in Chad (Continental Intercalary), Egypt and Libya. Henceforth the term "Sandstone" refers to the whole formation while "sandstone" is purely for lithological description.

Identification depends largely on lithology due to the lack of diagnostic fossils or marked beds. The sequence is mainly Cretaceous in age and probably covers a wide time range. In Sudan the lithology is dominated by arenaceous and rudaceous beds although mudstones and siltstones are not uncommon. Evaporites and lignite are rare. Most commonly it consists of a poorly sorted, coarse-to-medium-grained, cream or brown sandstone containing quartz pebbels and mudstones. The main minerals are quartz and feldspar. Cross bedding is common but graded bedding is only sometimes present. In some areas the sandstone is highly silicified. Poorly sorted quartz conglomerates a few metres thick also occur, usually near the base, but they rarely contain material from the underlying Basement. Mudstones and clays may form thick lenses: they are usually thinly bedded, purple, white or cream in colour. In all these lithologies very rapid facies changes occur. Dips are usually sub-horizontal. Fossils are rare except for silicified wood (Dadoxylon) fragments which are common locally. The sequence was deposited fairly rapidly in sub-aqueous, continental, changing facies conditions, probably in braided river systems debouching into delta fans across flood plains.

2.3.2 Yirol Formation

The Yirol Formation occurs as a number of isolated outliers near the village of Yirol (31°E; 7°N) and is thought to be the southernmost extension of the Nubian Sandstone Formation due to the similar lithology.

2.3.3 Gedaref Formation

The Gedaref Formation is also similar in lithology to the Nubian Sandstone and may be equivalent in age. It is located in the east of the country near the Ethiopian border and is exposed in places along the Atbara River valley but elsewhere is generally covered by basalts or clays.

The Nubian and allied formations reach their greatest thickness in fault bounded basins: faulting was active along structural weaknesses in the Basement and continued throughout deposition during the Cretaceous and early Tertiary. However the Nubian is also found in pediment areas around some of the major basins and also as isolated outliers away from the basins, indicating its former wide extent.

2.4 Tertiary Formations.

2.4.1 Coastal Deposits of the Red Sea

The coastal deposits of the Red Sea overlie Basement gneisses and thicken seawards, possibly in a series of step faults. They range from Cretaceous to Recent in age but Tertiary sediments are the most extensive. A number of formations have been recognised, most of which are separated by unconformities:

(a) Mukkawar Formation: Upper Cretaceous to Palaeocene; this consists of 200 m of shales, fine sandstones, marls and limestones.

(b) Hamamit Formation: Eocene to Middle Miocene; 225 m of coarse sandstones with conglomerates.

(c) Maghersum Formation: probably Middle Miocene; this formation has been identified on Mukawwar Island. It consists of 465 m of massive rock salt, anhydrite and silty marls followed by 860 m of gypsum and anhydrite interbedded with sandstones and sandy shales. The upper 100 m includes marls, sandstones and conglomerates with some limestone.

(d) Abu Imama Formation: Middle Miocene; this formation is 150 m thick and consists of conglomerates with a sandy or marly matrix which give way upwards to calcarenites, marly limestones and reef limestones.

(e) Dunganab Formation: post Middle Miocene; this formation is known north of Port Sudan where it consists of gypsum and clays beneath massive rock salt and anhydrite layers. The sequence reaches 700 m in thickness.

(f) Abu Shagara Formation and Raised Beach Complex: Pleistocene-Recent; marine and continental deposits overlie the Tertiary formations and include several hundred metres of gravels, boulder beds, coarse sands and reef limestones.

The continental facies includes the Tokar Delta and other smaller fans and deltas formed where wadis debouch onto the plain.

2.4.2 Hudi Chert Formation

The Hudi Chert Formation is also probably of Tertiary age. It consists of fossiliferous cherts which have been weathered at the surface to large boulders. It is found overlying the Nubian Sandstone Formation at several localities, usually close to the Nile and its tributary, the Atbara River. The chert is thought to have been formed by silification of lacustrine deposits associated with the proto-Nile drainage, while local volcanic activity might have provided the source of silica.

2.4.3 Tertiary Volcanics

Igneous activity in Sudan has extended from earliest Pre-Cambrian times to the present day, but the extensive volcanic terrains found in some areas are related to intensive activity which started in the Late Cretaceous and continued into the Quaternary.

The two main fields occur in the west, in Darfur Province forming the Jebel Marra and the Meidab and Tagabo Hills. Here basalt and trachyte flows and plugs, agglomerate, tuff, ignimbrite, pumic layers, cinder cones and dykes are all well developed. Hot springs and fumaroles testify to recent but dormant activity. Alighments of the volcanic features in this region show that Jebel Marra is at the centre of regional fracture patterns: one extends SSE from northern Libya to the East African volcanic fields along the Kenya-Uganda border; a second is aligned NNE from the Gulf of Guinea across the Tagabo and Meidab Hills and along Wadi el Hilk to the coast; a third alignment may exist from Jebel Marra NE to the Eastern Desert of Egypt.

Another main volcanic field is found in the east where the plateau type basalts have extended westwards from Ethiopia: around Gedaref 200 m of basalts overlies the Gedaref Formation and in the Gash Delta, north of Kassala, 160 m of basalts are found below alluvial deposits.

In several other areas basalts intrude the Nubian Sandstone Formation and the marine Tertiary beds of the coastal deposits.

2.4.4 Laterites and Ironstones

In many places, ironstones and laterites cap planated Basement Complex rocks and outliers of Nubian Sandstone. In some sedimentary basins they have been located at the unconformity with the overlying Umm Ruwaba Formation.

2.5 Quaternary Formations.

2.5.1 Umm Ruwaba and Related Formations

Much of central and southern Sudan is overlain by unconsolidated continental sands, sandy clays and clays which overlie both Basement rocks and the Nubian Sandstone Formation unconformably. The sediments vary considerably in lithology and thickness but it is not possible to separate the Tertiary and Quaternary deposits due to the lack of diagnostic fossils. It is often difficult to distinguish this formation from the Nubian Sandstone due to the wide overlap in lithology. The upper layers are relatively sandy in the north but clayey in the south.

Arid conditions are indicated by the presence of evaporites in places. The formation is thickest in faulted troughs which were reactivated during deposition along the same lines as Cretaceous faulting. Similar deposits are found between the White and Blue Niles and further south between the Blue Nile and its tributary the River Rahad. Since these two deposits are not continuous with the Umm Ruwaba deposits they have been given different names: the Gezira and El Atshan Formations respectively.

The Gezira Formation was built up by fast flowing streams from the south. At the type locality it consists of gravelly sand 9 m thick at the base followed by 35 m of clayey sand and 17 m of dark clays and silts which may be of Pleistocene age. Although rapid facies changes are common the upper clays are widespread. The formation reaches 111 m at its thickest (Wad Adam, $32^{o}37'E$; $14^{o}21'N$).

The El Atshan Formation commonly contains more calcrete nodules and gravels than the Gezira Formation. Heavy mineral analysis of clays has shown that the two formations have different provenances.

Another area of Tertiary to Pleistocene deposition is found between the Blue Nile and River Atbara where the Nubian Sandstone and Basement Complex are overlain by the clays of the Butana Plain which are also alluvial deposits.

Clay plains of probably Pleistocene age are typical of much of southern Sudan overlying the Umm Ruwaba and related deposits from which they are indistinguishable, and also in the Basement terrains such as the Nuba Mountains where they were probably formed by sheet floods.

2.5.2 Wind Blown Sands and other Superficial Deposits

Wind blown sands occupy the northern part of the country. They are more prevalent in the northwest than in the Red Sea Hills: in the former area the Nubian Sandstone Formation provides an unlimited source of material. South of the 300 mm isohyet the sands become fixed by vegetation and the 500 mm isohyet forms the southern limit of moving Sands. In the southern part older fixed sands have been weathered and show iron staining: these were formed during the arid Pleistocene period, probably something between 21,000 and 12,500 BP from the Umm Ruwaba deposits. The weathering resulted from the following humid period during which a B horizon rich in clay was formed and the dunes extensively degraded. Increasing aridity was marked by renewed dune formation which does not extend so far south. The new dunes are unweathered and white or grey in colour. The sands have trends varying from southerly to westerly indicating dominant winds from the north and northeast around the southern margin of the Sahara desert.

The term 'qoz' was originally applied to fixed dunes and sand sheets but is now also used for moving sand south of about 16^{o}N, the effective limit of settled habitation. 'Low qoz' refers to the older sands while 'high qoz' refers to the more recent dune fields which have greater topographical relief.

Between the qoz dunes there are clay and calcareous deposits, mainly from alluvial deposition in more humid times and from playa type deposition at present: movement of the sands has resulted in many areas of qoz being underlain by such clays and interfingering of the two lithologies.

During the humid periods of the Pleistocene wadi systems were more developed: Wadi Howar for example probably flowed from Jebel Marra to the Nile. In the period 3,500 to 3,000 BP stream flows were ten times present values depositing clays and silts over the sands.

Alluvial deposits of gravels, sands, silts and clays have been formed throughout the Pleistocene and Recent times and include wadi (khor) deposits, clay plains as mentioned above, delta fans and river terraces. Other superficial deposits are the clays and sands resulting from in-situ weathering, mainly of Basement Complex rocks and scree deposits around inselbergs.

The Nile terraces and the human artefacts contained therein have been instrumental in unravelling the Pleistocene and Recent geology of the Sudan.

3. HYDROGEOLOGY

Due to the long dry season and high evaporation over most of the country, groundwater has always been a vital source of supply for people and livestock. Even along the Nile rivers wells are increasingly being used for domestic water due to the deteriorating quality of Nile water. The expansion of settled agriculture in the north of the country away from the rivers, is also dependent on the availability of groundwater.

The distribution of population in relation to water supply is described by Mountjoy (1972). Apart from the problems of desertification mentioned above, many of the major towns are situated in PreCambrian terrains at a distance from the major sedimentary basins and a reliable source of groundwater. Since 1962 the Rural Water Corporation (RWC) has been drilling wells in rural areas to combat the effects of the recent drought in an Anti-Thirst Campaign. This project provided much basic data and has also stimulated more scientific investigations into the distribution and potential of aquifers.

Most of the geological formations in Sudan act as aquifers to some extent but by far the most significant, at least in terms of the quantity of groundwater available, are the Nubian and Umm Ruwaba and allied formations. Wadi deposits and alluvial fans are locally important while the qoz sands, Nawa Formation weathered Basement and weathered Tertiary volcanics form minor aquifers. Fresh Basement and volcanic rocks, together with mudstones and clays, where these are extensively developed in the sedimentary sequence, form effective aquicludes.

3.1 Minor Aquifers.

3.1.1 The Qoz

Sands of the qoz are highly permeable and it is this which makes them of minor significance as aquifers: only shallow lenses of groundwater accumulate where there is an underlying clay aquiclude and much of the infiltrating water drains into temporary pools between the dunes and soon evaporates. Dug wells tap groundwater in the clay hollows and the sands after surface sources have dried up but yields are low and the supply rarely lasts the length of the dry season.

In the qoz areas evaporation is high and although rainfall quickly penetrates the sand percolating water often only reaches a depth of 3 metres as observed in experiments reported by Hunting G & G and MacDonald (1970). It is not known under what conditions the infiltration experiments were carried out and the hypothesis that lower aquifers may be recharged from the qoz either where the clay aquiclude is absent or by downwards leakage from temporary lakes, is widely accepted.

3.1.2 Tertiary Volcanics

The Tertiary volcanics in the Gedaref and Shagera Basins are dealt with in sections 3.3.12 and 3.3.3. The volcanics of the Meidob-Tagabo Hills are also mentioned below in section 3.3.1 on the Sahara Tima Basin. These latter share many of the characteristics of the Jebel Marra region although the rainfall is significantly lower.

The hydrogeology of the Jebel Marra volcanics as far as it is known is presented in the Hunting T.S. 1977 report. The basalt and trachyte lavas and welded tuffs are only porous where fractured while the interbedded ashes and tuffs possess some primary porosity. The quantity of water in storage and amount of through flow depend on the subsurface relief and internal structure of the formation, which therefore only locally constitutes a good aquifer.

Rainfall in the area is relatively high due to the orographic effect of the hills and many streams and seepages from the volcanics feed wadis which radiate from the area and sustain their flow throughout the year. An area of high concentration of springs and seepages was located by Hunting T.S. (1958) along the periphery of a lobe of lava. Of six exploratory wells later drilled in this lobe one gave high yields: 30 m^3/hr for 7 m of drawdown from a static water level of 2.3 m below surface in a borehole 10 m deep. However the other wells were not successful even in this relatively productive area: Hunting T.S. (1977) conclusion was that the expense of many unsuccessful and low yielding wells which must be expected if drilling continues, cannot be justified when most of the groundwater from the volcanics can be utilised from springs or from the wadi alluvium which it recharges.

Several springs are warm and saline, giving rise to brackish streams on the northwest slopes with a generally high content of Na, Cl and HCO_3 ions and an electrical conductivity (EC) of 100 to 1,000 micromhos/cm. Only rarely are the salinities of the streams high enough to be unsuitable for irrigation.

3.1.3 Coastal Deposits of the Red Sea Hills

Excepting the alluvial deltas at the surface (see section 3.2.1) the groundwater potential of the coastal deposits remains largely unexplored. Although the sands of the various formations must be permeable, the extensive development of evaporites means that fresh water will be hard to find. At Port Sudan, the salinity of well water is due to saline intrusion of sea water. The best conditions for accumulation of fresh groundwater exist inland at the foot of the Red Sea Hills escarpment: here there may be recharge from delta fans where wadis sometimes debouch onto the flood plain during the rainy season.

Tertiary formations may be investigated further during the Port Sudan Authority's extensive exploratory drilling programme and the Geological Survey Department-German project of research in the Tokar Delta may extend northwards and provide more information on these deposits.

3.1.4 Nawa Formation

The groundwater potential of this formation is largely unknown but its limited extent and argillaceous nature means that it is of minor importance as a regional aquifer. Rodis et al. (1964) suggested however that it could be an important aquifer in comparison to the surrounding Basement Complex and that more test drilling should be considered. They predicted that moderately productive beds would be found but wells have generally been unsuccessful. Seven exploratory holes drilled in one area to depths of 45 to 140 m yielded an average 0.16 l/s.

Bannaga (1977) considered these clayey sediments to be practically impermeable, while the high sulphate and chloride content makes the water unsuitable for human consumption. The consensus of opinion at present is that further exploratory work in these sediments would be unproductive.

3.1.5 Basement Complex Terrains

Although rocks of the Basement Complex are intrinsically impermeable they can store and even transmit water where they are fractured and weathered. In favourable locations they can form aquifers of limited extent. Yields are generally low and unreliable with water of poor quality except where recharge is high, as below saturated alluvial deposits. The extensive distribution of Basement Complex rocks however makes it an important aquifer in many parts of the country.

Where jointing is well developed the weathered zone can be over 100 m thick, but the most productive layer is usually immediately above bedrock where lenses of a clayey-sandy texture may be formed. The upper part of the weathered zone is generally clayey and acts as an aquiclude. The aquifer has low transmissivity and storage characteristics, hence water level fluctuations are marked as at El Obeid where the seasonal fluctuation was 16 m in 1964 as compared to 8 m in the sedimentary aquifer at Bara to the north.

Due to the high surface runoff and low permeability of Basement terrains surface water from temporary pools is used and small reservoirs and dams are often constructed to increase the supply. As the dry season progresses, dug wells are used to tap the wadi alluvium and underlying weathered Basement. In the south of the country wells in the weathered zone may provide a permanent source of water, but as rainfall decreases northwards many of these wells dry up before the end of the dry season and as water levels drop the quality rapidly deteriorates. Due to the availability of only rather poor quality water in many areas the Sudanese government Ministry of Health's standards for human or animal drinking water give much higher maximum limits of dissolved solids compared to international and european standards.

T.D.S.	5,000 ppm
SO_4	750 ppm
Cl	2,000 ppm
Nitrates	220 ppm
Flourides	2 ppm

The water obtained from the Basement, especially when the wells are nearly dry, can be undrinkable according to these standards. Sulphates have been recorded at over 1,000 mg/l and nitrates are often high due to organic contamination of unprotected wells.

In the Southern Provinces where the weathered zone is extensively developed and recharge from rainfall is good, the Basement provides a regional aquifer. UNICEF has drilled over 175 wells in the Bahr el Ghazal Province: these have a diameter of 150 mm and are rarely more than 10 m deep. Water is generally found at shallow depths in sandy and sandy clay layers above fresh granite. It is abstracted by hand pumps and yields are sufficient for rural water supply but no tests have been run to determine hydraulic parameters of the aquifer. Although yields are adequate and the majority of wells successful, it is unlikely that the aquifer is continuous over large areas: most probably it relies on local but widespread recharge from the relatively high rainfall.

Further north wide diameter wells are usually required to sustain yields. There is little advantage in drilled wells since large diameters are difficult to attain and the productive zone is usually shallow. Some examples of groundwater conditions in different areas are given below.

Little has been written about groundwater conditions in the Basement Complex of the Red Sea Hills. Shallow wells along wadi beds are doubtless an important source of water and the Geological Survey Department is presently constructing large diameter wells to serve mines, quarries and cement factories.

In the Butana Plains along the divide between the Atbara and Blue Nile Basins groundwater is obtained from weathered greenschists and from fans around igneous intrusions. Static water levels in the weathered zone show a series of discrete basins along the bottom of the khors. The composition of water is dominated by Ca, Na and HCO_3 ions with a T.D.S. ranging from 400 to 680 mg/l. Water of the lowest salinity is found in the fan deposits and nitrates are generally low. The area constitutes a major well field for the Shakriya tribe but due to the low rainfall (less than 300 mm/yr) the wells dry up and the tribe migrates to the Blue Nile and Atbara Rivers in the dry season. To support the large livestock population throughout the year, Ahmed (1968) concluded that the water supply could only be increased by storing surface water.

Along the divide between the Eastern Kordofan and Sahara Nile Basins and the western part of the divide between the Central Darfur and Sahara Nubian Basins and around the margins of the sedimentary basins, the main aquifers (Nubian Sandstone and Umm Ruwaba Formations) are thin and dry. In many of these areas water is obtained from wells penetrating the underlying weathered Basement zone. In the first area water is found at a depth of 15 to 50 m but the T.D.S. is high: 3,000 to 4,700 mg/l and yields are insufficient. Nitrates are often high, sometimes reaching over 500 mg/l.

