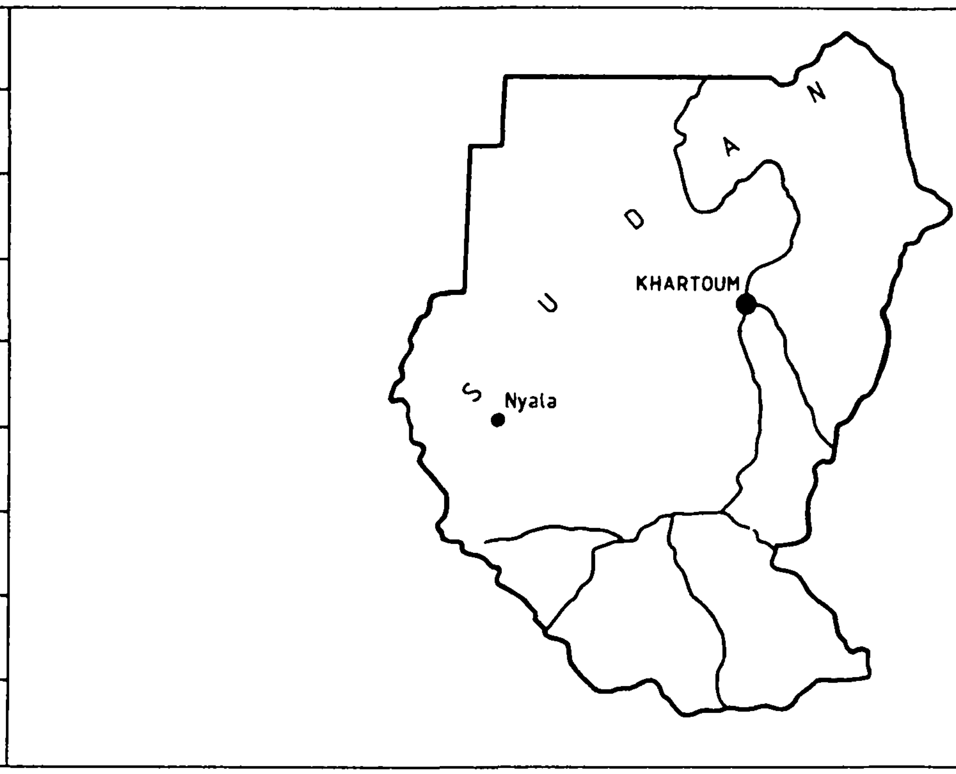
TNO-DGV institute of applied geoscience

NWC national water corporation

Water resources assessment program in the **Sudan** WAPS-2



Nyala water resources study

Final report

WATER RESOURCES ASSESSMENT PROGRAM IN THE SUDAN

W A P S - 2

N Y A L A   W A T E R   R E S O U R C E S   S T U D Y

FINAL REPORT

December 1985

National Water Corporation
P.O. Box 381
Khartoum
Sudan

TNO-DGV Institute of Applied Geoscience
P.O. Box 285
2600 AG Delft
The Netherlands

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SUMMARY

The Nyala Water Resources Study is part of the Water Resources Assessment Program in the Sudan, WAPS-2, and has been executed jointly by the National Water Corporation (NWC) and TNO-DGV Institute of Applied Geoscience of The Netherlands. The main objective of the study was to determine the available water resources near Nyala.
Nyala is the capital of Southern Darfur and is located in the south of the Darfur Region in west Sudan and has about 200 000 inhabitants at present.
The topography near Nyala is mainly flat, sloping southeastwards at an altitude of about 650 m above mean sea-level. The only topographic features near Nyala are some outcrops of the Basement Complex. This Basement Complex of Pre-Cambrian age is for the greater part covered by erosional products including the alluvial deposits of Wadi Nyala. The climate in the savannah belt is hot and dry during most of the year; the wet season lasts for three months, from June to September. The average annual rainfall at Nyala has been decreasing and the figure for the last 15 years is 366 mm. The average annual potential evapotranspiration is 2570 mm. The Wadi Nyala bisects the town of Nyala and flows intermittently during the wet season. The individual flood peaks never last longer than a few hours. The total annual runoff varies strongly and was 14.2×10^6 m^3 in 1984 and 112.4×10^6 m^3 in 1985.

The main water resource in the area of Nyala is the groundwater in the alluvial deposits of Wadi Nyala. The aquifer is mainly composed of medium to coarse sands and is underlain by the impervious Basement Complex. The aquifer geometry was ascertained by geo-electrical and electromagnetic surveys in combination with the data from existing boreholes and boreholes drilled by the project. The width of the aquifer is about 800 m and its maximum thickness is about 20 m.
The field investigations during the WAPS-2 project were concentrated along Wadi Nyala between Nyala Town and Bileil, a distance of about 18 km. The estimated groundwater storage capacity is 24.3×10^6 m^3. Of this, at present an average 11.3×10^6 m^3 is used during the dry season, leaving little scope for an increase in groundwater abstraction.

Despite the heavy exploitation, the aquifer is normally fully replenished during the rainy season.
The boreholes used for the town water supply are located in the Town Area. The groundwater storage capacity in this area is estimated to be 6.0×10^6 m³. On average, 3.5×10^6 m³ is consumed during the dry season, of which 1.9×10^6 m³ is for the town water supply.
In the area downstream of Jebel Nyala, the Downstream Area, the majority of the groundwater is lost annually by evapotranspiration, which in the dry season of an average year is 7.8×10^6 m³. The groundwater storage capacity of the Downstream Area is estimated to be 18.3×10^6 m³.
The behaviour of the groundwater in the alluvial aquifer in the Town Area and in the Downstream Area was simulated by groundwater models. The simulations indicate that the abstraction of groundwater for the town water supply can be increased to about 4.5×10^6 m³ in years with normal rainfall, if groundwater consumption for agricultural purposes remains unchanged.
The amount of available groundwater falls short of the projected water demand estimated by Humphreys (1983), which is 6.4×10^6 m³.
Because the groundwater resources at Nyala are limited, a proper water management plan must be introduced and an executing authority must be established. Water management will be vitally important, especially in years of low rainfall.

The chemical quality of the groundwater is generally good. Higher salinities only occur near the boundaries of the aquifer. Some wells were found to be bacteriologically contaminated as a result of human activities. At present no measures are taken to prevent water contamination, nor is there any treatment of drinking water.
There are no alternative water resources for the Nyala drinking water supply nearby. However, in some areas groundwater exploitation for irrigation can be increased, e.g. just upstream from Nyala at Romalia and in some areas downstream along Wadi Nyala. Furthermore, in neighbouring Wadi Bulbul groundwater exploitation can be increased in two areas.