Many exploratory programmes have been carried out in the Nuba Mountains where granitic inselbergs rise to 600 m above the surrounding clay plains. The orographic effect gives a relatively high rainfall of 600 to 800 mm and the most productive zones of groundwater are the aureoles of outwash deposits around the largest hills from which springs flow and which provide the highest and most reliable yields to wells. Khor alluvium is also productive where quartz veins dam up water. Elsewhere the alluvium is generally dry even where it reaches 30 m thick as along the lower courses of some of the major khors. Almost all productive holes lie in the weathered Basement Complex and yields sometimes reach 5 m^3/hr although specific capacities are generally less than 30 m^3/d/m.

Due to the extensive clay plains it is difficult to locate wells and many people have to travel long distances to water in the dry season. Resistivity methods may be useful to determine the presence of weathered lenses beneath the clays. The Ministry of Overseas Development-Huntings rural development project based in Kadugli will continue to investigate groundwater occurrence over the whole of South Kordofan, in which the Nuba Mountains lie, with the aim of improving rural supplies.

El Obeid, the provincial capital of Northern Kordofan lies north of the Nuba Mountains. It is favourably situated with regard to water supply from the Basement: there is a thick weathered zone which for many years has been used to supplement surface water during the dry season. El Fasher, the provincial capital of Northern Darfur is in a similar position: here the depth to water varies from 22 to 41 m and the saturated thickness of the weathered zone is from 5 to 45 m (Hunting G & G and MacDonald, 1970). However the local groundwater supply in both places cannot support the present development and yields have fallen and the quality of water deteriorated, particularly with respect to nitrates. Hunting G & G and MacDonald (1969) found that El Fasher was overdrawing on the estimated local recharge by 10,000 m^3/yr. In the last few years the supply of El Fasher has been met from increased surface storage and wells in the Nubian of the nearby Shagera Basin. A suitable alternative source for El Obeid is also being investigated and these two examples clearly illustrate that the Basement aquifer is not capable of supporting an urban population.

The quartzites of Northern Darfur are known to be relatively permeable, probably due to fractures, and may allow significant throughflow of groundwater between the adjacent sedimentary basins. Hydrogeological studies have been recommended to establish the amount of flow that takes place in order to give more accurate estimates of the water balance of the basins. The quartzites are not however considered to have much potential for groundwater abstraction due to the difficulties of locating successful wells and the proximity of productive sedimentary aquifers (Hunting G & G and MacDonald, 1970).

3.2 Alluvial Aquifers.

Alluvial aquifers are of greatest importance in the Basement terrains where high runoff allows the development of khor systems and the underlying impermeable rocks facilitate the accumulation of groundwater at shallow depths. Where khors flow over sedimentary basins the groundwater usually percolates quickly downwards and the alluvial sediments become dry. These aquifers possess the most favourable characteristics in their upper reaches where the sediments are more clastic. Many of the khors which are too small to provide reliable quantities of groundwater are nevertheless important in recharging the major sedimentary basins. Some of the major alluvial aquifers are described below.

3.2.1 Eastern Red Sea Hills

From the topographic divide, about 50 km from the coast, courses of khors generally run from south to north along structural lineaments in the Basement and then cut through north-south ridges, usually along fault lines, to the coast. The khors have formed valleys of variable width partly infilled with heterogeneous gravels, sands and silts derived from the Basement granites, gneisses and schists. Where they debouch onto the coastal plain, thick river outwash fans and river deposits are found. There is only perennial flow along short stretches of the khor beds, where groundwater is forced to the surface by ridges in the Basement. Surface flow occurs during the rainy seasons, usually twice a year (July-Sept. and Oct.-Jan.) but the flow rarely reaches the sea.

The alluvium forms an aquifer of limited extent. The most favourable conditions for groundwater storage and reliable abstraction are where valleys widen out and where subsurface ridges downstream form small basins and retard the flow of water.

The groundwater resources of the area north of Arbaat have not been studied due to its aridity and inaccessibility. From Arbaat southwards, groundwater in the alluvium has been utilised for many years for domestic supply, livestock and occasionally irrigation. Several studies have been carried out due to increasing demand for water in Port Sudan and Suakin and its seaport.

Groundwater from the alluvium of Khor Arbaat has been used to supply Port Sudan since 1924. The area exploited is in the lower end of a small elongated basin, about 10 km long and 12 km^2 in area, situated 30 km NW of Port Sudan. The upstream boundary is a narrow gorge 30 m wide (Upper Gate), while the downstream boundary (Lower Gate) is a stricture 450 m wide. The junction of Basement rocks and deposits of the Red Sea littoral occurs shortly downstream of the Lower Gate. Here the course of the khor is no longer confined and an outwash fan has been deposited.

Flow is only perennial within and for a short distance downstream of the Upper Gate, where groundwater in the alluvium is forced to the surface by a ridge in the Basement. During floods however, surface water passes through the Lower Gate.

The configuration of the alluvial basin and underlying Basement rocks have been determined from borehole records and a geophysical survey carried out by SOGREAH (Bazin, 1969). The alluvium is 8 m thick at the Upper Gate and fully saturated. The depth to the Basement and thickness of saturated alluvium increase downstream. There is thought to be another subsurface ridge about 3 km upstream of the Lower Gate which rises to 10 m below ground level (Salama, 197) which effectively divides the aquifer into two compartments, but the results of the geophysical survey are thought to be ambiguous due to the presence of calcrete layers (I.O.H., 1978c).

Water levels are generally 5 to 10 m below surface with seasonal fluctuation of 2 to 3 m. Between April 1973 and January 1978 there was an overall fall of 5 m in the water table near the Lower Gate due to heavier abstraction. Water levels fully recover after floods but the 7 to 8 year drought cycle is apparent in the longer term records: after such a drought recovery may take several years.

The alluvium consists of boulders, pebbles, sand and silt. The grain size decreases downstream, in the direction of decreasing surface gradient and flood velocity. Studies by Shell (this reference not listed) (1965) showed the permeability of the aquifer to be 170 m/d to 9 m/d, which if applicable to the total saturated thickness of the aquifer would give transmissivity values of 3,500 $m^3/d/m$ to 170 $m^3/d/m$ (Hussein, 1975).
A few pumping tests were carried out near the Lower Gate in 1974. Some of the data shown in Hussein (1975) has been re-analysed and the transmissivity at well 63 appears to be in the range 25 $m^3/d/m$ agreeing closely with the I.O.H. (1978) analysis. The higher value is thought to be more realistic due to the effect of well losses on drawdown in a pumping well. The test data from well 64 indicates a lower transmissivity but both tests were carried out at relatively low discharge rates (ca. 10 l/s) for only a few hours and without observation wells and cannot be expected to give reliable results.

Transmissivity probably decreases away from the stream bed as the aquifer becomes thinner and silts and clays more frequent and increases towards the Upper Gate in the direction of increasing grain size. From mechanical analyses Hussein (1975) estimated the specific yield to be 0.15 to 0.20.

The water quality is generally good with EC values less than 2,000 micromhos/cm and has dominant ions of Ca and Cl. The Ca content however is sometimes greater than 200 mg/l. There are pockets of very saline water thought to be derived either locally from the Basement or from a nearby tributary khor (I.O.H. 1978c). Here the EC can be as high as 15,000 micromhos/cm with a very high Cl content.

Recharge to the aquifer is from the perennial flow at the Upper Gate and from flood discharge. I.O.H. (1978) found that the quantity of recharge from floods is probably only 4% of the total amount of water available due to the limited infiltration. The amount of recharge assuming a seasonal fluctuation of 5 m and a specific yield of 0.05 would be about 3.3 x 10^6 m^3/yr. Evapotranspiration of groundwater is considered negligible due to the depth of the water table and throughflow from the Lower Gate, using the revised value of transmissivity may only amount to 0.03 x 10^6 m^3/yr. However abstraction from wells has reached 5.7 x 10^6 m^3/yr in recent years which cannot be sustained by recharge.

New wells are now being sited in areas of higher transmissivity and attempts are being made to tap the perennial flow of water at source. Proposals for reservoirs for flood water are not considered practicable due to the large storage capacity required and great quantities of sediment carried by flood waters. Similarly the suggestion of a subsurface dam at the Lower Gate is now known to be pointless due to the small amount of throughflow. The demand for water for Port Sudan is already well above the amount available from Khor Arbaat and could easily be over 10 x 10^6 m^3/yr by 1985.(Ewbank and MacDonald, 1974) depending on the amount of industrial growth. The limited water supply has greatly hindered development and the Port Authority has now started investigations further south in smaller khors and in the Tokar Delta.

Other khors which may be able to supplement the water supply to Port Sudan are Khor Sallom, some 40 km southwest of the town, and Khor Gwob, about 40 km south of the town. In Khor Sallom both water quality and the amount of recharge limit groundwater development. The water contains mainly Ca and SO_4 ions and the salinity increases downstream. A well field has been proposed (Ewbank and MacDonald, 1974) in an area where salinities are expected to be in the range of 1,000 to 1,500 mg/l. The reliable yield of the well field would probably be less than 2 x 10^6 m^3/yr.

Khor Gwob's catchment area is much smaller, but rainfall is higher with a range of 25 mm/yr to 643 mm/yr (ca. 150 mm/yr). Floods here are mainly from the autumn rains as the catchment is more sheltered from the southwest monsoon. Perennial flow in a short stretch of the khor is due to a Basement ridge, and there a dam has been proposed (Ewbank and MacDonald, 1974) to tap water downstream of the 'spring' although it is not expected to yield more than 2.6 x 10^6 m^3/yr in most years.

3.2.2 Tokar Delta

The Tokar Delta is situated 150 km south of Port Sudan. It consists of a large fan of alluvial sediments which extend to the Red Sea coast and have been deposited by Khor Baraka and its tributaries.

3.2.2.1 Previous investigations:

Until recently only the upper 20 m or so of saturated sediments had been investigated and exploited by wells (El Natiq, 1976, 1979). The Food and Agricultural Organisation of the UN (FAO) has carried out studies to determine the potential for groundwater irrigation (e.g. Burdon, 1974), and the area has been considered as a source of water for Port Sudan and Suakin (Ewbank and MacDonald, 1974). It was confirmed by geophysical surveys in 1977 that there are saturated sediments as deep as 200 m (Geol. Surv. Dept., Sudan), and investigations recently carried out by the Sudan Port Authority and the Geological Survey-German project included drilling and testing programmes to explore the lower aquifer.

3.2.2.2 Groundwater occurrence and aquifer limits:

The alluvial aquifer underlies an area of about 900 km^2 in a triangular basin bounded by the Basement Complex on two sides and by the coast on the third. The depth to the water table is about 10 m. There appears to be a fairly continuous clay layer about 18 m below the water table (El Natiq, 1976, 1979) but the thickness of sediments in the basin is not yet known. The main producing horizon is usually 10 m or so of coarse sand with gravel and pebbles overlying clays.

3.2.2.3 Groundwater movement:

Water moves seaward under a gradient of about 1 : 625. A water level recorder installed at Krimbit (37°30'E, 18°10'N) shows a seasonal fluctuation of 2 to 3 m in response to recharge from Khor Baraka. The water level recovers fully after floods which occur mainly during July and August.

3.2.2.4 Aquifer characteristics:

A few pumping tests have been carried out which indicate that the transmissivity of the upper 18 m may be around 390 $m^3/d/m$ (Ignatowicz, 1977). The aquifer is semi-confined due to silts and clays at the surface.

3.2.2.5 Water quality:

Hydraulic gradients are low, but saline intrusion is probably limited to a 10 km coastal strip (Ewbank and MacDonald, 1974). The TDS content of the shallow aquifer is only less than 500 mg/l near Krimbit increasing down-gradient to the north west. At Tokar the TDS is 5,000 mg/l and increases with depth.

3.2.2.6 Water resources:

Recharge is from floods of the Khor Baraka; Burdon (1974) estimated that the flow of the Baraka at the Ethiopian border averaged 330 x 10^6 m^3/yr between 1900-1969, with a range of 15 x 10^6 m^3 to 1200 x 10^6 m^3 for extreme years. On average 38% of the delta area is cultivated for cotton using water from the wadi floods. Wright (1977) estimated that 664 10^6 m^3/yr would be required to support this area, considerably more than the average flood, and concluded that recharge to the aquifer can only be expected in years of higher than average rainfall.

The amount of flow through the upper aquifer is unknown due to the poor quality of pumping tests but may be in the order of 9 x 10^6 m^3/yr if the above transmissivity value is applied to the whole area. This is about one-third of El Natiq's estimate.

The highest consumption of groundwater is for Tokar town and was about 0.2 x 10^6 m^3/yr in 1976, an increase of 50% over the 1970 level of abstraction.

3.2.2.7 Recommendations:

For several years the use of groundwater irrigation has been considered to make use of areas marginal to the floods which are not inundated every year. In extreme years 90% of the area of the delta has produced crops, mainly cotton, so the potential for increased agricultural production is great in terms of land resources. Projects at present include improvement of flood irrigation (Hydraulics Research Station and Crown Agents, 1978) and stabilisation of moving dunes. UNDP/FAO (1972) proposed a pilot groundwater scheme.

Recently the demand for water for Port Sudan has stimulated groundwater investigation. Proposals to install a well field near Krimbit would double the cost of water to the port, but still be cheaper than desalination of sea water. From the information so far available it appears that the shallow aquifer could easily become overdeveloped and the planned increase of abstraction for the port and for agriculture must await the results of recent investigations of the lower aquifer. It is planned to construct a mathematical model of the whole delta on the basis of these investigations.

3.2.3 Gash Delta

Alluvial deposits of the Gash river and its tributaries form an important aquifer in the region of Kassala, some 500 km east of Khartoum.

The headwaters of the Gash lie in Ethiopia, where flow is perennial. At Kassala there is flow for 88 days per year and an annual average discharge of 483 x 10^6 m^3. Kassala is situated at the apex of the river delta which extends northwards for ca. 60 km, in a ribbon up to 15 km wide. The delta is bounded by Basement rocks, mainly granitic and hornblend gneisses, which outcrop as N-S trending ridges on the east but are overlain by clays on the west. The delta and clays form a plain which slopes gently to the north-west at an average elevation of 500 m above mean sea level.

Tributary khors join the Gash from the east, and in places have deposited alluvium on the Basement rocks. The alluvium of the Gash River and tributary khors consists of intercalated unconsolidated beds of coarse to fine-grained sediments: gravel, sand, silt and clay.

3.2.3.1 Previous investigations:

El Tayeb (1969, 1972)(these are not listed) has investigated the hydrogeology of an area ca. 600 km^2 in the Kassala region.

3.2.3.2 Groundwater occurrence and aquifer limits:

Although water is sometimes found in sandy pockets in the clays of the plains close to the river, the alluvium of the Gash Delta is the only aquifer of significance. These heterogeneous sediments vary in thickness from 27 m at Kassala increasing to more than 113 m in the north (Lat. $15^{0}53'$N). North of latitude $15^{0}45'$N, the Basement rocks are down-faulted to depths exceeding 320 m and the alluvium is underlain by muds and shales with intercalated basalts. The average saturated thickness of the alluvial sediments is 27 m and the depth to water increases away from the river, varying from 5 m to 25 m below surface.

3.2.3.3 Groundwater movement:

Groundwater flows northwards under a hydraulic gradient of about 2×10^{-3}. Seasonal fluctuations are greatest near the river (ca. 7 m in 1963/1964), the peak being reached in August-September. Away from the river seasonal fluctuations are much lower (0.16 m) and the peak is not reached until about November. There is a general decline in the water table at the rate of 0.5 m/yr in an area west of Kassala where many irrigation wells are situated.

3.2.3.4 Aquifer characteristics:

Observation well data from a pump test at Kassala indicated a T of ca. 1,200 m^3/d/m and S of 13% (El Tayeb, 1969). The hydraulic characteristics are expected to be highly variable due to the heterogeneity of the aquifer and the permeability decreases downstream as the proportion of fine-grained sediments increases.

3.2.3.5 Water quality:

The water is of low salinity in the vicinity of Kassala, where the TDS is in the order of 250 mg/l and the dominant ions are Na, Ca and HCO_3. The salinity increases northwards due to the lower permeability of sediments and longer flow path of groundwater. At Aroma (lat. 15°49'N) the TDS is 2,860 mg/l and the dominant ions are Na and HCO_3. North of this there is a more rapid increase in salinity and at Alim (lat. 15°53'N) the TDS is 15,850 mg/l with a high proportion of Cl. It is possible that this area is affected by stagnant, saline waters in the underlying shales.

3.2.3.6 Groundwater resources:

Groundater from the alluvium is only usable as far north as Aroma, after which it becomes too saline for irrigation, livestock and domestic purposes. Recharge is mainly from the river. During the period 1907 to 1929 the minimum annual discharge at Kassala was 90×10^6 m^3 from a catchment area of 21,000 km^2. Less important sources of recharge are subsidiary khors which join the Gash from the east. In places these contain groundwater in their alluvial sediments and in the weathered surface of the Basement rocks. There may be some direct recharge from precipitation.

El Tayeb (1969) estimated the change in storage, or annual recharge, to be in the order of 75×10^6 m^3/yr over an area of 161 km^2. Of this some 62×10^6 m^3/yr was used for irrigation and domestic supplies, while evapotranspiration from the water table, mainly from woods in the south of the area was estimated to be ca. 11×10^6 m^3/yr. The amount of water in storage is probably in the order of 600 $\times 10^6$ m^3.

3.2.3.7 Recommendations:

In view of the fact that estimated total annual recharge is probably little more than the total used it is not surprising that water levels are declining in areas of heavy abstraction. The picture may not be so bad if a percentage of irrigation water is returned to the aquifer. However control of abstraction is obviously required. El Tayeb (1972) suggests construction of a canal to the most affected area to recharge more of the flood water.

The Rural Water Corporation has recommended that construction of irrigation wells should be halted for the time being but it appears that there is no control over drilling. RWC is now starting more intensive investigations together with Dutch advisors in an attempt to increase the amount of groundwater available. From what is known so far it is evident that siting of wells further apart and in the more transmissive areas as well as changes in pumping rates and regimes would help to reduce drawdowns.

3.2.4 Nuba Mountains

Major wadis flowing from the Nuba Mountains are Wadi el Ghalla and Wadi Shelengo which flow west into the Baggara Basin and Khor Abu Hable which flows east into the Eastern Kordofan Basin.

In Wadi el Ghalla water is derived mainly from the underlying Basement after stream flow stops in October. In Khor Abu Habl many agricultural schemes have been abandoned due to the unreliability of seasonal runoff (Rodis et al., 1964).

3.2.5 Wadi el Ku

Wadi el Ku flows eastwards from Jebel Marra across the pediment area through to the Sag el Naam Basin where it peters out to the south east in a clay flood plain. The hydrogeology has been studied by Hunting G & G and MacDonald (1970) and Dafalla (1973). Other khors in the pediment area rarely have alluvium more than 15 m thick but along Wadi el Ku the deposits reach more than 30 m, probably due to subsidence along the troughs that form the Shagera and Sag el Naam Basins (Hunting G & G and MacDonald, 1970).

The aquifer is most important in the pediment area west of the Shagera Basin where the permeability is greatest and between the Shagera and Sag el Naam Basins where the Basement Complex is close to the surface.

3.2.6 Wadi Nyala

Wadi Nyala drains southeastwards from the south part of Jebel Marra. In the vicinity of Nyala town the wadi widens out below a gorge and sands and gravels have been deposited in a shallow trough underlain by Basement rocks. The contact between the Umm Ruwaba Series and the Basement Complex is about 30 km downstream of the gorge.

3.2.6.1 Previous investigations:

The hydrogeology of the alluvial aquifer has been studied by Salama (1971) and Hunting T.S. and MacDonald (1974) in attempts to increase the water supply to Nyala town during the dry season.

3.2.6.2 Groundwater occurrence and aquifer limits:

The alluvial deposits are 100 m wide immediately below the gorge increasing to 600 m some 10 km downstream. The thickness increases in the same direction, from 6 m to about 20 m, as does the proportion of fine-grained sediments.

The average saturated thickness of the aquifer at the end of the wet season is 15 m over this 10 km stretch in the vicinity of Nyala town. Further southeast the wadi deposits are dry as water percolates down to recharge the Umm Ruwaba Formation.

3.2.6.3 Groundwater movement:

Water flows northwards and away from the khor bed. During the dry season water levels drop by 6 to 8 m on average and only wells situated where the aquifer is thickest, away from marginal Basement outcrops, can sustain a reliable yield.

3.2.6.4 Aquifer characteristics:

One reliable pumping test indicated a T of 4.0 g/d/ft and a storage coefficient of 0.33 (Salama, 1971). From this Hunting T.S. and MacDonald (1974) deduced an average hydraulic conductivity (K) of

50 m/d which was used for estimating groundwater resources. As in other thin alluvial aquifers, seasonal fluctuations of water levels cause high variation in the transmissibility of the aquifer.

3.2.6.5 Water quality:

Water is generally of low salinity, increasing where wells tap the weathered top of the Basement Complex or clay lenses within the wadi deposits. The composition is dominantly Na, HCO_3, but the percentage of calcium increases towards the banks.

3.2.6.6 Water resources:

At the end of the wet season total storage in the aquifer at a specific yield of 20% would be ca. 19.3 x 10^6 m^3. The depletion of storage during the dry season was ca. 11.06 x 10^6 m^3 for 1972/1973 (Hunting T.S. and MacDonald, 1974). Of this about 4.35 x 10^6 m^3 was accounted for by abstraction from wells for irrigation and the town supply, 0.33 x 10^6 m^3 by the excess of outflow over inflow through this stretch of the aquifer, and by difference, 6.38 x 10^6 m^3 from evapotranspiration. It is possible that the net outflow is overestimated since K might be expected to be lower in the downstream reaches. However it is evident that evapotranspiration is the most important process in depleting aquifer storage: the estimated amount is equivalent to 1.3 m/yr over the cultivated area of 460 hectares.

3.2.6.7 Recommendations:

Hunting T.S. and MacDonald (1974) recommended that a further 3.37 x 10^6 m^3/yr could be used from aquifer storage. This would leave a saturated thickness of 5 m, considered as dead storage. They estimated that a recharge of 19 x 10^6 m^3/yr would be required to replenish the aquifer, and that wadi flow of 27 x 10^6 m^3/yr, estimated to be equalled or exceeded in 49 years out of 50, can supply this recharge.

The pattern of abstraction should however be altered to reduce drawdowns: more wells should be pumped near the centre of the wadi where the saturated thickness is greatest. The maximum pumping time should be reduced from 24 hr/day to 16 hr/day to allow maintenance to be carried out and recovery of water levels. A subsurface dam downstream of the well field was not recommended, as it would only serve to increase evapotranspiration from the water table. Hunting T.S. and MacDonald also suggested that the use of water for irrigation should be controlled by issuing licenses for well construction and pump type. They and Salama recommended that open wells should be fenced around the reduce organic contamination, and that covered boreholes should be used.

Other wadis draining from the Jebel Marra region south to the Baggara Basin include the Ibra, Maia and Bulbul which flow towards Bahr el Arab. Their groundwater potential is discussed by Bannaga (1977). Over the Basement the sediments are sandy but rarely more than 10 m thick and provide useful supplies for domestic and livestock purposes. Along part of Wadi Bulbul there may be sufficient water for small scale irrigation where a dyke forms a subsurface dam. Further downstream, in the sedimentary basin the khor deposits are silty and there is little potential for groundwater development.

3.2.7 Wadi Kutum

Wadi Kutum flows from the east side of Jebel Marra. The area is a peneplain with thin Nubian Sandstone overlying Basement rocks. Because the Nubian is dry the upper part of this khor forms a locally important aquifer and was included in the Hunting G & G and MacDonald (1970) survey of the Darfur Province.

The alluvial aquifer is on average 200 m wide with a shallow water table easily tapped by shallow wells. The seasonal fluctuation was 3 m in 1969/1970 and flow downstream recharges the Nubian Sandstone. Sieve analyses indicate a specific yield of 20% and assuming that evapotranspiration accounts for 25% of the seasonal fall in water levels Hunting G & G and MacDonald calculated that 5×10^6 m^3/yr flows into the Nubian Sandstone while over the area the volume of groundwater in storage at the end of the dry season would be 200×10^6 m^3.

3.2.8 Wadi Azum

West of Jebel Marra the Wadi Azum system drains across the Basement Complex peneplain towards Chad. The alluvium is generally coarse and permeable and is the major source of water in the dry season. Most of the hydrogeological information on the area comes from the Hunting T.S. (1977) report.

3.2.8.1 Aquifer limits:

The alluvium has been deposited in long narrow troughs. Cross-sections have been determined mainly from geophysical surveys. Hunting T.S. found that resistivity methods indicated cross-sectional areas 60% greater than from seismic profile and boreholes have proved the latter to be more accurate. In many of the major khors sediments reach a maximum thickness of 20 to 40 m and widths are often more than 500 m although local constrictions are sometimes found. The water table is often close to the surface and perennial flow, with channels normally less than 5 m deep, occurs over some constrictions. During the 1976 rains water levels rose by 1.6 m on average.

3.2.8.2 Aquifer characteristics:

The sand content is predominantly medium to coarse-grained with a gravel fraction often as much as 40% while fine sands rarely exceed 20% of the total by weight. Sorting is poor. Pumping tests show T values to range from 30 to to 3,400 $m^3/d/m$ and in one borehole the vertical to horizontal conductivity ratio was found to range from 1 : 16 to 1 : 70. Most of the permanent dug wells have specific capacities around 960 $m^3/d/m$ while boreholes have much lower specific capacities.

3.2.8.3 Water quality:

The salinity of water is very low, usually less than 200 mg/l and sometimes less than 50 mg/l with mainly Ca and CO_3/HCO_3 ions. The field pH is from 7.8 to 8.5. Fluoride is often high and waters derived from the volcanics of Jebel Marra can be brackish or saline. It is possible that the high fluoride is due to lack of iodine: both goitre and fluorosis are common in the Jebel area. Encrustation of well screens by ferrophylic bacteria is also a problem but the source of iron is not known and may even be from the well screens themselves.

3.2.8.4 Water resources:

The amount of recharge is controlled by the infiltration rate of the aquifer rather than the amount of surface water available. Most recharge is thought to be from the stream bed. The total recharge to alluvial aquifers in the Wadi Azum system was estimated at 460 x 10^6 m^3 in 1976 after allowing for subsurface flow downstream and evapotranspiration. Discharge by the latter mechanism was probably in the order of 78 x 10^6 m^3. Since 1976 was a fairly dry year these figures are thought by Hunting T.S. to give a reasonable basis for long term predictions.

The total abstraction from temporary dug wells for domestic and livestock purposes and small scale irrigation was estimated at 3 to 4 x 10^6 m^3/yr. The weathered Basement is thought to act as temporary bank storage.

3.2.8.5 Recommendations:

It is apparent that groundwater resources in this area can be maximised by increasing abstraction: lowered water tables would reduce the amount lost by evapotranspiration. Wide diameter wells are more efficient than narrow diameter drilled wells in thin aquifers and Hunting T.S. recommended that maximum financial returns for agricultural development would be from dug wells equipped with centrifugal pumps.

3.3. The Sedimentary Basins.

The picture of a sedimentary cover steadily thickening northwards from a few tens of metres in Sudan to thousands of metres in northern Egypt has changed radically in the last 10 years as borehole drilling and geophysical surveys have located deep troughs in Sudan with sediments often more than 2 km thick. As investigations proceed more and more irregularities are being found in the underlying Basement and the concept of simple synclinal basins is being replaced by series of fault-bounded troughs and ridges.

The Nubian Sandstone and Umm Ruwaba Formations infilling these basins form the most extensive and dependable source of groundwater in Sudan but due to the vastness of the country, poor communications and lack of funds, hydrogeological investigations have generally been limited to preliminary reconnaissance.

The most striking feature of the Nubian Sandstone in Sudan is the excellent quality of water, due to the lack of soluble materials in the formation and its entirely continental history (Himida, 1970). It has been assumed that the aquifer is inexhaustible but with increasing abstraction,fears of overdeveloping the smaller basins may well be justified and the question of how much recharge takes place at present is becoming more important.

There is no doubt that most of the water in both formations was recharged during cooler and more humid periods of the Pleistocene. It is even possible that evaporation was low enough to permit direct recharge from rainfall over wide areas. Theoretical considerations (Burdon, 1977; Lloyd and Faraq, 1979) show that present day heads, at least in the basins draining towards Egypt could be due solely to head decay from a maximum at about 10,000 BP and that present day recharge is not necessary to maintain the low hydraulic gradients. No significant amount of tritium has been found in either of the formations which indicates that recharge is slow and probably insignificant. In many of the basins fluctuations of water levels are too insignificant to be measured. All these points have been used to support the hypothesis that recharge in the semi-arid belt of Sudan happens so rarely that is should be ignored and groundwater development based solely on the amount of water in storage.

Many authors have assumed that the amount of flow through the aquifer is equivalent to the amount of recharge at present, but if the head decay hypothesis is correct the assumption would be invalid.

On the other hand the drying up of alluvial aquifers where they lie over permeable strata of the Nubian and Umm Ruwaba shows that there must be some recharge by this means and the Hunting and MacDonald surveys of western Sudan in particular indicate that the amount of recharge to the larger basins is significant compared to the amount of abstraction. The hypothesis that recharge takes place from the qoz areas is still unproven: it is quite feasible that very slow downwards leakage takes places from surface ponds before they evaporate or that in a series of very intensive storms percolating water can move downwards quickly where there is no intervening clay layer.

Even in the smaller basins, such as Shagera and Sag el Naam Basins, which are known to receive significant recharge from wadi alluvium and the weathered Basement aquifers, the lack of reliable pumping tests and hence storage coefficients means that the calculated amounts of recharge are only very approximate.

These aquifers are normally penetrated to about 50 m by drilled wells, hence the hydraulic characteristics given below usually refer only to the upper part of the sequence. In many basins only one reliable transmissivity value may be available and has been applied to large areas for estimation of throughflow: in practice facies changes are so rapid that a close network of determinations of hydraulic characteristics is required to provide accurate estimates. The quality of pumping tests is usually too poor to determine specific yields of the aquifer where it is unconfined: in many places, both in the sedimentary basins and alluvial aquifers, grain size analysis using Johnson's (1967) method has been used to estimate the specific yield. This method gives reasonable results but without comparing them with pumping tests their accuracy is unknown. Many of the transmissivity values quoted below are based on the specific capacities of pumping wells.

In the following account Salama's (1976) classification of the major basins has been used as in Figure 3.

3.3.1 Tima Basin (Nubian)

The basin is situated in northwestern Sudan. It extends northwards from the Tagabo-Meidob groundwater divide, covering an area of about 324,500 km^2 up to the Egyptian border. In the southeast and southwest it is bound by rocks of the Basement Complex, and is separated from the Central Darfur Basin to the south by upwarping of the Basement over which the sandstone has thinned. Volcanic activity associated with the upwarping resulted in extrusion basalts and trachytes along the divide. In the northeast the basin is bounded by another, largely subsurface, Basement ridge.

3.3.1.1 Previous investigations:

The survey by Sandford (1935) is still the main source of information for the basin as a whole. However Hunting G & G and MacDonald (1970) have investigated the southern part in more detail.

3.3.1.2 Groundwater occurence and aquifer limits:

Groundwater occurs in the sandstones of the Nubian Formation and the volcanics of the Meidob-Tagabo hills. From the piezometric map in Hunting G & G and MacDonald, the two appear to be in hydraulic continuity.

For about 10 km north of the divide, and greater distances in the west, the sandstone is dry, but further north water is generally found at depths of 50 m to 70 m below surface just north of the divide and reaches the surface in water holes in the northeast. From Nukheila ($26^{o}15$'E; 19^{o}N) to Laqiya (28^{o}E; 20'N) waterholes are found in depressions along anticlinal flexures while at El 'Atrun ($26^{o}30$'E; 18^{o}N) they occur in deflation hollows at the foot of an east-facing scarp.

Aeromagnetic surveys have located two parallel trenches in the Basement which are oriented in a northeasterly direction. In these the saturated sediments may reach 1,000 m in thickness (Salama, 1976). Near the southern divide the saturated thickness is about 100 m.

3.3.1.3 Groundwater movement:

Groundwater flows to the north and northeast, with hydraulic gradients near the divide varying between 1 : 300 in the west and 1 : 1,600 in the east. The pattern of flow is not known north of Wadi Howar ($17^{0}30'$N) but Whiteman (1971) suggests that there would be little recharge to Kufra in Libya due to the Basement high in the region of Jebel Uweinat (25^{0}E; 22^{0}N). The trend of the troughs however is expected to result in northeasterly movement of water. Using T values of 500-1,000 m^3/d/m, Salama (1967) estimated the velocity of water flow to vary from 0.41 to 2.06 m/yr in the southern part of the basin.

3.3.1.4 Aquifer characteristics:

The volcanic series is a poor aquifer with only local permeability (Hunting G & G and MacDonald, 1970). No pumping tests have been carried out to determine aquifer parameters of the Nubian Sandstone in this area, but T is assumed to be 500-1,000 m^3/d/m), while S probably varied between 10^{-2} and 10^{-4} (Salama, 1976). The value given by Salama for T is high in relation to pumping test results and specific capacities of wells in other Nubian Basins.

3.3.1.5 Water quality:

Water abstracted from the Sandstone is of very low salinity, with a TDS content of 50 to 150 mg/l near the divide in the south. Water from the volcanics is more saline, around 550 mg/l with greater concentrations of Na and HCO_3 ions. The higher salinity is thought by Salama (1976) to be due to juvenile water in areas of volcanicity. It could however equally well be due to the presence of more soluble constituents than in the sandstone, and/or to more sluggish movement of groundwater.

3.3.1.6 Water resources:

Although the piezometric surface indicates recharge from the south and southwest, precipitation on the southern divide is only about 200 mm. Any significant recharge under present climatic conditions must depend upon concentrated surface flow. Sandford (1935) estimated that 1.5×10^6 m^3 of water annually passes into the superficial deposits flooring Wadi Howar, which must contribute to recharge of the Nubian Sandstone. Salama (1976), on the basis of the measured hydraulic gradient and assumed aquifer parameters estimated the annual throughflow to be ca. 20.6×10^6 m^3/yr. He found abstraction to be about 1.2×10^6 m^3/yr.

3.3.1.7 Recommendations:

Despite the lack of data it is clear that the amount of groundwater used is negligible in relation to the storage. Hunting G & G and MacDonald investigated a few sites near the divide as requested by RWC, but all lay in the zone of dry sandstone. Salama suggested that further investigations should be concentrated in Saniya Hayeih ($25^o20'$E; $14^o25'$N) where a shallow trough in the Basement has resulted in a saturated thickness of 100 m and more despite its proximity to the divide and in Wadi Howar, but there are no definite plans for groundwater development in the region due to the small population and its nomadic lifestyle. If water is required in further years for settlements in the south it will be necessary to carry out hydrogeological investigations to determine aquifer properties for localised development. It is possible that the present hydraulic gradient is residual from Pleistocene recharge, and until proved otherwise it must be assumed that present day recharge is negligible and that development of groundwater resources will be drawing on storage in the aquifer.

3.3.2 Central Darfur (Umm Keddada) Basin (Nubian)

This basin lies in Northern Darfur and Kordofan Provinces. It extends southwards from the Tagabo-Meidob divide covering an area of about 52,900 km^2. It is connected to the Sag el Naam Basin in the southwest and the Baggara Basin in the southeast.

3.3.2.1 Previous investigations:

The hydrogeology of that part of the basin lying in Northern Darfur was investigated by Hunting G & G and MacDonald (1969, 1970). The northeasterly extension of the basin into N. Kordofan, the Umm Badr area, is still largely unexplored.

3.3.2.2 Groundwater occurrence and aquifer limits:

The areal extent of the aquifer, configuration of the underlying Basement rocks, and saturated thickness have been determined from borehole data and geophysical sections (Hunting G & G and MacDonald). The width of unsaturated sediments around the basin margins is variable depending on the angle of inclination of the surrounding Basement rocks. It is greatest along much of the northern divide where a zone up to 50 km wide is dry. At the eastern end of the Meidob Hills however there is some continuity with the Tima Basin to the north. Over most of the basin the saturated thickness is 200-300 m, but is reduced to zero in places by irregular ridges in the Basement. The depth to water in the sandstone ranges from about 25 to 150 m.