CONCLUSIONS AND RECOMMENDATIONS

1 Hydrological Conditions

1.1 The rainfall at Nyala has been declining since 1965. Since 1971 the mean annual rainfall has been 366 mm.

1.2 The surface discharge of Wadi Nyala appears in floods of short duration and high intensity. The annual discharge varies strongly and was 14 x 10^6 m^3 in 1984 and 112.4 x 10^6 m^3 in 1985. Flood volumes and flood peaks seem to be increasing because of the deforestation of the catchment.

1.3 The mean annual potential evaporation at Nyala in the garden area near the wadi is 1935 mm.

2 Water Resources

2.1 It is not possible to use surface water during the dry season, because near Nyala there are no good locations for a surface water reservoir.

2.2 Reasonable quantities of groundwater are found in the alluvial sediments of Wadi Nyala. The groundwater storage capacity in the area near Nyala, the Town Area, is 6.0 x 10^6 m^3, and in the area downstream of Jebel Nyala until Bileil, the Downstream Area, it is 18.3 x 10^6 m^3.

2.3 Every year the groundwater is recharged during the wet season by the wadi surface runoff. In years with normal rainfall the recharge is sufficient for full recovery of the groundwater table. In years with low rainfall, recharge is insufficient, especially in the Downstream Area, mainly because the duration of runoff is shorter.

3 Groundwater Development

3.1 Almost all the domestic water supply is pumped from the Town Area. The existing town water distribution net supplies about 50 000 to 60 000 people. The total supply of water that is pumped from boreholes varies between 1.4 x 10^6 m^3/year to 2.0 x 10^6 m^3/year. The remainder of the town population, about 150 000 people, buy their water from street water vendors. This water is mainly from dug wells and amounts to about 0.4 x 10^6 m^3/year. Therefore the people who are not connected to the distribution net consume ten times less than those that are connected.

3.2 In the Town Area (total area 3.2 km^2) the present groundwater consumption by evapotranspiration is 0.95 x 10^6 m^3/year in irrigated areas and 0.31 x 10^6 m^3/year in other areas.
In the Downstream Area (total area 14.2 km^2) total groundwater consumption by evapotranspiration is 8.4 x 10^6 m^3/year, of which 0.9 x 10^6 m^3/year is consumed by irrigation.

3.3 The future water consumption for domestic purposes was estimated by Humphreys (1983) at 6.4 x 10^6 m^3/year for a population of almost 300 000. The analysis of the groundwater resources at Wadi Nyala indicates an availability of about 4.5 x 10^6 m^3/year in the area near Nyala. Therefore the future water demand of the town can only be supplied if supply rates lower than those determined by Humphreys (1983) are maintained. The maximum that can be supplied per capita for a population of 300 000 is about 40 litres/day. (Excluding pipe leakages).

3.4 The future groundwater consumption for agriculture can only be increased to a small extent in the Downstream Area. Agricultural consumption of groundwater in the Town Area should be kept at the present level, so that the resources not used at present can be reserved for domestic use.

3.5 In a dry year, groundwater resources will be almost sufficient to supply the domestic demand. But wells used for irrigation that are located near the boundary of the aquifer and in the Downstream Area might dry up because of the insufficient recharge in such a year.

4. Water Management

4.1 A water management plan is needed at Nyala to achieve a proper use of the water resources and to avoid occurrence of excessive drawdowns, well interference, water contamination, etc.

4.2 A Regional Water Authority needs to be established, responsible for the formulation and execution of the water management plan.

4.3 A Technical Committee from the National Water Corporation is to advise the Regional Water Authority and should monitor surface and groundwater resources.

4.4 Legal provisions in the form of a Water Act are required for the optimal functioning of the water management.

1. INTRODUCTION

1.1 The WAPS-2 Project

In the framework of the Technical Cooperation between the Kingdom of The Netherlands and the Democratic Republic of Sudan, it was agreed to execute a programme of studies on water resources development, to be known as "Water Resources Assessment Program in the Sudan". WAPS-2 is the second phase of this programme. The two countries were represented by the Ministry of National Planning of Sudan and the Ministry of Foreign Affairs of The Netherlands, whereas the executing authorities are the Ministry of Energy and Mining and the Directorate of International Cooperation respectively. The agencies responsible for the execution of the project were the National Water Corporation (NWC), Khartoum, Sudan and TNO-DGV Institute of Applied Geoscience, Delft, The Netherlands.

The intensive stage of the project started at the beginning of January 1983 and finished December 1985, during which period the activities were carried out by the National Water Corporation with the assistance of some experts of TNO-DGV.

The objectives of the WAPS programme are as follows:
- Strengthening the Research and Water Resources Development Department of the National Water Corporation.
- Promoting a systematic regional water resources assessment programme in the entire Sudan.

More specifically, the objectives of phase 2 are:
- Supervision of the continuation of the activities in the Kassala Gash Basin were the WAPS-2 project was executed from 1979 to 1982.
- Carrying out water resources assessment studies in Nyala and Geneina in order to come to an adequate water resources development and management.

- Improving the accessibility of hydrological and hydrogeological data and studies by organizing a national information centre for an optimal analysis and use of existing data.
- Promoting the institutions of regional water authorities.

The contribution to the WAPS-2 project from The Netherlands amounted to 6 250 000 Dutch Guilders. About 15 man year was involved of which 4 man year were for visiting experts. The Dutch resident team consisted of a project manager stationed in Khartoum and a geohydrologist, a geophysicist and a technical supervisor stationed in Nyala.

The equipment provided by The Netherlands comprised a.o.:
- a truck and trailer with a 15 000 l tank and a container;
- 5 landrovers;
- the complete equipment for a mechanical workshop;
- hydrological, hydrogeological, geophysical and chemical equipment;
- microcomputers.

The Sudanese budget was estimated at 2 150 000 Sudanese Pounds. The manpower involved was about 150 man year, most of it employed in Nyala. The equipment provided by the Sudan consisted of hydrological and hydrogeological equipment, drilling material, furniture and further miscellaneous material.
In Nyala the NWC has built an office for the WAPS-2 project activities and two guesthouses for the Sudanese staff. In the compound of the Regional Office of the NWC in Nyala, the Regional Manager facilitated the set-up of a workshop by placing the former workshop building of the Western Savannah Development Corporation at the disposal of the WAPS-2 project.

1.2 Nyala Water Resources Study

In this report the results are presented of the investigations carried out from beginning 1983 until after the rainy season of

1985 in Wadi Nyala. The objective of the assessment study was to determine the quantity of the existing surface - and groundwater resources, in order to achieve a proper use and management of the available water.
For this, accurate and sufficient hydrological and hydrogeological data are essential. Therefore the WAPS-2 activities in Nyala were focussed on collection of data including a well inventory, the drilling of boreholes, periodical groundwater level measurements and the installation of automatic water level recorders, chemical and bacteriological analysis of water samples of selected wells, aquifer and well tests, geophysical surveys (geoelectrical and electromagnetic) and stage and discharge measurements in the Wadi Nyala during flood events.