3.3.2.3 Groundwater movement:

Groundwater flows towards the south and southeast under hydraulic gradients of 1 : 250 to 1 : 450 depending mainly on the configuration of the underlying Basement and saturated thickness of the aquifer. The spur of Basement rocks extending eastwards and dividing the Central Darfur from the Baggara Basin to the south is formed of bedded and fractured quartzites which appear to be permeable. There is no deflection of southwards moving water near this outcrop, and leakage through the quartzites is inferred. Seasonal fluctuations in water levels of 0.1 to 0.3 m have been measured at Umm Keddada (26°30'E; 13°30'N) but there appear to be no general decline.

3.3.2.4 Aquifer characteristics:

Mudstones in the Nubian are generally thin and impersistent but do give rise to local perched water tables as at Umm Keddada.

Transmissivities determined from a few pumping tests are low: 5 to 40 $m^3/d/m$, for a saturated thickness of about 50 m. The aquifer is generally confined with S of 1×10^{-4} to 6×10^{-4}. Only at one site was drainage complete enough to determine the specific yield: at Umm Bayada al Humeira the pumping test indicated an Sy of 11%. Salama (1976) quotes values for T of 300 to 700 $m^3/d/m$ but his source of information is unknown.

3.3.2.5 Water quality:

Salinity is generally low, in the order of 100-200 ppm. Salama (1976) states that there is an increase of dissolved salts in the direction of flow, but this trend is not apparent on Hunting G & G and MacDonald's (1970) map. In the south, evaporites in the Nubian cause locally high salinities reaching as much as 18,000 ppm in the vicinity of Jebel Hilla. Water obtained from wells tapping the Basement, near the margins of the basin, usually has a salinity of 350 ppm or more. The composition of dissolved solids is dominated by Ca, Na and HCO_3 ions except where there are evaporites, which result in dominantly Na Cl water. The high sodium content in these areas may make the water unsuitable for irrigation.

3.3.2.6 Water resources:

Hunting G & G and MacDonald (1970) mention that experiments in the qoz have shown that rainfall only penetrates to 3 m before being evaporated. It is expected that the main source of recharge to the sandstone is via the wadis which flow south from the Meidob, and to a lesser extent the Tagabo Hills. Further south there may be a small contribution to recharge from surface runoff along the margins. Another major source is groundwater flow from the Sag el Naam Basin in the southwest, although much of this may flow southeast through the quartzites, thus having little effect on the water balance of the Central Darfur Basin.

Hunting G & G and MacDonald (1970) estimated recharge to the basin assuming a K of 1 m/d and that active flow would only take place in the uppermost 200 or so metres of saturated aquifer. On this basis, flow from the northeast was calculated to be 14.87 x 10^6 m^3/yr, but only 4.33 x 10^6 m^3/yr flows southwards through the Nubian Formation to the Baggara Basin, supporting evidence of leakage through the quartzites. Flow through the sandstone from the Sag el Naam Basin was estimated at ca. 0.83 x 10^6 m^3/yr but since then the water balance of the Sag el Naam Basin has been reviewed (Hunting T.S. and MacDonald, 1976) and 2 x 10^6 m^3/yr seems likely, with possibly 21 x 10^6 m^3/yr flowing through the quartzites. There is however insufficient data to quantify recharge from the Basement areas surrounding the rest of the basin.

Abstraction is probably between .83 x 10^6 m^3/yr (Hunting G & G and MacDonald's estimate for 1969/1970 for Darfur) and 5.63 x 10^6 m^3/yr (Salama's estimate for the whole basin).

Hunting G & G and MacDonald give a figure of 3 x 10^{12} m^3 of water in storage in the aquifer, which would be somewhat higher if the Umm Badr area was included. Salama's calculation used S of 10^{-4} instead of the specific yield, resulting in the meaningless figure of 7.9 x 10^8 m^3.

3.3.2.7 Recommendations:

Previous work has helped in a general description of the aquifer and water resources but data is too scattered to enable predictions to be made confidently.and more detailed investigations will be required if development of the basin is planned. Salama (1976) proposed further work in the Umm Bayada area, just southeast of the Meidob Hills.

3.3.3 Shagera Basin (Nubian/Volcanics/Alluvia)

This small basin is located to the west of El Fasher town in Northern Darfur. It lies within the Wadi el Ku drainage system and covers an area of ca. 1,500 km^2. The Nubian Sandstone Formation is overlain by Tertiary volcanics, largely trachytes and basalts, in the centre of the basin. The whole area is overlain by superficial deposits: wadi fill along surface drainage lines and qoz dunes elsewhere.

3.3.3.1 Previous investigations:

The Shagera Basin was considered in the hydrogeology of Darfur by Hunting G & G and MacDonald (1970): seismic spreads determined the shape of the basin where boreholes were lacking, water levels were monitored and one pump test was carried out. A.R.M. Mohamed (1975) presented the hydrogeology in more detail including results of three more pumping tests on wells fully penetrating the Nubian sandstone.

3.3.3.2 Groundwater occurrence:

The main aquifer consists of pebbly sandstone beds within the Nubian Formation. The upper layer of volcanics consists of trachytes which form a locally important aquifer where they lie below wadi alluvium and are weathered. The Basement Complex is also permeable where it is weathered, and pebbly sands of the wadi fill deposits also form minor aquifers.

3.3.3.3 Aquifer limits:

The basin is elongated west-east and the underlying Basement drops in the same direction to a depth of 270 m below surface in the eastern part. South of El Fasher a Basement ridge lies close to the surface and forms the eastern limit of the basin. The depth of the piezometric surface varies from 30 m along the wadis to about 50 m elsewhere. In the centre of the basin volcanics up to 120 m thick act as a confining layer over the Nubian.

3.3.3.4 Movement of groundwater:

Groundwater flows to the southeast, in the same direction as the surface drainage, under a hydraulic gradient of ca. 1 : 550 (Hunting G & G and MacDonald, 1970) at a velocity of about 0.7 m/yr (K = 1 m/d) to 2.1 m/yr (K = 3 m/d). During the period 1970-1972, 50 wells were monitored for fluctuations in water levels. Along the drainage courses rises of 1.5 m were measured in the volcanics and Nubian during and shortly after the rainy season. The recession during the subsequent dry season was at the rate of 0.3 m per month. Elsewhere diurnal fluctuations of 0.1 m have been measured in the Nubian, interpreted variously as due to well discharge by Mohamed (1975) and as due to barometric pressure effects on a confined aquifer by Hunting G & G and MacDonald (1970).

3.3.3.5 Aquifer characteristics:

Several pumping tests have been carried out, and drawdown and recovery data obtained from observation wells. Values of T for the Nubian aquifer calculated by Hunting G & G and MacDonald (1970) and A.R.M. Mohamed (1975) vary from 80 m^3/d/m to 370 m^3/d/m. Mohamed gave an average value for S of 2×10^{-4}, but his analyses imply a modal value of 1×10^{-4}. Permeability was found to increase towards the southwest, due to increasing homogeneity of the aquifer. At the periphery of the lava flows leakage from the upper wadi deposits occurred towards the end of the tests. The Nubian aquifer is unconfined where the volcanic flows are absent or above the water table, and rest water levels indicate hydraulic continuity with groundwater in the alluvial deposits.

3.3.3.6 Water quality:

Water from the volcanics and Nubian has a salinity ranging from 200 mg/l to 900 mg/l. The salinity increases in the direction of the flow and decreases during the wet season. In places in the volcanics there is a rise in salinity during the wet season indicating recharge of more saline water (av. 1,000 mg/l) from the adjacent Basement Complex.

At lower concentrations water from the volcanics, Nubian and wadi fill is generally dominated by Ca, Na and HCO_3 ions.

3.3.3.7 Groundwater resources:

Using a T of ca. 200 $m^3/d/m$ and a flow net constructed from measured water levels, Mohamed (1975) calculated a recharge of 1 x 10^6 m^3/yr. Despite the poor construction of the net and lack of water level data for the south of the basin, the estimated throughflow is of the same order as that reached by Hunting G & G and MacDonald (1970) of 0.7 x 10^6 m^3/yr outflow to the Sag el Naam Basin.

Recharge mainly takes place through wadi alluvium and flow from the Basement where this is permeable. The volcanic highlands of Jebel Marra which bound the basin the west have a relatively high rainfall of ca. 800 mm/yr and most recharge is therefore from this direction. Groundwater is discharged to the southeast, mainly through the weathered top of the Basement Complex and/or alluvial deposits underlying Wadi el Ku.

Abstraction of water from the Nubian was estimated to be ca. 48,000 $m^3/year$ from five boreholes by Hunting G & G and MacDonald (1970), but with the development of a well field production has been rising by about 709,000 $m^3/year$ (Mohamed, 1975) from 14 drilled wells. Of this, 30% is used for irrigation and the rest for El Fasher water supply. The demand for water is almost twice the amount abstracted from groundwater, which is already 65% of the estimated recharge.

Figures given for the amount of water in storage vary considerably: in Hunting G & G and MacDonald (1970) the area of the basin is taken as ca. 1,500 km^2, the specific yield as 10%, resulting in a value of 20 x 10^9 m^3 in storage. Mohamed's estimate of 4.6 x 10^6 m^3 used the storage coefficient for a confined aquifer and is therefore not applicable.

3.3.3.8 Recommendations:

Despite the investigations already carried out the amount of recharge and storage in the Nubian aquifer are not well defined due to the lack of data in the south of the basin and the lack of pumping tests on wells to determine the specific yield where the aquifer is unconfined. If further development of groundwater is required a drilling and testing programme will be necessary in those areas to improve on present estimates. However El Fasher is also supplied from surface water sources, which are expected to be adequate for its forseable requirements. Mohamed's recommendation to increase well spacing from 300 m to 600 m to reduce drawdowns during pumping should be implemented.

3.3.4 Sag el Naam Basin (?Nubian/Alluvium)

This basin is formed by a faulted trough in the Basement Complex extending along Wadi el Ku. It is located some 40 km south of El Fasher and is ca. 2,700 km^2 in area. There is some evidence (Hunting T.S. and MacDonald, 1976) that the Nubian Sandstone Formation has been reworked, resulting in greater permeability. The average rainfall over the basin is ca. 275 mm.

3.3.4.1 Previous investigations:

Most information on the hydrogeology of this basin comes from the Hunting G & G and MacDonald (1970) and Hunting T.S. and MacDonald (1976) surveys.

3.3.4.2 Groundwater occurrence and aquifer limits:

The sandstones and mudstones of the 'Nubian' are overlain by about 100 m of alluvial sands, clays and silts which are thought to be hydraulically continuous and make up a single aquifer system.

The area underlain by saturated sediments is more than 1,000 km^2. Except in the east, where the sandstone continues into the Central Darfur Basin, the aquifer is surrounded and underlain by rocks of the Basement Complex. The form of the underlying Basement is very irregular and reaches 2,000 m below surface.

Clays in the flood plain of Wadi el Ku are thought to form a continuous aquiclude in the central and southern parts of the Basin (Salama, 1976): in the centre they are 15 m thick but one borehole in the south has proved 200 m.

The depth of the piezometric surface is generally between 70 m and 90 m, but is less in the east.

3.3.4.3 Movement of groundwater:

Groundwater flows from the margins of the basin to the centre and then eastwards under hydraulic gradients averaging 1 : 290. The directions of flow in the south of the basin are poorly known. Hunting T.S. and MacDonald (1976) did not find any evidence of seasonal fluctuations of water levels along Wadi el Ku, but ACSAD (1979) quotes a rise of 3 m after one rainy season. Away from the wadi seasonal fluctuations in the water table are insignificant.

3.3.4.4 Aquifer characteristics:

Hunting G & G and MacDonald (1970) carried out a pumping test at Sag el Naam town (25°40'E; 13°20'N), where T was calculated to be 560 m^3/d/m from a well penetrating 48 m of saturated aquifer. Lost circulation during drilling has shown the upper layers of saturated sandstone to be very permeable. At Sag el Naam town, Hunting T.S. and MacDonald (1976) estimated that 80% of the saturated sequence is permeable, with a hydraulic conductivity, K, of ca. 7 m/d.

The aquifer is unconfined near the margins of the basin, but semi-confined to confined beneath and between mudstones. The storage coefficient, S, at Sag el Naam was calculated to be 1.3×10^{-4}, but no reliable data for determination of the specific yield is available.

3.3.4.5 Water quality:

The salinity of groundwater from the 'Nubian' sediments is low, from 80 to 500 mg/l. The dominant ions in solution are Ca, Na and HCO_3, but both Na and Cl become more important downstream.

For irrigation purposes the water has a low sodium hazard and medium salinity hazard (U.S. Salinity Laboratory Standard). High nitrates are thought to be caused by nitrate bearing desert clays (Hunting T.S. and MacDonald, 1976).

3.3.4.6 Water resources:

Hunting G & G and MacDonald (1970) estimated recharge from the western end of the basin to be ca. 6.6 x 10^6 m^3/yr. This calculation used values for K taken from tests in the Umm Keddada basin, since when further pumping tests have shown the 'Nubian' in Sag el Naam basin to be far more permeable. Using a K of 7 m/d for 80% of the saturated thickness, Hunting T.S. and MacDonald (1976), the revised figure is ca. 35 x 10^6 m^3/year. As they point out, this is on the high side as K is unlikely to be so high over the whole basin due to greater thickness of mudstones. A recharge of 25 x 10^6 m^3/yr is thought to be more realistic.

It appears that recharge takes place laterally through wadi alluvium and the weathered top of the Basement Complex. The outflow from the basin is not known. If K is 5 m/d the flow through the sandstone to the Central Darfur Basin would be ca. 2 x 10^6 m^3/yr. Abstraction was around 0.18 x 10^6 m^3/yr in 1969/1970 increasing to 1.5 x 10^6 m^3/yr in 1975. If the new estimate of recharge is in the right order then about 20 x 10^6 m^3/yr must pass out of the basin by leakage through the Basement. The quartzites in the east are known to be relatively permeable but Hunting T.S. and MacDonald (1976) do not believe that they could accomodate this flow of water.

The amount of water in storage in the aquifer may be in the order of 100 x 10^9 m^3 (Hunting G & G and MacDonald, 1970). A proportion of this is expected to be stagnant in depressions in the Basement and therefore saline.

3.3.2.7 Recommmendations:

Hunting G & G and MacDonald (1970) suggested further investigations to locate pilot irrigation schemes, and at least 20 irrigation wells have since been constructed despite the depth to water.

ACSAD (1979) are proposing an infiltration study to determine the amount of direct recharge from rainfall. The study by Hunting T.S.

and MacDonald (1976) makes it apparent that the water resources for the basin as a whole are poorly known. Data from the new irrigation wells should help in this matter, but the following work will be essential to an overall understanding of the basin.

1. To determine the form of the piezometric surface in the south of the basin. There may be outflow in this direction.

2. To estimate the quantity of outflow to the east, transmissivity tests in the sandstone and quartzites are required.

3. To determine the amount of recharge from the wadis requires more comprehensive monitoring of water levels.

Present development is concentrated in the north west of the basin and the above may therefore require a new drilling programme.

Hunting T.S. and MacDondald suggested that until further studies have been carried out it would be unwise to plan for an abstraction of more than 25 x 10^6 m^3/yr. However, since the major developments will continue to be in the northwest, for irrigation and possibly in the future for El Fasher water supply, only a porportion of this estimated recharge can be used

3.3.5 Nahud Basin (Nubian)

This basin is an isolated outlier some 1,000 km^2 in area situated in Northern Kordofan. The Nubian Formation is covered by ironstone, clays and fixed sand dunes which provide topographical relief of about 80 m.

3.3.5.1 Previous investigations:

The Geological Survey started investigations in 1961 to determine the groundwater potential of the basin and an authoritive account was written by Rodis and Iskander (1963). In 1970 Strojexport identified a major graben in the east: the Sa'ata-Gefaua trough. Several authors have since reviewed work in the eastern area in attempts to find a groundwater source for El Obeid water supply (Hunting T.S. and MacDonald, 1974); Bannaga, 1977; Institute of Hydrology, 1978c). Abdel Salam (1972) attempted to draw up a water balance for the basin as a whole.

3.3.5.2 Groundwater occurrence and aquifer limits:

The Sandstone dips gently away from the surrounding Basement Complex rocks towards the centre of the basin, reaching 150 m in thickness. In the east however, sediments in the Sa'ata Gefaua trough reach 350 m. This trough is 40 km long, from east to west between the two towns after which it is named and 5 km wide, opening out westwards in the region of Sa'ata.

The depth to water is from 75 to 100 m below surface. Hence the margins, including much of the northern part of the basin and the areas north and south of the Sa'ata Gefaua trough are dry. The saturated thickness is ca. 130 m on average but probably reaches up to 250 m in the Sa'ata Gefaua trough. The area underlain by saturated sediments is ca. 6,600 km^2.

3.3.5.3 Movement of groundwater:

Many authors agree with Kheiralla (1970) that water flows towards the centre of the basin. Kheiralla's interpretation was based on Carbon 14 dating of water samples which gave values of 4,000 to 5,000 years BP increasing in age towards the centre. However both C^{14} and water level data are so scanty, particularly in the south east, that the form of the piezometric surface can be interpreted quite differently, as by Abdel Salam (1972). He shows flow to the southwest and east from a mound 32 km east of Nahud. The hydraulic gradient is ca. 1 : 2,000 to 1 : 5,000 towards the east, and the estimated velocity is 0.3 m/yr (Abdel Salam, 1972) so that water moves approximately 3 metres in 10,000 years.

Rodis and Iskander (1963) found that there had been no long term trend in water levels since regular measurements started in 1932. According to them the 1961 abstraction rate of 0.47 x 10^6 m^3/yr would lower the piezometric surface by only 1 m in 550 years even without recharge. This assumes that water is yielded from storage at a specific yield of 5%, but where the aquifer is confined head losses will be more rapid. Measurements of water levels have not been taken frequently enough to determine seasonal fluctuations.

3.3.5.4 Aquifer characteristics:

Well yields are generally low, about 1 l/s, but specific capacities are relatively high: 25-40 m^3/d/m in the Sa'ata-Gefaua trough. From this and results of pumping tests and grain size analyses, the Institute of Hydrology (1978c.) estimate T to be in the order of 125 m^3/d/m. From the same data, Hunting T.S. and MacDonald (1974) found that T varies from 50 m^2/d to 350 m^2/d, and most estimates by other authors lie in this range. Approximately 50% of the sedimentary sequence in the Sa'ata Gefaua trough is thought to be transmissive to water (Strojexport, 1970), while further west the permeable sandstone may make up only 20% of the sequence (Rodis and Iskander, 1963). The range of T of 300 m^3/d/m to 1,000 m^3/d/m quoted by Salama (1976) for the whole basin therefore seems too high.