Previous studies were carried out at Nyala by Salama (1971), Hunting Services Ltd. and Sir MacDonald & Partners (1974), Abdul Razig Mukhtar (1979) and Howard Humphreys & Partners (1983). These studies, however, involved limited amounts of fieldwork and therefore the extent of water resources in Nyala was still largely unknown before the start of the project.
A review of the WAPS-2 activities in Nyala is included in Appendix G. The names of the WAPS-2 team members involved in the investigations at Nyala are also listed in appendix G.

1.3 Acknowledgements

The project received much appreciated advises and assistance from various local authorities. We especially like to thank the director-general of the Ministry of Housing, Water and Public Utilities, Mr. Adam Idris Silake, the regional manager of the NWC in South Darfur, Mr. Youssouf Adam Mustafa and the water engineer of the PEWC Nyala, Mr. Ahmed Musa.
The geology of the area was elucidated by the regional manager of the Department of Geology, Mr. Fathi Ali Khalil, who also drafted the geological map.
Valuable help in solving technical and logistical problems was

also received from RBPC/joint venture Stevin Roads-Euro Consult and the Western Savannah Development Corporation. Thanks also go to Mr. Brian Kerr land-use expert of WSDC, for his comments on the text. Further more we like to thank all other governmental departments, organisations etc. which contributed to the successful completion of the project.

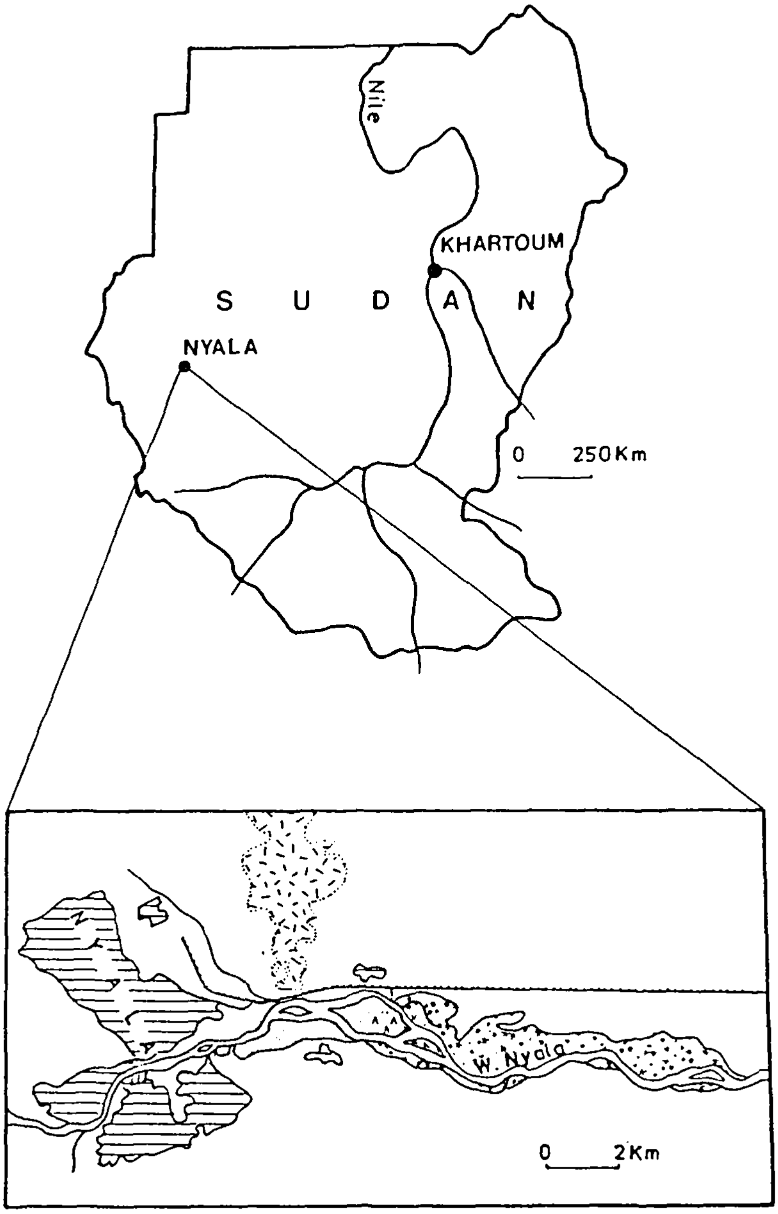
2. GENERAL SETTING

Nyala is the capital of Southern Darfur Province and is situated in the western part of the Sudan, roughly 250 km east of the border with Chad. It lies about 900 km southwest of Khartoum, the capital of Sudan, as shown on figure 2.1. Its longitude is $24^{o}53'$ E and latitude is $12^{o}03'$ N.

The mainly flat and dry savannah landscape of central Darfur Region comprises a pediment of weathered rocks, sloping gently south-southeastwards at a gradient of about 1 : 400. The only dominant features are mainly quartz dykes, which form prominent ridges in the area. The altitude of the town is about 650 m above sea-level. Jebel Nyala (791 m in height) to the east of the town provides the only significant relief feature in the immediate neighbourhood. Directly southwest of the town fossil sand dunes are found, of aligned northeast to southwest and up to 25 km in size. Some 100 km northwest of the town, Jebel Marra massif is located. This dominant volcanic mountain area has no significant effects on the climate of the catchment area of Wadi Nyala. The upper reaches of this wadi are about 25 km southeast of Jebel Marra massif; see figure 2.2. In a northern direction the landscape becomes dryer due to the vicinity of the transient zone to the Sahara Desert. The encroachment of this transient zone to the south is estimated to be 7 km/year.

Nyala is the endpoint of a single track railway linking the town to Khartoum and Port Sudan. In the dry season, October to June, it takes about three days to travel by train to Khartoum; during the rainy season the travel time is frequently increased by several days and often the railway is washed out during heavy rainfall. There is no all-weather road from Nyala to Khartoum, a distance of about 1300 km; in the dry season the journey by lorry takes up to six days; in the wet season much longer.
Since 1983, there has been an asphalted road connecting Nyala to Zalingei (220 km). In 1985 a gravel road to the capital of the

Figure 2.1



WAPS–2 Study Area Wadi Nyala

Darfur Region, El Fasher (210 km) was completed. The roads from Nyala to other directions are unpaved and frequently become impassable during the rainy season.

Sudan Air operates three times a week from Khartoum to Nyala. However, the capacity of 32 seats is not sufficient and the foreign funded development projects often charter small planes. External communications by telephone are difficult.

A map of Nyala town and the study area along Wadi Nyala is shown in Map 1. The town is divided by the Wadi Nyala, running west-east through the town. The majority of the population is concentrated in the older part of the town on the northern (left) bank of the wadi. On the east side, this part of town is bordered by the Jebel Nyala, rising 140 m above the average altitude of Nyala. The houses in the extended outskirts of the town are traditional grass huts.

Nyala is a fast growing town, and extends over an area of approximately 8 by 6 km. The number of inhabitants is estimated to be some 205 000 (1985). There is a movement of people from the rural areas of the Darfur Region to Nyala town, placing increased pressure on the public utilities. This movement is accelerated by the prevailing drought, which forces large groups of people to move south from North Darfur.

Nyala town is an important commercial centre for the central Darfur Region and has several public facilities like a hospital, a broadcasting station, schools (secondary, technical, teachers' training), a cinema and horticultural nursery. Being the capital of the Southern Darfur Province, there are several governmental buildings, as well as municipal offices and a military garrison. South of the wadi are the headquarters of the Western Savannah Development Corporation. Industrial activities are concentrated on textile (cotton) and groundnut processing (oil). As Darfur is a region with a large livestock population a meat market and a

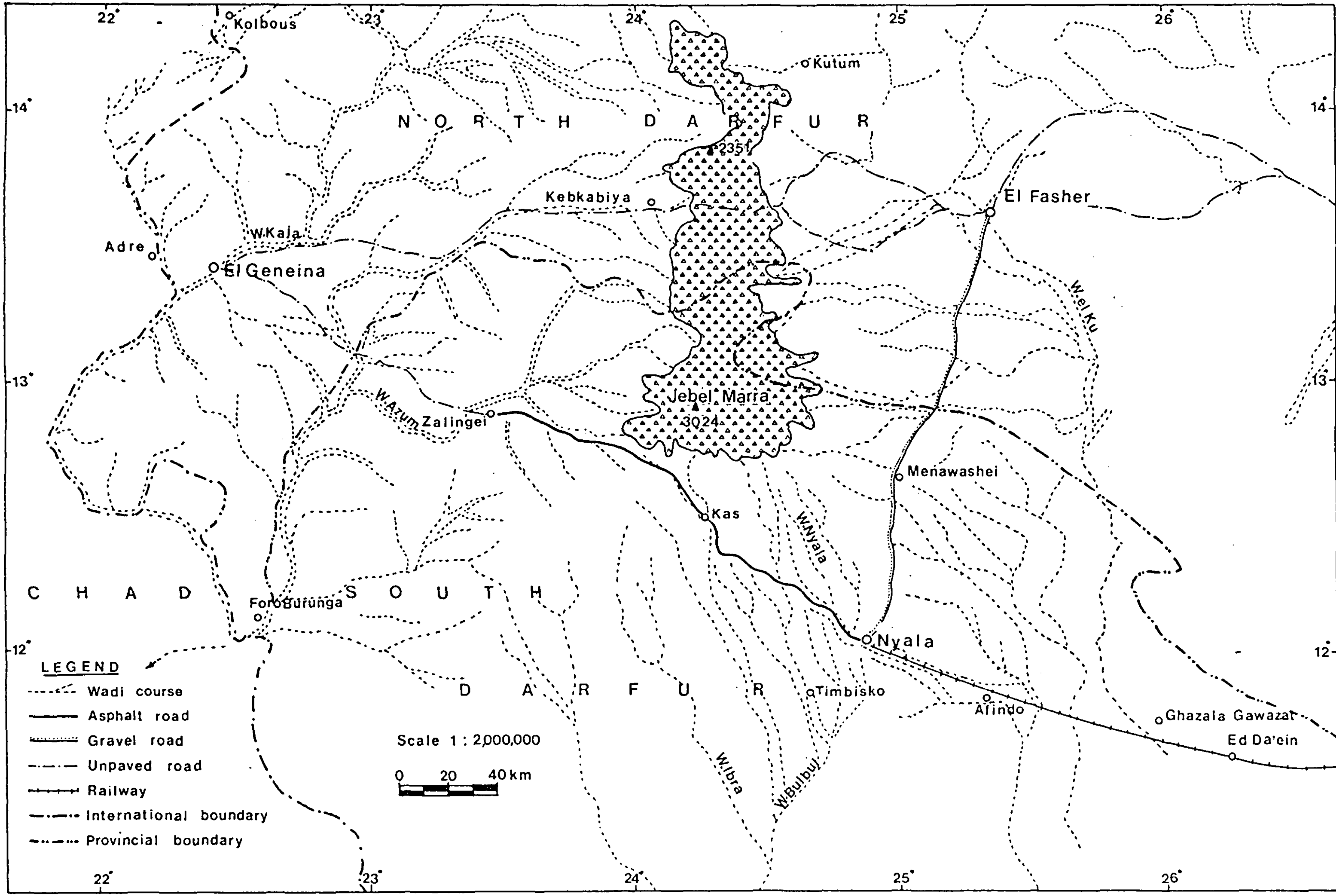


Figure 2.2 MAP OF CENTRAL DARFUR

crush for livestock vaccination are established in Nyala.