The aquifer is under water table to confined conditions, but few pumping tests have enabled the coefficient of storage to be determined. One pumping test analysis by Abdel Salam (1972) gave a value of 8 x 10^{-4}.

3.3.5.5 Water quality:

There is generally a low TDS content of 112-260 ppm in the main part of the basin and 220-320 ppm in the Sa'ata-Gefaua trough. In the Nahud well field only the water is more saline, around 1,800 ppm. Because of this, Rodis and Iskander (1963) suggested that the area could be hydraulically discontinuous from the rest of the basin. If Abdel Salam's interpretation of groundwater flow is correct, the high salinity could be due to stagnation. The presence of evaporites is not known.

3.3.5.6 Water resources:

Salama (1976) estimated that recharge to the basin is ca. 15.4 x 10^6 m^3/yr but other authors think that recharge is negligible. No significant tritium and low values of O^{18} (-9‰ to -18‰) and deuterium (-65‰) were found in water from the sandstone, indicating that significant recharge would have taken place under cooler conditions in the past (Kheiralla, 1970). Abdel Salam (1972) suggested that most of the groundwater has been stored in the aquifer since Pleistocene times.

Surface drainage is very poorly developed, hence concentrated wadi flow which is an important recharge process in other basins in the semi-arid zone, is inoperative. Abdel Salam (1972) estimated the eastward flow of groundwater to be ca. 0.2 x 10^6 m^3/yr, and more would flow in other directions from the hypothetical recharge mound east of Nahud town.

The rate of abstraction has increased at ca. 0.2 x 10^6 m^3/yr between 1961 and ca. 1974, when it was estimated at 2.5 x 10^6 m^3/yr by Salama (1976). This is several times more than the predicted rate of recharge, but very small in comparison to the volume of water in storage: ca. 20 x 10^9 m^3 at a specific yield of 5% for one half of the saturated thickness.

Several authors have hypothesised leakage from the basin into the Basement Complex which is fractured to a depth of 150 m in places.

3.3.5.7 Proposed investigations:

It is evident that the resources of this basin cannot be quantified without a better spread and more frequent measurements of water levels, and several pumping tests using observation wells. Hunting T.S. and MacDonald (1974) and the Institute of Hydrology (1978) have drawn up proposals for drilling and pump testing of exploration wells, concentrating on the eastern part of the basin. Salama (1976) recommended that further investigations should be carried out in the well field supplying Nahud town. Bannaga (1977) concluded, as indicated by the preliminary estimates shown above, that there is little excess groundwater within the basin to supply towns outside such as El Obeid. Development of the aquifer for this purpose may require mining of stored water, making quantification of transmissivity and the storage coefficient imperative.

3.3.6 Baggara Basin (Nubian/Umm Ruwaba)

The Baggara Basin constitutes an extensive aquifer system located mainly in southern Darfur and Southern Kordofan Provinces. The Nubian Sandstone and Umm Ruwaba Formations extend over an area of about 120,000 km^2.

3.3.6.1 Previous investigations:

The hydrogeology of the eastern part is described in general terms in Rodis et al. (1964). Hunting T.S. and MacDonald (1974, 1976) have made more detailed studies covering most of the basin during two separate projects. El Tohami (1977) synthesised the previous work and presented some new data for the basin as a whole.

3.3.6.2 Groundwater occurrence and aquifer limits:

In the north there is a connection with the Central Darfur Basin. In the south-east the boundary is somewhat arbitrary and for a large part follows the course of the Bahr el Arab. Elsewhere the basin is enclosed by rocks of the Basement Complex. The lateral limits are ill defined due to the cover of superficial deposits but the effective limit of water bearing strata is the 100 m isopach giving an area of about 115,000 km^2. In the north of the basin some ridges stand as high as 50 m below surface in places: one such (the Abu Tama-Umm Dobai ridge) forms the northern limit of the basin. Around the margin of the basin a few small sub-basins have been located both in the west (Dargalla: 24^{o}30'E; 11^{o}25'N and Babaya Dereisa) and east, Debbat Abeid.

The subsurface form of the basin is fairly well known from boreholes and geophysical surveys (Texas Instruments, 1962; Strojexport, 1971-72; Hunting G & G, 1973; Hunting T.S. and MacDonald, 1974).

There is a series of troughs and ridges in the Basement formed by step faulting with greatest depths along the central troughs (up to 4,000 m). These structures are oriented E-W in the western bulge and NW-SE in the rest of the basin. The thickness of infilling sediments average about 850 m. The depth to the piezometric surface decreases from 110 m in the north to less than 50 m in the southeast.

3.3.6.3 Groundwater movement:

Groundwater flows from the basin margins towards the centre and then southeastwards to the Sudd Basin. Hydraulic gradients vary from 1 : 4,000 to 1 : 1,000, being steepest in the southeast where the Umm Ruwaba is thickest. At Bargalla and Debbat Abaid the sub basins have a water table some 25 m above the regional level, and steeper hydraulic gradients, indicating buried basement ridges acting as dams.

There is little information available on seasonal fluctuations of water levels. In two boreholes near Bahr el Arab water levels rose by 0.5 m and 0.9 m over a period of six months, including a rainy season during 1972-1973, indicating that there is recharge to the aquifer from stream flow in the Bahr. However there is little long term variation in water levels even in the areas of heavy abstraction such as El Dein, Babanusa and Muglad.

3.3.6.4 Aquifer characteristics:

Yield tests have enabled the specific capacity to be determined for over 170 wells. The range was found to vary between less than 1 $m^3/d/m$ to about 1,000 $m^3/d/m$, with the middle 50% of values ranging from about 6 $m^3/d/m$ to 73 $m^3/d/m$. The transmissivity of the aquifer has been estimated using these values in Logan's formula:

$$T = \frac{2.2\,Q}{smw}$$

where: T = transmissivity $m^3/d/m$

Q = discharge m^3/d

smw = maximum drawdown in well, m

The middle 50% of wells lay in the range 7 $m^3/d/m$ to 90 $m^3/d/m$. A short drawdown test in a pumping well indicated a transmissivity of 120 m^2/d (El Tohami, 1977). The Nubian Formation is more transmissive than the Umm Ruwaba, highest values occurring in the western trough. Lowest transmissivities were found in the central Umm Ruwaba trough, especially in the south east of the basin. Observation wells were not used in any of the tests, so the values of T are very approximate, and the storage coefficient could not be quantified alone. The percentage of permeable strata in the sequence is of course highly variable: in the Nubian sandstones they can make up 60% to 90% of the total while in the north of the basin the sequence of 200 m is almost wholly mudstone. The specific yield was estimated to be about 5% (Tohami, 1977) from grain size analysis both here and in Northern Darfur.

Water table conditions are found at the margins of the basin, but the aquifer becomes increasingly confined in the direction of groundwater flow, there may be hydraulic discontinuity between the Nubian and Umm Ruwaba in the southeast where rather poor borehole records indicate that the piezometric surface may be 10 to 30 m higher in the Nubian.

3.3.6.5 Water quality:

In most of the basin the quality of water is excellent, with a salinity rarely more than 1,000 mg/l. In the east and western margins it is 100 mg/l or less, and increases in the direction of water flow. Lowest concentrations are found in the Nubian, while the highest salinities are found in the Umm Ruwaba, especially where this is thick as in the central trough. The difference between the two formations is thought to be due to the lack of soluble materials in the Nubian strata compared to the Umm Ruwaba which contains lenses of evaporites. Relatively high concentrations in the north east could be due to stagnation of water behind a buried basement ridge.

Water from the Nubian is generally dominated by Ca, Na and HCO_3 ions. Sodium concentrations increase at the expense of calcium downstream, indicating that base exchange is effective. Water with higher concentrations of dissolved solids from the Umm Ruwaba has much higher proportions of Cl, SO_4 and Mg ions, probably due to solution of evaporites.

Nitrates are high in open wells due to organic pollution.

3.3.6.6 Water resources:

El Tohami (1977) estimated that the total flow of groundwater passing southeastwards to the Sudd Basin is approximately 23 x 10^6 m^3/yr. He equates this value with annual recharge, equivalent to 0.2 mm/yr over the area underlain by the aquifer. This would be about 0.03% of the average annual rainfall of 600 mm. The lack of any significant tritium in water samples (Kheiralla, 1970; El Tohami, 1977) indicates that rapid recharge through superficial deposits is not significant. However evidence of seasonal fluctuations in the water table near wadi courses supports the view that concentrated surface flow in the wadis is the main source of recharge to the Nubian-Umm Ruwaba aquifer. A recharge of 23 x 10^6 m^3/yr is equivalent to 3% of surface flow entering the basin. Most of the wadis flow from June to October, but flow in Bahr el Arab may persist until December.

$Oxygen^{18}$ and Deuterium analyses so far indicate that water in the aquifer was recharged during climatic conditions much cooler than present (Kheiralla, 1970; El Tohami, 1977). Carbon 14 analyses give ages of 4,000 to 5,000 years before present, increasing in the direction of flow but there are many discrepancies in the data.

It is possible that the throughflow to the Sudd Basin is partly due to residual hydraulic gradients from Pleistocene recharge and that recharge today is not as great as the amount above.

Abstraction accounts for only 1 x 10^6 m^3 of water per year according to El Tohami, but Salama (1976) quotes a figure of 11.9 x 10^6 m^3/yr.

The amount of water in storage is estimated at 6.6 x 10^{12} m^3, but for well abstraction only the top 500 m of saturated thickness is economically exploitable through wells, an estimated storage of 2.5 x 10^{12} m^3.

3.3.6.7 Recommendations:

El Tohami (1977) and Hunting T.S. and MacDonald (1974) delineated areas of specific capacity higher than 75 m^3/d/m and a piezometric surface less than 50 m below surface as the most favourable areas for development. Hunting T.S. and MacDonald (1974) suggest that 38 new wateryards are required in the qoz regions for domestic and livestock supply. Where the aquifer limits are less well known, along the southern edge of the western bulge, boreholes should be drilled 10 km away from the basement outcrops. El Tohami (1977) suggested development of the 'rainlands' in the south of the basin to relieve pressure on the savannah areas further north.

Any concentrated development, for increasing town supplies or for irrigation, will require more accurate determination of the hydraulic characteristics of the aquifer, particularly the storage coefficient, and pumping tests of several days using observation wells should be envisaged. Determination of the storage coefficient together with monthly observations of water level fluctuations near wadi courses would help in the estimate of present day recharge. Further tritium and stable isotope analyses should also help to clarify the recharge processes, but a programme should be designed on the basis of water level data collected over a few years.

3.3.7 Sudd Basin (Umm Ruwaba)

The Sudd Basin is the largest sedimentary basin in Sudan. Some 365,300 km^2 in area, it is connected to the Baggara Basin in the north west and to the Eastern Kordofan Basin in the north east. It is drained by several major tributaries of the White Nile and by many smaller rivers. The discharge at Malakal is about 30 x 10^9 m^3/yr. The rainfall varies from 1,000 mm/yr in the south to 500 mm/yr in the north.

3.3.7.1 Previous investigations:

Due to the relatively high rainfall and abundance of surface water, groundwater investigations have taken low priority. Salama and Salama (1974) and Salama (1976) have presented a general outline of the hydrogeology of the basin. Strojexport (1977) carried out geophysical investigations in the northeast of the basin. The results of Terwey's (1979) survey of the area around Bor (6°15'N; 31°30'E) are not yet known.

3.3.7.2 Groundwater occurrence and aquifer limits:

The lateral limits of the basin are formed by rocks of the Basement Complex. In the northwest is it is continuous with the Baggara Basin along the Abu Gabra-Duk Faiwal axis, and in the northeast with the Eastern Kordofan basin along the Gelhak-Akobo axis. The boundary in the northeast is poorly defined due to a complexity of troughs and ridges in the underlying Basement and limited information on the form of the piezometric surface. Salama (1976) considers the basin to extend as far north as Er Renk (11°40'N; 32°40'E).

The sediments are 60 to 120 m thick in the marginal zones and reach more than 500 m along the major troughs, the Abu Gabra-Duk Faiwal and Gelhak-Akobo axes. The depth to water is generally 10-25 m. Salama (1976) states that the saturated thickness varies from 100 to 3,000 m implying much greater depths to the Basement. Individual permeable layers range from several centimetres to several metres in thickness but only form a small proportion of the total sequence. Strojexport considers the northeastern area to consist of independent basins separated by conspicuous ridges but connected to each other in places.

3.3.7.3 Groundwater movement:

Water moves from the margins of the basin towards the Sudd area near the confluence of the two major tributaries of the White Nile, The Bahr el Ghazal and Bahr el Jebel. Here the piezometric surface lies above ground level and there is discharge of groundwater in swampy terrain. Due to the low permeability velocities are as low as 0.1 m/yr (Salama, 1976). Low permeability and the presence of Basement ridges may cause stagnant conditions at depth, particularly in the northeast of the basin.

3.3.7.4 Aquifer characteristics:

The transmissivity of the Umm Ruwaba aquifer was estimated by Salama and Salama (1974) to range from 6 to 120 $m^3/d/m$ in the south and from 12 to 250 $m^3/d/m$ in the north. The permeability is generally low and decreases with depth. It is lower than average along the Akobo axis where there is a higher percentage of fine sediments. Due to the heterogeneity of the sediments and high percentage of claystones and fine sands, Strojexport (1977) consider there is no horizontal and probably little vertical connection between individual water-bearing layers in the northeast, and that the Umm Ruwaba here constitutes a "hydraulically discontinuous multi-layer aquifer system".

3.3.7.5 Water quality:

The salinity varies from 200 to 500 mg/l in the peripheral zones, increasing to 5,000 mg/l in the central part where velocities are lowest. Salinity also increases with depth, and there may be connate water due to the difficulty of flushing. Near the margins of the basin in the south, groundwater in the Umm Ruwaba has a similar composition to water in the weathered Basement, with HCO_3 being the dominant ion. The proportion of SO_4 in solution increases in the direction of flow at the expense of HCO_3.

3.3.7.6 Water resources:

Salama (1976) estimated the recharge to the whole basin to be 341×10^6 m^3/yr, although the amount flowing to the centre of the basin is only 200×10^6 m^3/yr. Of this 23×10^6 m^3/yr is thought to flow from the Baggara Basin. It appears that most of the recharge is from khors flowing from the Basement areas in the north, southwest and southeast and from the tributaries of the White Nile. Despite the relatively high rainfall, direct recharge will be low due to the thick surficial clays. Discharge to the streams and lakes in the Sudd area is put at about 200 x 10^6 m^3/yr and abstraction from wells is about 2 x 10^6 m^3/yr. This accounts for 202 x 10^6 m^3/yr of recharge, the other 133 x 10^6 m^3/yr is unaccounted for.

Salama (1976) estimated there to be ca. 11 x 10^9 m^3 of water in storage in the aquifer, but it appears that a storage coefficient for confined conditions was used in the calculation. For a specific yield of 0.05, an area of 365,000 km^2 and a saturated thickness of 250 m (at greater depths in many areas water may be stagnant and highly saline), a volume of about 5 x 10^{12} m^3 is obtained.

3.3.7.7 Recommendations:

Strojexport (1977) have recommended drilling boreholes to depths of 350 m to verify the presence of Nubian Sandstone below the Umm Ruwaba in the northeast of the basin. Other drilling sites were suggested to investigate the Umm Ruwaba and alluvial deposits in the same region, and exact locations and well specifications given.

There is a high demand for good quality potable water for domestic purposes throughout the area but the high salinity of groundwater in the Umm Ruwaba compared to river water has limited development. Strojexport expect that alluvial sands recharged by the rivers will be the most productive source of potable water.

It is expected that the various rural water supply schemes in the southern provinces will in the future help to elucidate the hydrogeological conditions, and it is hoped that the UNDP plan to coordinate present drilling activities and data collection will be implemented.

Strojexport's resistivity surveys have located a layer of relatively high resistivity underlying the Umm Ruwaba sediments at depths of about 250 m. It was inferred that the high resistivity is due to a lower clay content, and possibly lower salinity of water and hence the probable presence of Nubian Sandstone Formation, which may reach hundreds of metres in depressions and a few tens of metres on ridges. Some lenticular occurrences of similar characteristics were found near the Nuba Mountains, but in most places it would be too deep to be of any practical significance. Horizontal connection of the Nubian Sandstone if present with the Eastern Kordofan is unlikely and the hydraulic connection with the Umm Ruwaba is not known.

3.3.8 Eastern Kordofan Basin (Umm Ruwaba/Nubian)

The Eastern Kordofan Basin occupies a surface area of about 68,400 km^2, mainly in Northern Kordofan Province. In the southeast it continues into the Sudd Basin while in the north it adjoins the Sahara Nile Basin. The surface is generally covered by 1-55 m of qoz sand dunes, and drainage is poorly developed except in the south at a latitude ca. $12^{o}40'$N where the Khor Abu Habl intermittently flows eastwards from the Nuba Mountains ending in a large delta which extends from southeast of Tendelti (ca. 32^{o}E; $12^{o}40'$N) to the White Nile.

Average annual rainfall varies from 200 mm in the north to 400 mm in the south.

3.3.8.1 Previous investigations:

Several studies have been carried out in the western part of the basin, mainly in relation to El Obeid water supply (Hunting T.S. and MacDonald, 1974a; Bannaga, 1977; Inst. of Hydrology, 1978a) and settlement in the qoz (Hunting T.S., 1970). The areas west of Kosti and Jebelein, important towns on the White Nile, have been investigated by the Institute of Hydrology (1978b) and RWC/ Netherlands (to be published) respectively. There is also a thesis on the area by Mabrook (1972).

3.3.8.2 Groundwater occurrence and aquifer limits:

The major aquifer is the Umm Rubwaba Formation, but water is also abstracted from the underlying Nubian Sandstone Formation where this is present at relatively shallow depths, and from the weathered top of the Basement Complex on the tops of ridges where the saturated thickness of overlying sediments is small. Shallow groundwater also occurs in the qoz sands and near the basin margins in the wadi alluvium.