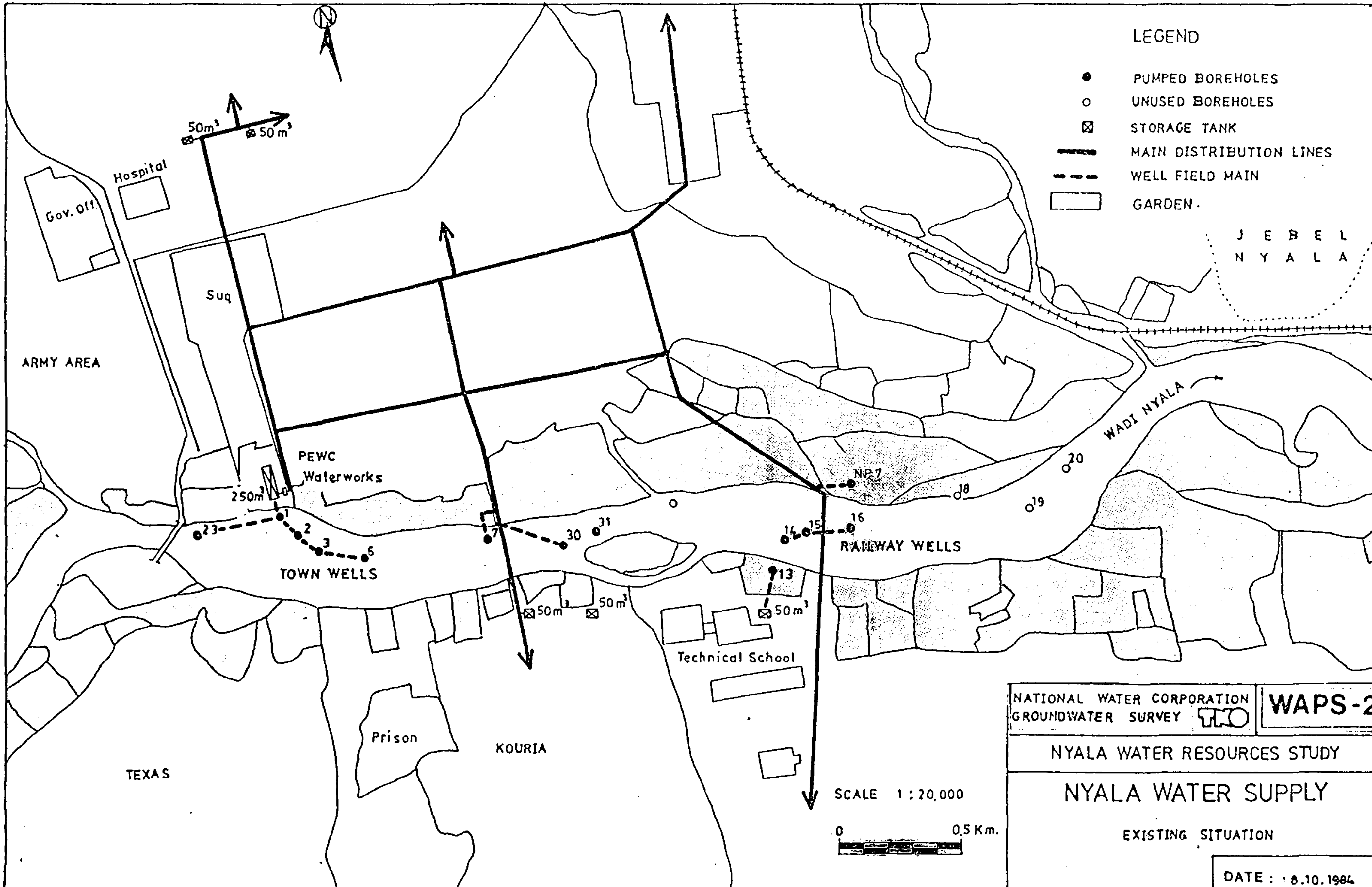
Near the town centre and several kilometres downstream, there is an almost continuous band of gardens on both banks of the wadi. These gardens mainly comprise mango, citrus and guava orchards, but there are also many small plots where other fruits and vegetables are grown, e.g. bananas, tomatoes, aubergines, sweet potatoes, cucumbers, carrots, ocra, alfalfa, etc. Many of these gardens contain one or more dug wells for irrigation.

The Wadi Nyala, in general, has a NNW-SSE flow direction. Near Nyala town, however, the wadi shows both a remarkable deviation from this general direction and a widening of the stream channel. For about 8 km, its flow direction is more or less west-east and the width increases from about 100 m to nearly 400 m near the Railway Wells site. Beyond Jebel Nyala, the general direction again is to the SSE. Here the wadi flow changes course periodically, on some stretches having more than one stream bed, e.g. at Kundua Forest. Further downstream more branching occurs and soon the clear main channel disappears. The banks are flooded extensively in this area.
At several places on both banks on the wadi, small brick-yards are found, where clay layers in the wadi alluvial fill are used as raw material.

Nyala obtains all its water for domestic use from boreholes and wells located in the wadi or on the banks.
The public water supply run by the Public Electricity and Water Supply Corporation (PEWC) is drawing water from eight boreholes. The boreholes BH 2, BH 3 and BH 6, located at the so-called Town Wells site, are connected to storage tanks (capacity = 250 m^3) in the yard of the PEWC. The other boreholes situated further downstream are BH 7 and BH 30, and at the Railway Wells site BH 14, BH 15 and BH 16. These boreholes are directly connected to the distribution system. All boreholes are equipped with electric submersible pumps, but usually not all are pumping, due to

mechanical defects or other causes. The capacities of the pumps are about 32 m^3/hr, except for the pumps in BH 3 and BH 16: 20 m^3/hr. In 1984 BH 16 was abandoned and replaced temporarely by NP 07, while also BH 23 was connected. One dug well (number 1) was abandoned by the PEWC during 1984, due to pollution from the nearby market (Suq), but reconnected again in 1985 after the suq was cleared out the wadi.

The distribution system only serves part of the town. According to the PEWC there were 7000 consumer connections in 1984, serving about 50 000 to 60 000 people. In 1984 about 1000 new connections were made, but in 1985 no further extension was possible. The system was designed 20 years ago for about 20 000 people and the capacity is insufficient at present to provide a reliable supply.
The majority of the population relies on water vendors, street water points or other sources. About 10 to 15 open dug wells are used by water vendors, who transport water from the garden area into the town in horse-drawn tanks of about 1 m^3 capacity.



NYALA WATER SUPPLY.

Figure 2.3

3. CLIMATE

3.1 General Climate

The climate in Southern Darfur is controlled by the seasonal movement of the Intertropical Convergence Zone (ITCZ) associated with the movement of the sun. The description of the phenomenon presented here was based on a text from Hunting (1974).

During the winter months the ITCZ lies to the south of the equator and Southern Darfur is in a zone of dry north-easterly Harmattan Winds. Average temperatures are around 24°C as shown in Table 3.1. With the northern movement of the sun during February to May, temperatures rise and the ITCZ moves north, towards the area. Temperatures reach a maximum under the generally clear skies in April and May. From June through to September, the front lies to the north of the area, reaching a maximum latitude of almost 20°N in July. Southern Darfur then lies in the south-westerly moist monsoon airstream from the Atlantic. Travelling disturbances in these winds initiate the fast westward moving local thunderstorms with preceeding high winds and intense, short duration rainfall. These storms mainly occur during the late afternoon and evenings, and are called "duhuria". Often in the beginning of the rainy season, these storms cause the traditional dust storms or "haboobs".

The rain is sometimes distributed over a larger area, in storms appearing usually during the night, the so-called "sarraya", or the early morning, the so-called "dahawia". This rain is less intense and of longer duration than the duhuria, but the total rainfall can be considerable.
The wettest months in the rainseason are July and August.

With the subsequent southward movement of the sun, the ITCZ and the monsoon retreat, giving the last rains in October and the return of the Harmattan winds in November. Under the clearer skies of October and November, temperatures rise marginally and then fall towards December.

Table 3.1 Monthly Averages of Mean, Maximum and Minimum Daily Temperatures in ^{o}C at Nyala (1951 - 1980)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mean *	23.3	25.3	28.5	30.3	30.9	29.7	27.1	26.3	27.5	28.3	26.5	23.7	27.3
Maximum	31.2	33.2	36.3	38.3	38.4	36.3	32.4	31.3	33.5	35.4	33.8	31.2	34.3
Minimum	15.5	17.4	20.6	22.2	23.4	23.2	21.8	21.4	21.5	21.2	19.3	16.1	20.3

* Mean taken as average of maximum and minimum

The catchment of Wadi Nyala is situated in the transient zone of low to intermediate annual rainfall amounts, the annual mean at Nyala being (period 1921 - 1985): 459.7 mm.

In the first half of the 1970's a prolonged drought occurred in the Sahel, the semi-arid zone south of the Sahara. The area of Darfur, located to the east of the Sahel, suffered from this also, but not as badly as the areas to the west. The drought was attributed to several diverse factors (Barry, R.G. and Chorley, R.J., 1982):

1. The shifting of high and low pressure areas from their normal positions, which interfered with the movement of ITCZ.
2. Lower sea-surface temperatures in the Atlantic Ocean.
3. The continuing desertification in the Sahel.

The rainfalls improved during the second half of the 1970's, but declined again during recent years, due to the same factors. In the near future it seems that more years with lower than normal rainfall can be expected, as desertification will continue to aggravate conditions. In this respect the very low, indeed disastrous rainfalls of 1983 and 1984, show the severity of the situation.

3.2 Rainfall

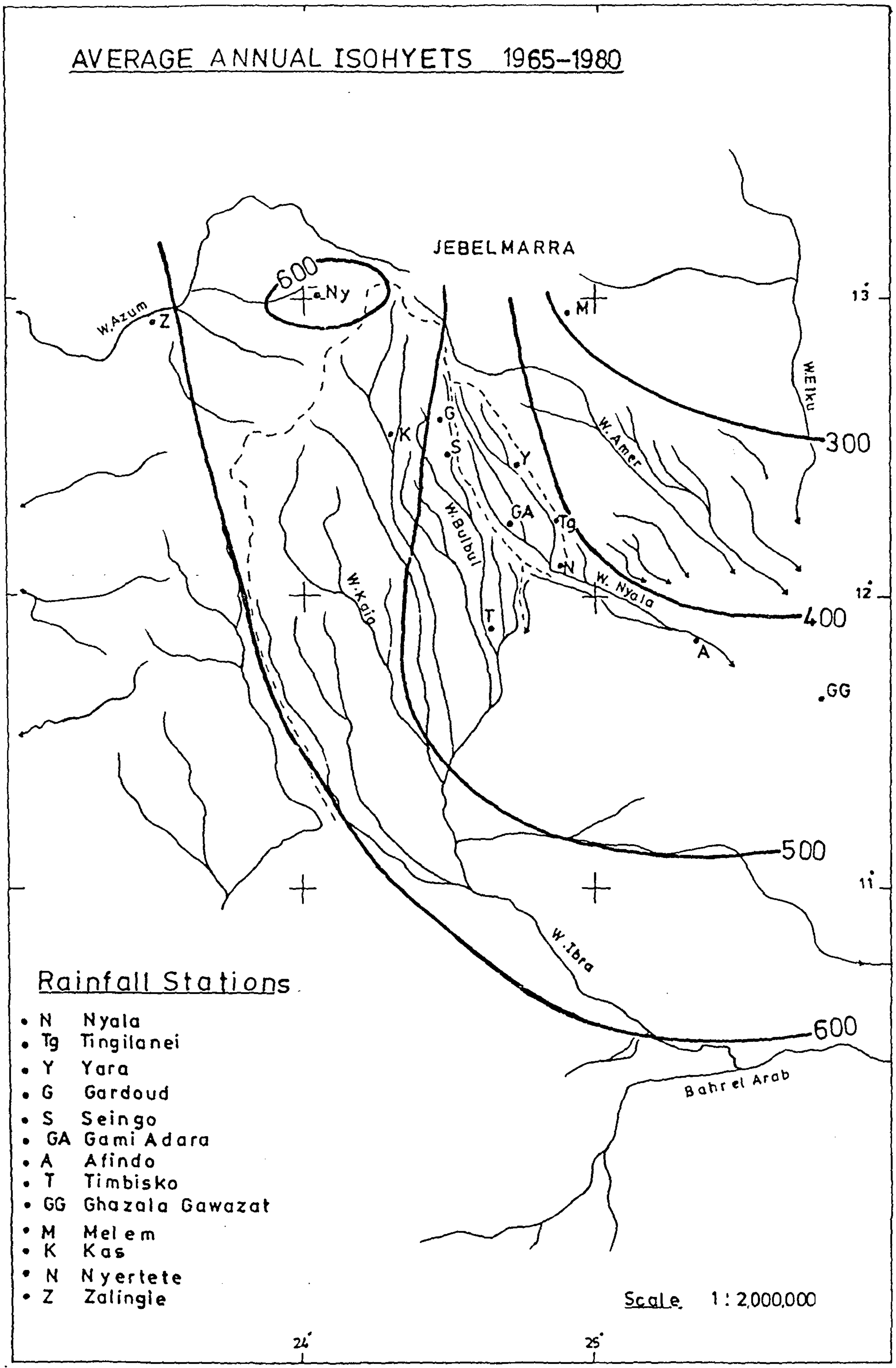
3.2.1 Introduction

At Nyala, rainfall data has been collected for a considerable length of time. The data extends back almost uninterruptedly until 1921 (see Table A.1). Several other rainfall stations exist in the area of southern Darfur but with shorter recording periods.
Most of these stations are situated inside the project areas of the Jebel Marra Rural Development project and the Western Savannah Development Corporation.
In the catchment area of Wadi Nyala, which is relatively small, no stations have existed before the WAPS-2 project established in May 1983 six rainfall stations equipped with automatic rainfall recorders (see Table 3.2). These operated throughout the project period (for locations, see figure A.1) and provided good records (Table A.2). The data from these stations was used to analyse the relation between catchment rainfall and runoff at Nyala.
Rainrecorders were also introduced at the NWC wadi gauging stations at Afindo (Wadi Nyala) and Timbusku (Wadi Bulbul). Rainfall has been measured at these stations since 1978.