The Nubian Sandstone Formation is predominant in the north of the basin where it is faulted against the Umm Ruwaba. It is also present at places in the Bara trough, particularly on the northern limb, and may also be found at depths exceeding 400 m in the southeast of the basin. Elsewhere the basin is infilled with Umm Ruwaba sediments. The two formations are in hydraulic continuity and water is produced from lenses of sand, gravel, sandstone and conglomerate separated by thick layers of clay and silt.

The basin is bound by the Basement Complex except in the northeast where the Nubian Sandstone continues into the Sahara Nile Basin and in the southeast where the Umm Ruwaba continues into the Sudd Basin. The eastern margin is formed by the White Nile, east of which the Basement Complex again crops out.

The main trough is the Bara trough which runs NW to SE through Bara town. It is 30 km to 60 km wide and sediments are more than 540 m thick but thin considerably over the ridge to the north, which in places lies above the piezometric surface resulting in dry wells. In the southeast, the recent RWC/Netherlands geophysical survey has located two troughs reaching depths of 2,000 m, separated by a ridge about 400 m below surface. These join up in the south and are continuous with the Er Renk depression in the Sudd Basin located by Strojexport (1971). It is possible that one of these depressions is continuous with the Bara trough.

The depth to the piezometric surface varies from 0 to 70 m in the Bara trough, shallow water levels being mainly associated with confined conditions. In the east the White Nile may be perched some 40 m or more above the piezometric surface.

3.3.8.3 Groundwater movement:

Water in the Bara trough flows southeastwards and then branches so that about 25% of the flow is eastwards, across the ridge into the northeast of the basin, while the rest continues southeastwards. The hydraulic gradient east of Bara is about 1 : 700. To the west it is much shallower and there may be a westward component of flow. North of the ridge bounding the Bara trough, in the west of the basin and in the southeast there may be stagnation: hydraulic gradients are low; in the first two areas there are no apparent outflow channels; in the latter sediments are very fine-grained and flow is impeded by subsurface ridges. Elsewhere directions of flow have not been determined.

Seasonal fluctuations of 1 to 2 metres were found by Mabrook (1972). The rainy season is between May and October, most rainfall taking place in July and August. Water levels start to rise in July reaching a peak in October to December, a delay of 2 to 4 months. It is not clear whether these fluctuations were measured in the main aquifer, in one of the perched water tables or in wadi deposits at the margin of the basin.

3.3.8.4 Aquifer characteristics:

The aquifer varies from unconfined to confined in the direction of flow. Flowing artesian conditions are found at Umm Balgi ($30^{0}36$'N; $13^{0}41$'E) 25 km NE of Bara. Although the aquifer here and elsewhere on the northern limb of the Bara trough and in the north of the basin is probably Nubian Sandstone, the differences to the Umm Ruwaba Formation in lithology are indistinct and identification uncertain and the two formations are therefore treated as one hydraulically continuous aquifer system, though it seems that the basal conglomerate of the Nubian could be the most productive horizon

(El Boushi et al. 1968). In the Bara trough the main aquifer is confined below mudstones over which perched water table conditions can occur.

Due to the heterogeneity of the aquifer the hydraulic conductivity is variable. From specific capacities of wells and bail tests in the Bara trough, Hunting T.S. and MacDonald found T to vary in the range 1 $m^3/d/m$ to 200 $m^3/d/m$, with a median value of 12.6 $m^3/d/m$. These authors, and the Institute of Hydrology (1978) expected the results to be affected by well losses, and the real median value for the southern part to be around 25 $m^3/d/m$. The northern part of the Bara trough has not been so closely investigated as it is further from El Obeid, but Mabrook (1972) found that coarse sands and gravels of the Nubian Sandstone Formation are more predominant and that the specific capacities of wells are greater, indicating a higher hydraulic conductivity. The transmissivity is expected to decrease to the east and southeast where the Umm Ruwaba Formation is finer grained.

Most authors have assumed that the specific yield of the aquifer is about 5% in the water producing srata.

3.3.8.5 Water quality:

In the Bara trough the salinity is generally less than 1,000 mg/l. Higher salinities at the northwestern margins of the basin are thought to be associated with the Basement Complex. The water is of low salinity in recharge areas around the Nuba Mountains and can have a T.D.S. of 300 mg/l and less. Low salinities have also been recorded in the northwest and along the Khor Abu Habl as far east as the apex of the delta, south of Tendelti.

Hunting T.S. and MacDonald (1974) found no obvious pattern in the distribution of salinity, but the main controls are distance from recharge, the damming effect of Basement ridges, the decreasing grain size of sediments to the east and southeast together with low hydraulic gradients and probable stagnation resulting in a T.D.S. of 7,000 mg/l and more. There also appears to be stagnation and poor quality water north of the major ridge which forms the northern boundary of the Bara trough. At places along the White Nile the quality of water from the Umm Ruwaba improves locally due to recharge.

In the southeast where the groundwater is stagnant the major ions in solution are Na, Cl and SO_4. Fluoride is sufficiently high in places to cause fluorosis, and nitrates are often high due to organic contamination of open wells. Away from the recharge sources and the Bara trough the salinity of water can limit its use for domestic purposes while the high proportion of Na can limit its use for irrigation.

3.3.8.6 Water resources:

The only attempt at a water balance for the whole basin is by Salama (1976). He estimated a recharge probably based on throughflow calculations, of 15.8×10^6 m^3/yr. Halcrow T.S. and MacDonald (1974) estimated the flow through the Bara trough to be in the order of 0.7×10^6 m^3/yr.

Due largely to poor determination of the piezometric surface, sources of recharge and quantities of water involved are not well known. It appears that the main source of recharge is from concentrated flow in ephemeral wadis draining the Nuba Mountains region where rainfall is relatively high. Of these Khor Abu Habl which flows from June to October, is probably the most important. Another major source may be from surface water courses draining the Basement in the north west. The White Nile recharges the aquifer by downward leakage at Kosti and probably along other stretches where the alluvium is sufficiently permeable. The recent RWC/Netherlands survey indicates that recharge does not take place along the whole river. Recharge from rainfall within the basin is an unknown quantity but may be important where the aquifer is unconfined: a recharge mound may be present west of Bara, and in places perched aquifers in the Umm Ruwaba/Nubian, as at Bara, must be recharge by this means. Due to the lack of surface drainage lines in the superficial qoz, it has been postulated that recharge may take place from temporary ponds in interdunal hollows.

Abstraction of groundwater was estimated at 4.5 x 10^6 m^3/yr by Salama (1976). Abstraction in the Bara trough, including discharge from the artesian well was estimated at 0.86 x 10^6 m^3/yr by Hunting T.S. and MacDonald (1974), which is more than the probable recharge. Most of the abstraction is for rural water supply and therefore widely distributed. It is only intense at Bara where wells pump 20 hr/day from the perched aquifer.

Salama (1976) gives a value of 2.3 x 10^6 m^3/yr for throughflow. This presumably refers to flow into the Sudd Basin, but water levels and aquifer characteristics are too poorly known to obtain a meaningful value. However, if this is of the right order, 9 x 10^6 m^3/yr, over 50% of Salama's recharge estimate is unaccounted for.

The exploitable storage over 9,000 km^2 of the Bara trough was estimated by Hunting T.S. and MacDonald (1974) to be 36 x 10^9 m^3, a value found acceptable by the Inst. of Hydrology (1978). If similar assumptions of specific yield of 5% for 80 m of permeable sediments is applied to the whole basin, the total useable storage would be 270 x 10^9 m^3.

From the above it appears that any large scale development of water resources in the Bara trough will be using water from storage. However, water recharge from the alluvium of Khor el Habl is hardly touched.

3.3.8.7 Recommendations:

Recommendations have been made by many authors to delineate areas of high transmissivity in the areas nearest to El Obeid for the town's water supply. Hunting T.S. and MacDonald (1974) suggested that this development, to provide 2.3 x 10^6 m^3/yr by the year 2000, would only be feasible at T of 50 m^3/d/m or more over a well field diameter of 12 km. Aquifer tests have so far been inadequate and although the median T indicated is only 25 m^3/d/m this may be on the low side. Also the heterogeneity of the aquifer increases the chances of finding areas of relatively high transmissivity.

There is still insufficient data to facilitate a choice between the Bara trough and the Sa'ata-Gefaua trough of the Nahud Basin as sources for supplementing El Obeid water supply. The latter has higher transmissivities, but the depth to water is greater and storage is more limited.

Along the White Nile it is possible that the river alluvium will be a more useful source of groundwater than the Umm Ruwaba aquifer on the west bank which tends to be saline, relatively deep and of low transmissivity. The Institute of Hydrology (1978) has suggested a simple exploratory drilling and pump testing programme on both banks in the Kosti area to determine the suitability of the alluvium for the town water supply. The RWC/Netherlands investigations have not yet been published, but they will probably recommend a geophysical and drilling programme along the White Nile to determine where recharge to the Umm Ruwaba aquifer takes place. RWC is establishing 7 rain gauges in the basin, as well as a drilling, logging, chemical and isotope analysis programme.

Another area for concentrated investigations should be the Khor Abu Habl: the recharge in this region might be sufficient to support irrigation for agricultural development near the apex of the delta. As Hunting T.S. and MacDonald (1974) point out, it is essential to determine the form of the piezometric surface. Altimetric measurements require collation and mapping and should be extended, and many borehole locations need checking. A monitoring programme is required for water levels and nitrate content. They also recommended that abstraction metres at water yards should be put in order.

3.3.9 Blue Nile Basin (Gezira Formation/El Atshan Formation/Nubian)

The Blue Nile Basin covers an area of ca. 75,800 km^2. It is an elongated basin extending from southeast to northwest. It is bounded by outcrops of Basement Complex rocks except in the north where the boundary is taken to the Basement ridge extending from Jebel Qeili in the east ($15^o40'$N; $33^o40'$E) to the River Nile in the west. In the northwest the boundary is the River Nile and White Nile.

3.3.9.1 Previous investigations:

The northern part of the basin, between the White and Blue Niles and east of the River Nile has been most thoroughly investigated due to its proximity to the capital, Khartoum. The most recent work in the vicinity of Khartoum was completed by the Geological Survey Department/German project early early in 1979, but is not yet published. The southern part of the basin has not been studied in detail largely due to the abundant supply of surface water from the Blue Nile and relatively high rainfall.

The most comprehensive reports available to date are by Saeed (1976) for the northern part and by Abdel Latif (1976) for the southern part.

3.3.9.2 Groundwater occurrence and aquifer limits:

The basin occupies a series of SE-NW trending troughs and ridges in the Basement Complex which are overlain by Nubian Sandstone and Tertiary sediments: the El Atshan Formation in the south and the Gezira Formation in the north. The Nubian Sandstone is exposed in the northeast, east of the Blue Nile and Nile rivers. The geophysical survey by REGWA (1977) located a major tough reaching depths of 300 m below sea level, immediately north of the horst which separates this basin from the East Kordofan Basin and forms the divide between the East Kordofan and Sahara Nile Basins. The form of the sub-Nubian surface in the north of the basin is delineated in Saeed (1976).

Lenses of conglomerates and sandstones in the Nubian, and sands and gravels in the Gezira and El Atshan Formation constitute important aquifers. Static water level in the Nubian range from 5 m near the Niles to 100 m below surface away from the rivers. The saturated thickness of this formation ranges from 20 m to 230 m, being thinnest over Basement ridges. In the Gezira and El Atshan Formations the depth to water increases from a few metres near the rivers to 60 m away from the source of recharge while the saturated thickness ranges from 10 m to 100 m.

the El Atshan Formation in which gravels are more common. Sandy beds can reach 40 m in thickness, while gravels in the El Atshan Formation are between 2 and 5 m thick. Clays are well developed west of the Blue Nile resulting in steep hydraulic gradients compared to the eastern bank. The specific yield of these unconsolidated sediments may be as high as 25% (Abdel Latif, 1976) but is very variable and must be much lower in the clays. The Nubian aquifer is generally confined below the Gezira and El Atshan Formations, but is unconfined at outcrop, as in the northeast of the basin or where the younger formations are thin. Except where the Nubian is very thin, as over ridges in the Basement, it is more productive than the Gezira and Al Atshan aquifers. Twenty-four hour tests on production wells indicate a wide range of transmissivity, from 40 to 6,000 $m^3/d/m$ (Saeed, 1976). The few pumping tests carried out with observation wells indicate storage coefficients of 8×10^{-4} to 6×10^{-5}.

Although the Nubian aquifer is confined below the shallower aquifers and has a different piezometric surface there is some hydraulic continuity between the two, with downwards leakage recharging the Nubian in the vicinity of the rivers. In the north of the basin, the recent investigation by the Geological Survey Department/German project has confirmed that the Nubian aquifer consists of a shallow unconfined aquifer recharged mainly from the Nile, and a deeper confined aquifer in which water moves northwest under the river. There is probably downwards leakage from the shallow aquifer in the vicinity of depressions in the water table.

3.3.9.5 Water quality:

The quality of groundwater in all the formations is generally good, with T.D.S. contents of less than 1,000 mg/l. In the Gezira Formation the salinity is 200 mg/l or less near the Blue and White Niles, increasing to 2,000 mg/l in the area of stagnation between the rivers. The distribution of salinity reflects the form of the piezometric surface, and confirms the lower recharge due to clays west of the Blue Nile. This results in an area of high salinity west of the Blue Nile which is accentuated by intercalations of carbonate nodules and gypsum. The composition of groundwater in the recharge areas reflects that of the river water: Blue Nile water has high proportions of Ca and HCO_3 while the White Nile has high proportions of Na and HCO_3.

The proportion of Cl and SO_4 increases in the direction of flow at the expense of HCO_3, while Na progressively replaces Ca. Water from the El Atshan Formation has a similar chemical composition.

Water from the Nubian aquifer is also of very low salinity, 200 mg/l and less, near the rivers, but increasing in the direction of flow. Cations are mixed, with Ca dominant in recharge zones, while the major anion is HCO_3. The salinity increases locally: where the aquifer is thin and affected by chloride salts concentrated on the underlying erosional surface (Abdel Latif, 1976);up to 1,500 mg/l of dissolved solids has been reached. Fairly high salinities are also found where Basement ridges, thick mudstones and depressions in the piezometric surface impede the flow of water. East of the Blue Nile salt deposits are formed in surface playas overlying depressions in the water table and downward leakage is thought to cause the locally high salinities (El Boushi, 1972).

The pH of water from the three formations is often more than 8 and fluoride can reach 1.6 mg/l in the Nubian aquifer (Saeed, 1976). Although groundwater in the basin is generally suitable for most purposes, locally high Na and Cl may limit its application for irrigation, and SO_4 is occasionally greater than the government's limit of 750 mg/l for drinking water.

3.3.9.6 Water resources:

Seepage from perennial rivers is the main source of recharge, but the quantities vary considerably depending on the clay content of the underlying sediments. Concentrated flow from the Basement outcrops around the basin provide a secondary source. There may also be some direct recharge from rainfall during July and August, when precipitation can exceed potential evapotranspiration. This would be most effective in the south of the basin where rainfall can exceed 1,000 mm, but is not expected to be significant in the north due to lower rainfall and the presence of thick surface clays between the White and Blue Niles.

The isotope analyses (Kheiralla, 1970; Saeed, 1976) indicate that recharge from the Blue Nile is slow, with significant tritium so far found only in one well close to the river. Typical isotope values for river water are the following:

	Tu	D‰	O^{18}‰
Blue Nile	168	-0.1	+11.0
White Nile	86	+1.9	+16.0

The White Nile water is enriched in isotopes due to evaporation in the Sudd region.

Recently recharged groundwater has a similar isotope content, but is quickly depleted in heavy isotopes away from the river. East of the Blue Nile, deuterium falls from -4 to -70‰ while O^{18} falls from +0.0 to -9.8‰. The results confirm that the effective limit of river recharge is 10 to 25 km, coinciding with the stagnant, saline troughs mentioned above.

Salama (1976) estimated that the total groundwater recharge to the basin is in the order of 71 x 10^6 m^3/yr, which corresponds fairly well with the 22 x 10^6 m^3/yr of recharge to the south of the basin proposed by Abdel Salam and Abdel Latif (1976). Evapotranspiration is probably a significant factor in the discharge of groundwater near the rivers where the water table is shallow and tapped by phreatophytes in the south. Deep cracking of clays in the dry winter season may also permit evaporation from the water table. The amount of groundwater discharged by these processes may be in the order of 70 x 10^6 m^3/yr (Saeed, 1976) or more, the figure including the west bank of the White Nile but excluding the Blue Nile and its tributaries south of 15°N.

The amount of abstraction from wells was estimated by Salama (1976) to be 21.6 x 10^6 m^3/yr. Abstraction locally exceeds recharge as evidenced by falling water levels in some wells northeast of Khartoum.

The quantity of water in storage is considerable compared to both recharge and abstraction: assuming that on average the saturated thickness accessible to wells (to a depth of 150 m below surface) is permeable with a specific yield of 10% the exploitable storage would be at least 500 x 10^9 m^3, while for an effective saturated thickness of 40 m it would be only 300 x 10^9 m^3.

3.3.9.7 Recommendations:

Many authors have recommended further studies of this area. Unsuccessful wells, falling water levels and high salinities in some localities have stimulated research but there is still a lack of basic data essential to a full understanding of the groundwater potential of the basin. It is expected that the results of the Geological Survey Department/German survey will elucidate the relationship between the shallow and confined Nubian aquifers east of Khartoum. Elsewhere, first priority should be given to rigorous aquifer tests to determine horizontal and vertical permeability, transmissivity and specific yields: efforts should be concentrated along the rivers to determine the distribution and amounts of recharge and natural discharge and in depressions of the piezometric surface to determine the importance of leakage between shallow and confined aquifers.

It is probable that the already extensive irrigation schemes using surface water from the rivers will continue to expand while groundwater will continue to be used mainly for domestic purposes. Any expansion of groundwater irrigation will however require control over the siting of wells and amount of abstraction.

3.3.10 <u>River Atbara Basin (Nubian/Alluvium)</u>

The Atbara Basin has an area of nearly 23,900 km^2. The annual rainfall ranges from 200 mm in the south to 130 mm in the north.

3.3.10.1 Previous investigations:

Groundwater occurrence in the western part of the basin was discussed in Kheiralla (1966). RWC has carried out a more detailed study of the Upper Atbara, including geophysical, drilling, test pumping and water level monitoring programmes.

3.3.10.2 Groundwater occurrence and aquifer limits:

Groundwater is abstracted from gravelly sandstones in the Nubian sequence and from alluvial deposits along the rivers Atbara, Nile and khor beds. The basin is bounded in the north, east and south by the Basement Complex, in the west by the River Nile and Sahara Nile Basin. The geophysical survey and drilling by RWC near the junction of the Rivers Atbara and Nile, located Basement Complex rocks at a depth of nearly 300 m. Salama (1976) quotes depths of more than 500 m in the centre of the basin where mudstones make up almost half of the saturated thickness. Elsewhere it seems that the saturated thickness averages 100 m, with water levels ranging from a few metres below surface near the rivers to 100 m away from them.

Permeanent supplies of groundwater are also obtained from wadi deposits overlying the Nubian Formation along Wadi el Hawad, a tributary of the Atbara from the south with water at 3 to 5 m deep.

3.3.10.3 Groundwater movement:

Water moves away from the margins of the basin towards the centre and then northwest into the Sahara Nile Basin, and away from the rivers under hydraulic gradients averaging 1 : 1,000. Seasonal fluctuations measured during the RWC study were about 1.5 m near the Nile to 0.75 m about 6 km away from the river and negligible further away.

3.3.10.4 Aquifer characteristics:

Pump tests by RWC indicate high transmissivities in the order of 2,000 to 3,000 $m^3/d/m$. Salama (1976) quotes values of 100-1,000 $m^3/d/m$, more consistent with results from the Sahara Nile Basin.

However, yields of wells can be around 50 l/s for a maximum drawdown of 12 m indicating a T in the order of 2,000 $m^3/d/m$. Relatively high transmissivity can be expected in the alluvium of the River Atbara where chert gravels are present in the upper reaches.

Storage coefficients determined from pumping tests range from 0.15 near the rivers to 1×10^{-4} where the aquifer is confined below mudstones.

3.3.10.5 Water quality:

Several chemical analyses of groundwater were carried out during the RWC survey but results have not been translated. From other areas an Na, Ca, HCO_3 water can be expected with low salinities.

3.3.10.6 Water resources:

Salama (1976) estimated that recharge to groundwater from the margins of the basins and the rivers Atbara and Nile amounts to 23×10^6 m^3/yr of which 0.5×10^6 m^3/yr is abstracted from wells while 3.7×10^6 m^3/yr is thought to flow through to the Sahara Nile Basin. If these figures are of the right order there is a great discrepancy between recharge and outgoings as yet unexplained. It is expected that most of the recharge does in fact reach the Sahara Nile Basin. With an area of 23,900 km^2, a specific yield of 10% and an average saturated thickness of transmissive sediments of 75 m, the amount of water in storage would be in the order of 180×10^9 m^3.

3.3.10.7 Recommendations:

The investigations in the upper reaches of the Atbara were aimed at agricultural expansion using groundwater irrigation, a project which is expected to go ahead as soon as funds are available.

Elsewhere the potential for groundwater development seems excellent except in areas where thick mudstones are present, water levels are deep and around the margins of the basin where the aquifer is thin, but a regional water resources survey should be carried out first.

3.3.11 Sahara Nile Basin (Nubian/Alluvium)

The Sahara Nile Basin extends northwards from the divide with the East Kordofan Basin to the Egyptian border over an area of some 274,000 km^2.

3.3.11.1 Previous investigations:

The southern part of the basin, up to $14^{o}30'N$ was covered by the REGWA/RWC survey (1977). Saeed (1976) discussed the area lying within Khartoum Province while El Natiq (1977) has written about the groundwater resources east of Dongola. A short survey of the effect of the water table on irrigation has been carried out on the west bank of the Nile at Wadi Hamid by Sir M MacDonald and Partners who are now investigating the possibility of groundwater irrigation in the Dongola area. Oases in the northwest of the basin were investigated by Sandford (1935).

3.3.11.2 Groundwater occurrence and aquifer limits:

Groundwater is found in the Nubian Sandstone and in the alluvial sediments of khors where these are underlain by clays, usually Nubian mudstones. Wadi Mugaddam ($16^{o}06'N$; $31^{o}49'E$) is of particular importance as it provides a permanent supply of good quality water to the region.

The basin is bound by the Basement Complex and by the Atbara and Blue Nile Basins in the east. The Sub-Nubian surface is poorly known: in the south and southwest it is shallow with Basement inliers breaking the surface in places, resulting in large areas of unsaturated Nubian Sandstone. Several small basins with sediments of 100 m or more in the area of uplifted Basement forming the southern divide with the Eastern Kordofan Basin were located by the REGWA/RWC survey and are expected to form isolated aquifers. North of this Kheiralla (1966) has mapped areas where the Basement Complex lies above the static water level in the Nubian Sandstone.

In general the saturated thickness of the Nubian away from the Basement margins is about 500 m, though greater thicknesses may be found in structural depressions. The wadi deposits vary from 5 m to more than 20 m in thickness.

Depths to the water table are generally quite shallow in keeping with a shallow base to the aquifer. Near the Nile and in the upper reaches of Wadi Mugaddam (16°15'N; 31°45'E) the depth to water in the Nubian Sandstone and alluvium respectively is 10 m or less. Away from the sources of recharge the depth to water increases to 25 m but the water table is at the surface in the oases close to the western divide with the Sahara Nubian Basin.

3.3.11.3 Groundwater movement:

The main direction of groundwater movement is from southeast to northwest until about 18°N where it changes to NNE. Recharge from the Nile and wadi alluvium results in locally different directions of flow. Hydraulic gradients in the recharge zones are relatively steep, in the order of 1 : 400, reducing to 1 : 2,500 with distance. Seasonal fluctuations of the water table are in the order of 6 m close to the Nile.

3.3.11.4 Aquifer characteristics:

West of the White Nile and a stretch of the Nile south of Ed Damer thick sequences of mudstones make up most of the Nubian sequence. In the top 200 m there may be only 10 to 30 m of permeable sandstones. Mudstones occur to a lesser extent throughout the aquifer creating semi-confined and confined conditions in places.

One pumping test just northwest of the junction of the Blue and White Niles indicated a transmissivity of 950 $m^3/d/m$ and a storage coefficient of 6×10^{-5}. Another test 40 km south of the junction and a few kilometres west of the White Nile indicated a T of 330 $m^3/d/m$ (Saeed, 1976). In the Dongola area, where mudstone layers more than 20 m thick are found between 20 m and 100 m below surface, T is probably in the range of 300 to 700 $m^3/d/m$ with storage coefficients of 10^{-4} where the aquifer is confined, to 0.15 near the river (El Natiq, 1977).

3.3.11.5 Water quality:

Salinities are very low, from 200 to 400 mg/l, with Na, Ca, HCO_3 water. The T.D.S. content is higher in the mudstones, and in one area west of Khartoum basalt intrusions are thought to affect the quality with the T.D.S. reaching 2,000 mg/l and dominant ions of Ca, Mg, Cl and SO_4.

3.3.11.6 Water resources:

The main sources of recharge are from the White Nile and Nile rivers and throughflow from the Blue Nile and Atbara Basins. Subsidiary sources are concentrated flow from the Basement outcrops at the margins of the basin and the alluvium of ephemeral wadis. The amount of recharge was estimated to be 136 x 10^6 m^3/yr by Salama (1976). In the area east of Dongola, the recharge from the River Nile over an area of 141 km^2 was estimated to be 85 x 10^6 m^3/yr by El Natiq (1977). About 13.7 x 10^6 m^3/yr is thought to be contributed from the Blue Nile and Atbara Basins. Abstraction from wells is around 7.4 x 10^6 m^3/yr while throughflow out of the basin into Egypt is in the order of 7.3 x 10^6 m^3/yr (Salama, 1976).

The amount of groundwater in storage is probably in the order of 2,000 to 5,000 x 10^9 m^3.

3.3.11.7 Recommendations:

Present investigations are concentrating on extending irrigated areas which use surface water from the Nile by increasing the amount of groundwater irrigation at a distance from the river. In the present state of knowledge there appears to be no constraint on this development except in the mudstones near the Nile and White Nile in the south. Several authors have suggested that the alluvial aquifers of Wadi Mugaddam and Wadi el Milk should be investigated with a view to developing groundwater irrigation: the potential of Wadi el Milk is not known where it overlies the Nubian Sandstone, but upstream where it flows over the Basement Complex considerable quantities of groundwater may be available due to the large catchment. Since the population of the basin away from the Nile is very low and largely nomadic there is no immediate requirement for extensive investigations except for better estimation of total water resources: the amount of water flowing northwards into Egypt is of course of particular interest to that country.

3.3.12 Gedaref Basin (Nubian/Basalt)

The Gedaref Basin covers an area of just over 28,000 km^2 in eastern Sudan and extends across the border into Ethiopia. The area is traversed by the river Atbara and its tributary the Setit which flow for four months of the year. The average annual rainfall is about 560 mm at Gedaref (14^oN; $35^o20'E$), increasing to 1,000 mm in the south and decreasing to 400 mm in the north.

3.3.12.1 Previous investigations:

Only the vicinity of Gedaref town (Suleiman, 1968) and the region southwest of Gedaref (RWC/Netherlands project, nearing completion) have been investigated in any detail and the findings are discussed below.

3.3.12.2 Groundwater occurrence and aquifer limits:

Groundwater is found in the sandstones and conglomerates of the Gedaref Formation and also in weathered basalts which overlie the Gedaref Formation unconformably in multiple sheets. The basalts extend over much of the investigated area and are thickest in the southwest: at Gedaref they are 195 m thick. The weathered zone is soft and deeply fractured, is 8 m in thickness southwest of Gedaref and 30 m thick at Daka (80 km southeast of Gedaref). The weathered zone is generally overlain by a dark, highly calcareous clay which is largely the product of in-situ weathering. On the Sudan side the basin is bounded and underlain by rocks of the Basement Complex, but the form of the sub-Gedaref Formation surface is only known from the geophysical survey of the RWC/Netherlands project which found that the base of the aquifer in the southwest of the basin is quite shallow. Near Gedaref town the sandstone aquifer and weathered basalt aquifer are separated by thick mudstones and fresh basalt flows.

The piezometric surface of the sandstone generally lies at 50 to 75 m below surface.

3.3.12.3 Groundwater movement:

Salama (1976) states that the general direction of flow of groundwater in the sandstone is to the northwest, away from the River Setit. However there seems to be little water level or altimetric data from which to determine flow directions, the only definite information is from Suleiman (1968) who found that 7 km SW of Gedaref town ('Basin' A) the flow is westwards under a hydraulic gradient of 1 : 60, while 14 km SW of the town the flow is locally eastwards under gradients of 1 : 25 to 1 : 50. There is some evidence of recharge in the west and southwest where the basalts are absent near the margin of the basin, and the main directions of flow in this area are therefore expected to be east and northeastwards.

Seasonal fluctuations of water levels will be greater in the shallow weathered basalt aquifer which only has a small saturated thickness by the end of the dry season. It is probable that this aquifer is not continuous on a regional scale, especially at the end of the dry season when water may only be found in deeper pockets of weathering.

3.3.12.4 Aquifer characteristics:

In both areas investigated close to Gedaref town ('Basin' A, 7 km to the southwest and the Abu Naga wellfield 14 km to the southwest) the water in the sandstones of the Gedaref Formation is confined below mudstones and basalts. In Basin A, the mudstones are 120 m lower than in the Abu Naga well field, a fault downthrown to the east being inferred between the two areas. Hence in 'Basin' A the piezometric surface stands 152 m above the base of the mudstones while in the Abu Naga well field it is 46 m above the base of the confining layer.

At Idd el Tin ($14^{0}05'N$; $35^{0}23\frac{1}{2}'E$) there is a flowing artesian well (El Boushi and Ahmed, 1972). One pumping test has been run in the sandstone of the Abu Naga well field. The analysis is presented in Suleiman (1968) is erroneous. T was found by Suleiman to be 77 $m^3/d/m$ and S to be 1.6×10^{-3} from a straight line drawn through all the observation well data. However there is a distinct break in the data after two days indicating a very low T of ca. 10 $m^3/d/m$, while the few measurements taken before two days indicate a much higher T value. The conclusion is that this test cannot be used to determine aquifer characteristics without more detailed interpretation.

Salama (1976) quotes values of 100 to 250 $m^3/d/m$ for transmissivity and S of 10^{-4} to 10^{-5}. His source of information is unknown and these may be values taken from other parts of Sudan. However it is probable that the sandstone aquifer is unconfined where basalts are absent and mudstones thinner, as in the western part of the basin only 3½ km west of the Abu Naga well field, and that it becomes increasingly confined as the water flows beneath the basalts.

Yields of wells in the Abu Naga well field are around 5 l/s with specific capacities around 15 $m^3/d/m$. The sandstones in'Basin' A are finer grained but no aquifer tests have been carried out. The shallow basalt aquifer may be semi-confined below clays. Yields are low, indicating low transmissivity.

3.3.12.5 Water quality:

Water in the sandstone is generally of good quality with less than 1,000 mg/l of dissolved solids, the highest values occurring where it is overlain by basalts. Wells which produce from both aquifers give poorer quality water with a T.D.S. of some 5,000 mg/l.

In the Abu Naga well field the average T.D.S. is about 350 mg/l, with large proportions of Na, CO_3 and HCO_3. The salinity is even less in the outcrop to the west, but increases eastwards towards 'Basin' A, where the dominant ions in solution are Mg, CO_3 and HCO_3 with a large amount of dissolved CO_2 and the T.D.S. often more than 2,000 mg/l. This latter water supply was rejected on the grounds of high hardness, but a sample from a non-pumping well showed much better quality with a TDS of only 450 mg/l. In both areas the groundwater from the sandstone is alkaline, with pH values generally over 8. It therefore appears that the Gedaref Formation contains more soluble solids than the Nubian Sandstone in other parts of Sudan.

3.3.12.6 Water resources:

One major source of recharge to the sandstone is throughflow from Ethiopia. Other sources are ephemeral streams and rivers, direct recharge from rainfall, and runoff from the Basement Complex at the margins of the basin. Rainfall on the basalts moves quickly down to recharge the shallow aquifer and there is some evidence that in places this water leaks downwards into the sandstone.

The RWC/Netherlands project has found that subsurface flow in the sandstone in the southwest of the basin amounts to 6.3×10^6 m^3/yr. Salama (1976) estimated that 12×10^6 m^3/yr flows through the sandstone across the border from Ethiopia, and that another 30×10^6 m^3/yr is recharged to the sandstone within the basement but the basis for his calculation is not known.

Outflow from the basin is another unknown quantity. Abstraction from wells is probably most intensive in the Abu Naga well field with 6 producing wells each yielding about 5 l/s. In the southwest abstraction from surface sources, shallow wells (basalt aquifer) and deep wells (basalt and sandstone aquifers) have been estimated by the RWC/Netherlands project to be in the order of 1.3, 0.9 and 0.1×10^6 m^3/yr respectively. The number of wells in this area is about 70 and the requirements for domestic and rural water are about 4.7×10^6 m^3/yr. Although these figures are very approximate, it is evident that Salama's estimate of abstraction from the whole basin of 1.2×10^6 m^3/yr is too low.

3.3.12.7 Recommendations:

It is apparent that the water requirements in the southwest are of the same order as recharge and that the aquifer could easily be over-developed unless well drilling is controlled.

Although surface water from the Atbara, some 55 km away is seen as a long term solution to Gedaref town's water supply, the river only flows for 4 months of the year and large storage facilities will be required in the dry season if wells are not to be used. Rural areas will continue to depend on locally available surface water and well.

The survey by RWC/Netherlands will help to delineate the hydrogeology and water resources potential of the southwestern area, but similar studies including geophysical exploration to determine aquifer limits, well inventories with topographic data and water level measurements, aquifer tests to determine the properties of transmissivity, storage, leakage etc., exploratory drilling, chemical analyses are all required to determine the groundwater potential of this basin.

4. DEVELOPMENT AND MANAGEMENT OF GROUNDWATER RESOURCES

4.1 Government Agencies.

There are many agencies involved in the exploitation of groundwater in Sudan. Most are in the public sector, based in Khartoum, and include the following:

Rural Water Corporation (RWC)
Geological and Mineral Resources Survey Dept.
Ministry of Irrigation
Public Electricity and Water Corporation (PEWC)

The Rural Water Corporation is concerned mainly with drilling wells. In recent years more emphasis has been put on data collection for assessment of regional resources including pumping tests on new production wells and monitoring of water levels.

The Geological Survey Department has been more concerned with regional investigations of aquifer characteristics and availability of water, and as the RWC becomes more involved with analysis of data the work of the two organisations increasingly overlaps.

The Ministry of Irrigation and the PEWC are concerned respectively with agricultural and urban supplies. Where groundwater is required either RWC or the Geological Survey Department may be called upon for advice. The contractural aspect of drilling is normally carried out by RWC.

Outside Khartoum, the Sudan Port Authority is responsible for groundwater exploration and abstraction for use in Port Sudan, and Suakin and its new seaport. This Authority is based in Port Sudan, although as for the public sector organisations all projects must be approved by the Ministry of Planning in Khartoum.

The Southern Provinces have a more or less autonomous regional government based in Juba. There is a separate water authority for the region which is assisted by the RWC in Khartoum.

The University of Khartoum has a thriving hydrogeological section which has been active in research and training and has undertaken investigations for groundwater in certain areas.

4.2 Recent Development Projects.

A list of most of the major groundwater development projects being carried out at present, or planned for the near future, is given below:

(i) Southern Provinces.

a) UNICEF: Wells are being drilled for village supply largely in Bahr el Ghazal Province. The project includes training in drilling techniques and setting up a chemical laboratory for water analysis. Technical advice is being given by RWC. The project will last until 1982 at the earliest and it is planned for drilling to extend from the Basement area into the Sudd Basin.

b) RWC/Netherlands: Provision of groundwater for domestic supplies in the area of Bor where a pilot agricultural project is being set up.

c) Norwegian Church Relief: Integrated rural development including provision of groundwater for domestic supplies in eastern Equatoria Province.

d) Swedish: Drilling for rural water supply in western Equatoria.

e) PEWC (Khartoum): Plans to improve the supply of water to the towns of Wau and Malakal, possibly using groundwater.

There are several other rural water supply projects in the south and UNDP plans a further one to co-ordinate ongoing work, under the Ministry of Cooperatives and Rural Development. Maintenance centres and mobile teams for maintaining wells, pumps etc. are being set up in each province by UNICEF and UNDP and expansion of the rural water supply programmes is planned. In the future there will be more emphasis on data collection and analysis.