3.2.2 Areal rainfall distribution

Southern Darfur is situated in the zone between the arid desert climate of Northern Sudan and the humid tropical climate of Southern Sudan. Rainfall amounts increase from north-east to south-west with local higher quantities around the Jebel Marra massif (see figure 3.1).
The catchment area of the Wadi Nyala is located between the 400

Figure 3.1


AVERAGE ANNUAL ISOHYETS 1965–1980
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Rainfall Stations
• N Nyala
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• Y Yara
• G Gardoud
• S Seingo
• GA Gami Adara
• A Afindo
• T Timbisko
• GG Ghazala Gawazat
• M Melem
• K Kas
• N Nyertete
• Z Zalingie
Scale 1:2,000,000
24°
25°

Table 3.2 WAPS-2 Rainfall Stations

Rainfall Stations	Coordinates Latitude	Longitude	Alt. (m)	Equipment (*)	Location of station
Nyala	12°04'	24°54'	680	1,2	WAPS-2 office
Tingilanei	12°18'	24°51'	775	1	School
Yara	12°26'	24°43'	830	1,2	School
Gardoud	12°36'	24°31'	980	1	School
Seingo	12°31'	24°33'	880	1,2	School
Gami Adara	12°17'	24°38'	800	1	Village
Afindo	11°47'	25°20'	540	1	Gauging station
Timbusku	11°49'	24°37'	680	1	Gauging station

(*) 1 = Rain recorder
2 = Rain Gauge

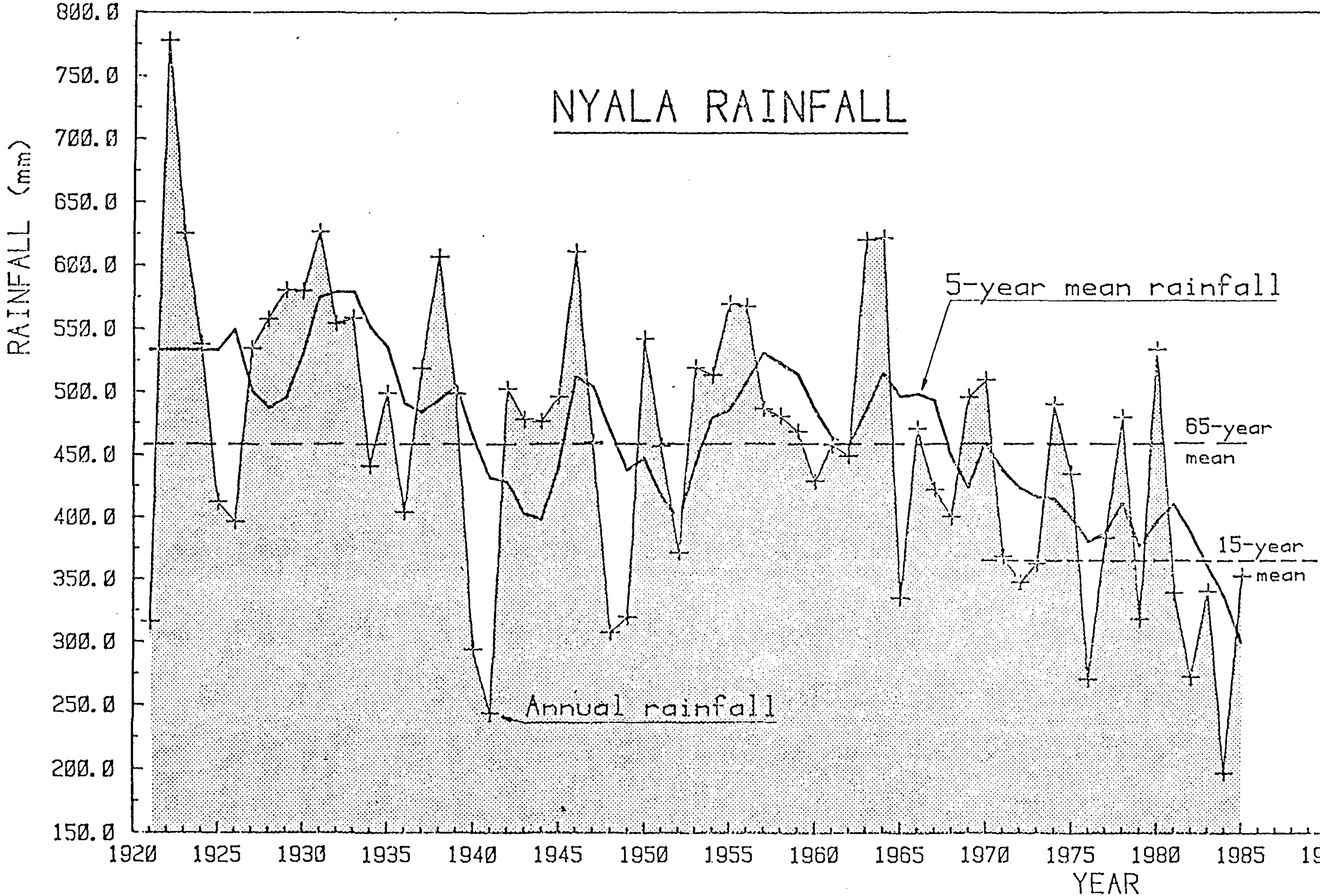
and 500 mm isohyets, and rainfall amounts generally do not increase in an upstream direction.

The recorded rainfall at the project rainfall stations in the catchment area is shown in Table A2. The figures show that rainfall does not increase towards the upper parts of the catchment. The orographic effect of the Jebel Marra massif seems not to affect the rainfall in the catchment area.

3.2.3 Annual rainfall

The annual rainfall has been fluctuating between 197.3 and 778 mm at Nyala during the 65 years observation period (the minimum annual rainfall at the WAPS-2 office was 154.3).

Figure 3.2 shows the 5-year moving mean of the annual rainfall. It is evident that periods with high and low rainfall quantities can be distinguished. However, most remarkable is the extended period since 1965 during which rainfall has been generally below average. Since 1971, rainfall has been very low and this period



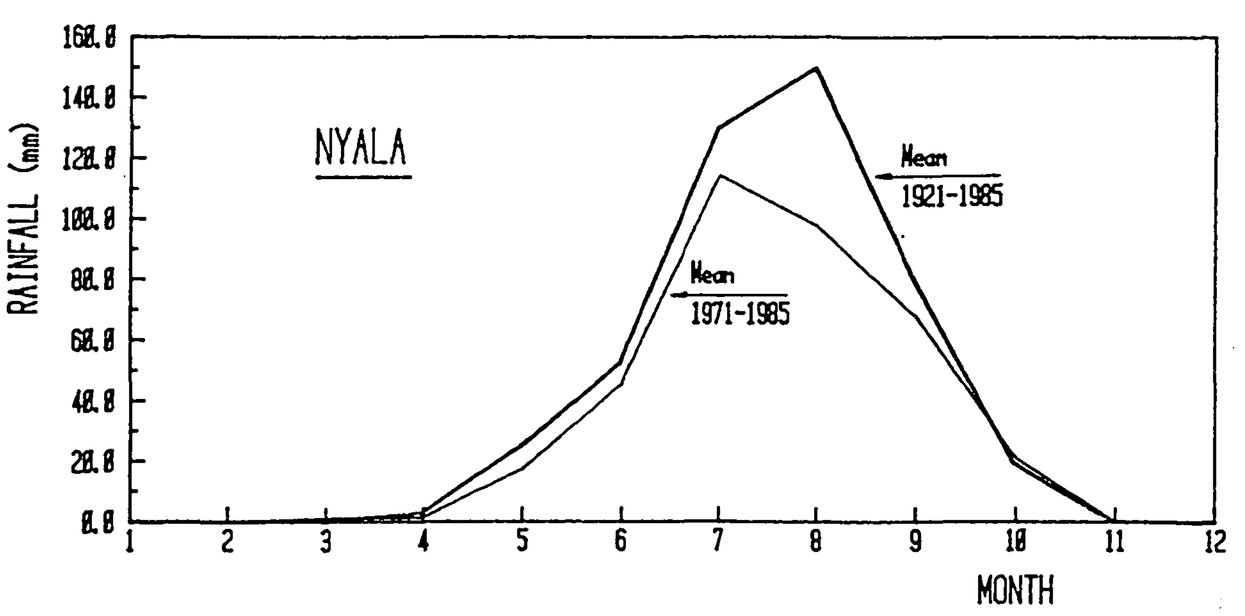
FIVE YEAR MOVING MEAN RAINFALL NYALA. Figure 3.2