Due to the relatively high rainfall and presence of several large tributaries of the White Nile there are no plans to use groundwater for irrigation in this region.

(ii) Darfur.

a) Ministry of Irrigation: Agricultural development using groundwater irrigation in Qoz Dango in the Baggara Basin is planned.

b) PEWC: Plans to improve water supply to Geneina, El Fasher and Nyala towns.

c) Ministry of Irrigation: A project to investigate the possible use of groundwater for irrigation in the Jebel Marra area is awaiting finance.

d) RWC/ACSAD (Arab Centre for Studies of the Arid and Dry Zones): Plan infiltration studies in Sag el Naam Basin.

(iii) Kordofan.

a) Huntings/ODM: Part of the agricultural project based at Kadugli will be to continue groundwater investigations and assessment for the whole of South Kordofan Province during the next three years.

b) UNICEF: Drilling for rural water supply.

c) Agrar (German consultants): Domestic water supply for agricultural pilot project north of Kadugli.

d) PEWC: Investigations are underway to find a reliable groundwater supply for El Obeid town.

(iv) White Nile Province.

a) PEWC: Water supply for Kosti town.

(v) Blue Nile Province.

a) PEWC: Water supply for Damazin town.

(vi) Kassala Province.

a) RWC/Netherlands: This project aims to improve dry season irrigation from groundwater in the Gash Delta.

b) RWC/Netherlands. Hydrogeological investigations in the southwest of the Gedaref Basin have been recently completed.

(vii) Red Sea Province.

a) Port Sudan Authority: Investigation and drilling programmes underway in khors and Tokar Delta to find a water supply for Port Sudan and Suakin New Port.

b) Geological Survey Department: Supply of groundwater from dug wells to mining centres in the Red Sea Hills.

c) Geological Survey Department/German: Groundwater investigations of the Tokar Delta have recently been completed.

(viii) Northern Province.

a) Ministry of Irrigation: Investigations north of Dongola, east of the Nile, to use groundwater for agriculture.

(xi) Nile Province.

a) Ministry of Irrigation: Plan to extend groundwater irrigation near the confluence of rivers Atbara and Nile.

(x) General Projects.

a) Ministry of Agriculture: Improvement of cattle routes within western Sudan and between western Sudan and Khartoum. The number of wateryards along these routes will be increased.

b) International Hydrological Programme: RWC will select areas for investigation and UNESCO will provide technical assistance.

c) Ministry of Health: A project may be implemented to drill more wells and upgrade existing wells in health centres throughout the country.

d) UNDP: Will assist in establishment of a Water Drilling Training Institute.

e) University: An International Development Research Centre is being established. It will include social and managerial aspects of water supply.

f) Water Data Centre: A centre is being built near Khartoum. One or more Sudanese are in France being trained with BRGM in handling of groundwater data to be carried out at this centre. It is planned that advisors from BRGM will come to Sudan for 2 years to continue training and establishment of the centre.

4.3 Future Plans and Recommendations.

Within the last month RWC has been placed in the same ministry as the Geological Survey Department, the Ministry of Mining. It is intended that the two agencies will collaborate on drawing up a programme for groundwater investigation, possibly forming a separate water department for both ground and surface water with a central office in Khartoum and regional offices in each province. Planned decentralisation would make the regional offices responsible for data collection (stream discharge, pump testing, monitoring water levels, etc), and local investigations. Specialised staff would be supplied from the central body. Each regional centre would be self-sufficient in equipment and maintenance and the central office would then be concerned with broader aspects of development for the whole country. To some extent this has already happened in the RWC which employs staff to monitor wells in several areas.

There is talk of a water resources administration being set up to incorporate the water department of all the government agencies, including the Sudan Port Authority. It is generally agreed that this would form the best basis for tackling water management problems, introduction of a legislative framework and making more effective use of limited funds and technical resources. At present the World Bank and Project Planning Unit are trying to organise a seminar for the interested agencies to discuss the proposal. Hopefully there will also be some collaboration with University departments such as the International Development Research Centre and the Institute of Environmental Sciences.

While such large-scale reorganisation is being considered it is difficult for the individual agencies to draw up new plans but the following proposals were discussed informally during the author's visit to Sudan.

All agencies wish to see a completed national well inventory. Most of the wells drilled by RWC have been put on file but much of the information is kept in the regional centres. The Geological Survey Department and several consultancy projects have made inventories for some areas but collation and standardisation of information is required. The hydrogeology department of the University would like to embark upon an inventory of dug wells in the areas of the Basement Complex rocks.

It was generally agreed that in most areas aquifer and hydrometeorological parameters have not yet been determined sufficiently accurately to predict recharge, effects of abstraction, etc. Several organisations would like to see rigorous pumping tests carried out in possible development areas, but such work has been limited by lack of funds. It is possible that the new data centre being established by the French will include facilities for aquifer modelling and one student working for a Ph.D. is intending to model the Tokar Delta aquifers. Other alluvial aquifers where data are readily accessible and intensive development of groundwater is underway have been suggested for modelling: Sag el Naam Basin and Gash Delta. The University and RWC hope that the proposal by ACSAD (Arab Centre for Study of Arid Zones and Dry Lands) for the Ministry of Overseas Development UK to study recharge in the Sag el Naam Basin will go ahead soon.

The Geological Survey Department requires feasibility studies for water supply in the Basement areas where mineral exploration is being carried out: Nuba Mountains, Red Sea Hills, Ingessana Hills (south of Khartoum). This should be a combined surface and groundwater exploration project, the aim being to establish cost of supplies. The University is interested in carrying out research into hydrochemical processes in these areas.

It is apparent that the most fundamental requirement at present is the setting up of the proposed water authority in Khartoum and its regional centres. Practical legislation is required to carry out recommendations for management, investigation of resources and further development. It has been suggested that outside advice on these aspects of management would be welcome, and that a joint ground and surface water project, either resource evaluation in the Basement areas or a related research project in Khartoum would act as a stimulus to this reorganisation.

Other large-scale projects required are detailed investigations of recharge to groundwater along the White Nile and a country-wide pumping test and monitoring programme. Smaller scale projects are suggested above in the recommendation sections for different aquifers.

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FIGURE 1 RAINFALL

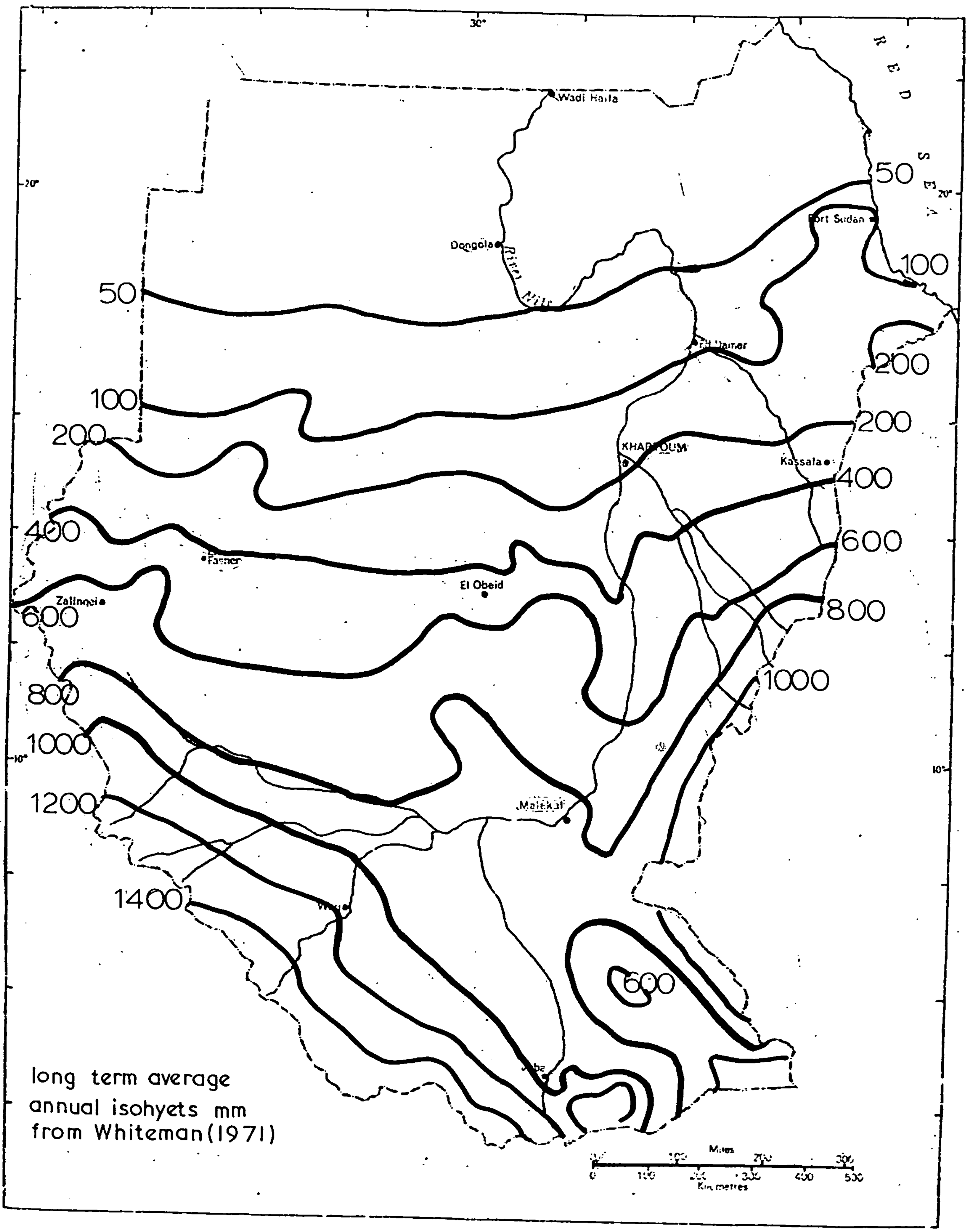
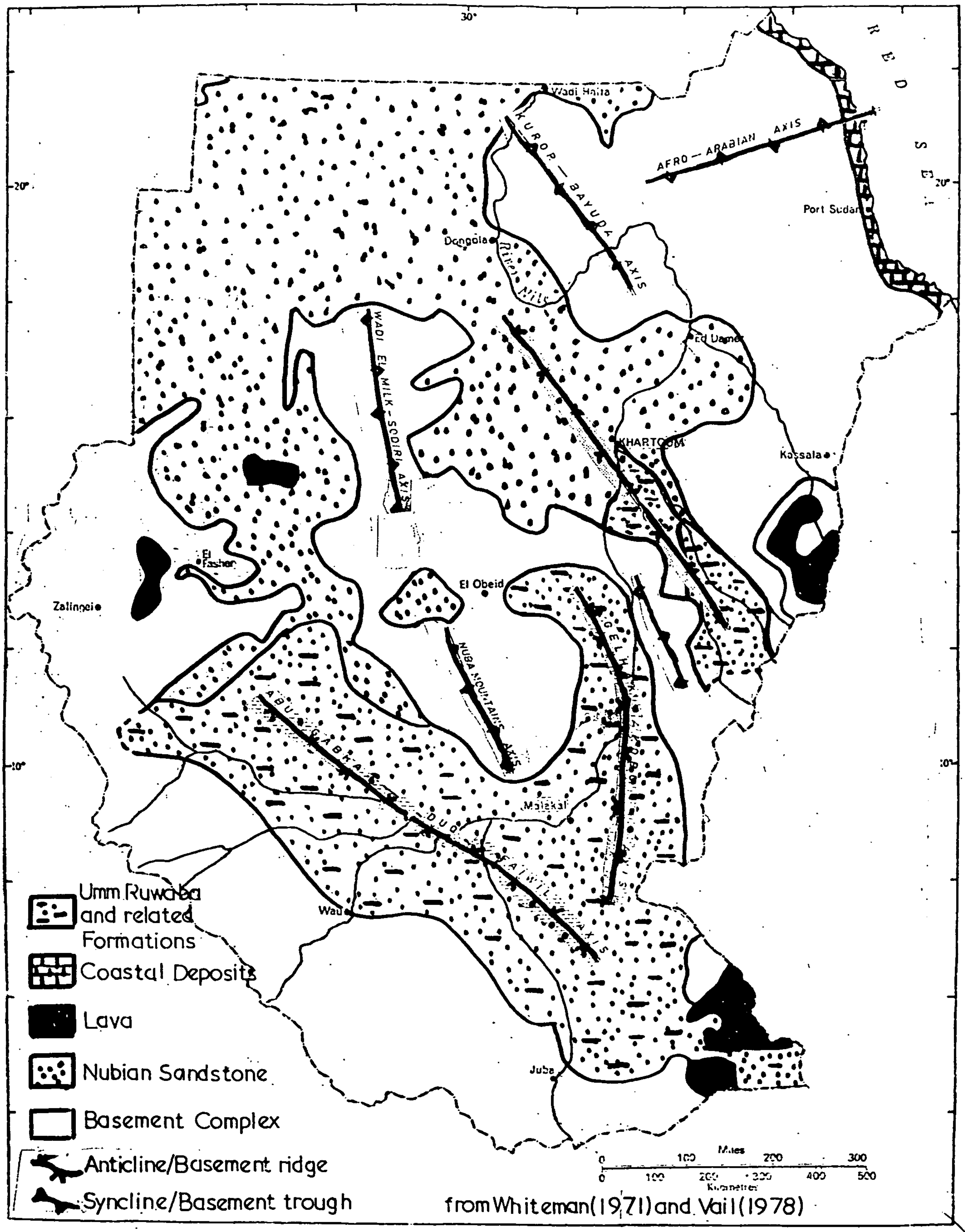


TABLE 1. GEOLOGICAL SEQUENCE

FORMATION	AGE	SURFACE AREA (%)
Superficial Deposits	Quaternary-Tertiary	
Coastal Deposits	Quaternary-Tertiary Mesozoic	<1
Umm Ruwaba, Gezira and El Atshan Formations	Quaternary-Tertiary	19
Volcanics	Quaternary-Tertiary	2
Hudi Chert	?Tertiary	<1
Nubian Sandstone, Yirol and Gedaref Sandstone Formations	Late Cretaceous	28
Nawa Formation	?Palaeozoic	<1
Palaeozoic Sandstones	?Palaeozoic	<0.5
Basement Complex	Palaeozoic-PreCambrian	49

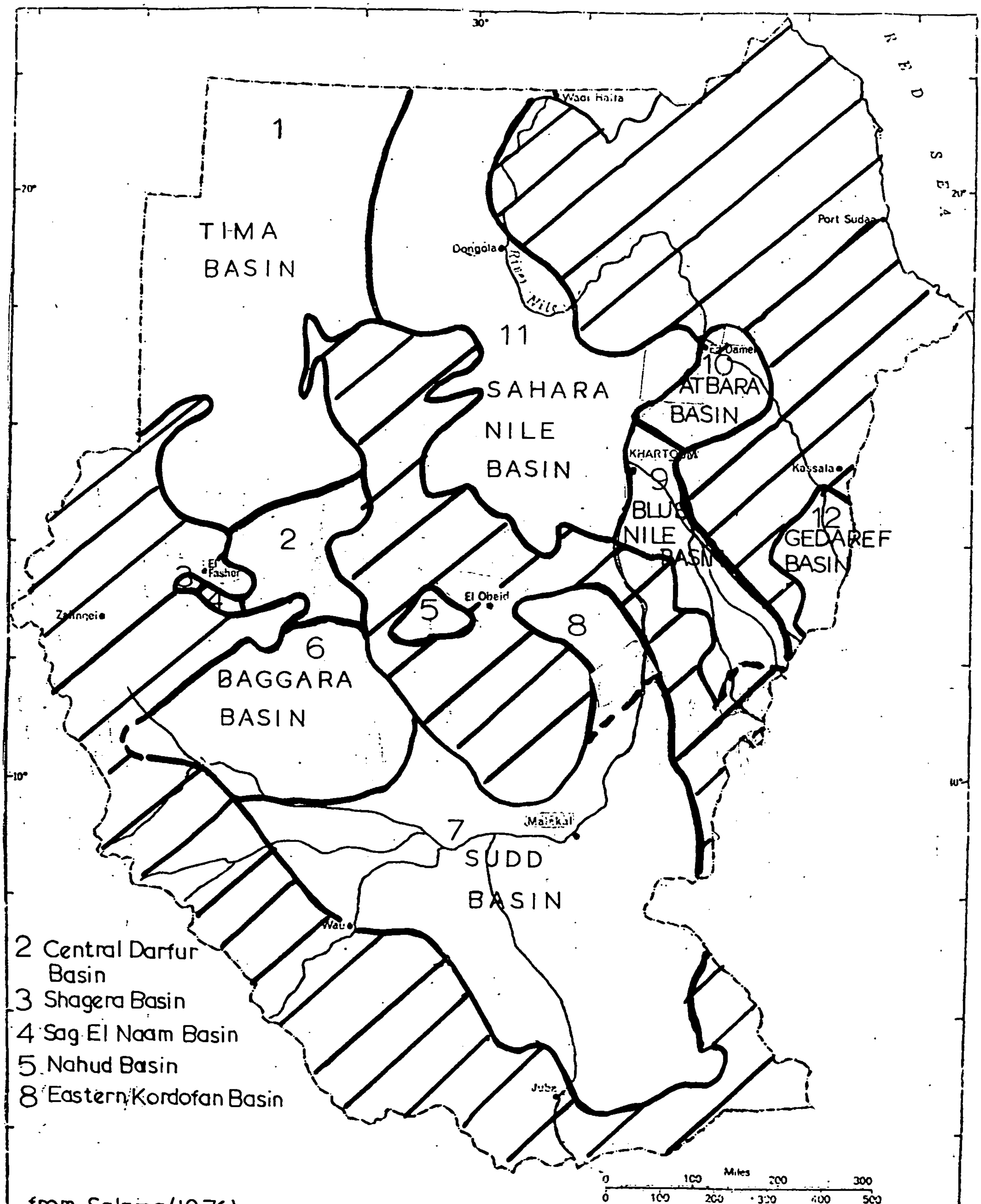
from Whiteman (1971) and Vail (1978).

FIGURE 2 GEOLOGY



from Whiteman (1971) and Vail (1978)

FIGURE 3 SEDIMENTARY BASINS



from Salama (1976)