comprises 10 of the 15 driest years on record. Mean rainfall since 1971 has been only 366.2 mm compared to 459.7 mm for the whole period 1921 - 1985. As discussed in section 3.1, the low rainfall is probably related to the lower rainfalls in the Sahel zone immediately south of the Sahara desert. An improvement of the rainfall totals is not likely in the near future and it therefore seems prudent to take into account only rainfall data pertaining to the period since 1971, for the planning for future water resources development.

3.2.4 Monthly rainfall

The rainy season generally lasts from May to October, but is concentrated between the end of June and the middle of September. The wettest months are July and August with 61% of the total annual rainfall (1921 - 1985). The lower annual rainfall seems to have been caused mainly by lower rainfall during the months August and September. A comparison of the record since 1971 with the full 65 year record for Nyala reveals significant lower rainfalls during these months in recent years (figure 3.3 and table 3.3).

Figure 3.3 Monthly Rainfall at Nyala



This may have been caused by the smaller size of the rain storms in dry years. In the beginning of August the ITCZ is reaching its most northerly position at 20°N and generally the rain storms will develop at this latitude north of Nyala. However, in dry years the storms do not develop adequately to travel as far south as Nyala, giving lower rainfalls in August and September at Nyala.

Table 3.3 Mean Monthly Rainfall at Nyala (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1921-1985	0.0	0.0	0.6	3.3	25.1	52.4	129.7	149.5	79.8	19.4	0.2	0.0	459.7
1971-1985	0.0	0.0	1.3	1.4	17.4	45.5	114.3	97.5	67.8	21.0	0.0	0.0	366.2

3.2.5 Daily rainfall

The monthly and annual totals of rainfall are composed of a limited number of storm events of short duration. The mean rainfall duration during the project period was only 1.3 hours per rainday (see table 3.4). In 1983 half of the total rainfall 52%, was produced in only 4 days during a total time of 12.9 hours.
The short duration of the rainfall shows that high rainfall intensities occur. The intensive period of a rainstorm at Nyala is often not longer than 30 minutes or less. These high rainfall intensities produce large flood peaks in the wadi, which is discussed in section 4.4.
The number of raindays did not vary much during 1983-1985 at Nyala. Apparently the number of raindays does not relate to the total station rainfall (table A.3).
The difference between a wet and a dry year seems to be caused by the occurrence of a few large rainfall events, and not by the number of rainfall events. In dry years storms do develop, but

their size remains small and they are quickly depleted from water.

Table 3.4 Rainfall Data Nyala

	1983	1984	1985
Number of raindays	33	32	25
Rainfall duration (hrs)	48	29	37
Maximum 30 min. rainfall (mm)	43.2	23.0	53.8
Maximum 1 hr. rainfall (mm)	63.6	23.8	59.4

3.3 Evaporation and Evapotranspiration

3.3.1 Methodology

Various methods exist to estimate evaporation. The most widely used and probably also the most accurate is the Penman method. This method provides an estimate of the open water evaporation, by using data of meteorological variables which are usually observed in meteorological stations.

The direct measurement of evaporation is carried out in Sudan with an evaporation pan or a Piche evaporimeter. The Nyala meteorological station is only equipped with a Piche evaporimeter. The evaporation pan, however, provides a better estimate of the evaporation. The WAPS-2 project installed pans at the WAPS-2 office and at the veterinary laboratory, with the objective of studying the difference in evaporation between the meteorological station site and a garden area.

The potential evapotranspiration at Nyala was determined, based on the evaporation estimates from both the direct measurements and the Penman method. The actual evapotranspiration which takes into account factors like soil moisture availability, land use, type of vegetation, etc. was finally estimated for the area of the alluvial aquifer. The results are presented in section 3.3.3 and the analysis in appendix A2.

3.3.2 Estimating evaporation

The Penman method was used to obtain an estimate of the evaporation. The method requires data on four meteorological variables:
- net energy supply by radiation;
- temperature;
- humidity;
- wind velocity.

The Nyala meteorological station only provides data on temperature and humidity. The net energy supply by radiation was obtained from tables and from an estimate of the sunshine duration. The wind velocity was estimated from visual estimates made by the staff of the station. The Penman equation is presented in appendix A2, together with a description of the meteorological data required as input.
The results of the calculations are presented in table A.4, which also includes the input data.

The direct measurement of the evaporation is done in the meteorological station with a Piche evaporimeter and at the sites of the WAPS-2 office and the veterinary laboratory with evaporation pans. The results of these measurements do not comply very accurately with the Penman estimate, but they could be used to correct the evaporation estimate for conditions prevailing in the garden area (see appendix A2).
The total annual evaporation at the meteorological station estimated with Penman is 2155 mm or 5.9 mm/day. The corrected estimate for the garden area is 1935 mm or 5.3 mm/day.

3.3.3 Evapotranspiration at Nyala

The evapotranspiration is the process by which water from water-surfaces or from bare soils (evaporation), and from vegetation (transpiration) is transformed into vapour, which is mixed with the atmosphere by turbulent wind currents. Evaporation from open water surfaces is solely controlled by meteorological conditions whereas evaporation from bare soils is also dependent on availability of soil moisture. Evapotranspiration is also related to vegetation type, density and growth stage. Evapotranspiration is at its potential level if water supply and other growing conditions are optimal.

Evaporation by far exceeds rainfall in semi-arid Darfur, which implies that soil moisture shortages prevail most of the year. When estimating the actual evapotranspiration (AE) from potential evapotranspiration reduction factors should thus be applied, which depend on moisture availability, vegetation type, growth stage etc. Only in areas which are irrigated will the actual evapotranspiration be near the potential evapotranspiration rate.

The area covered by the alluvial aquifer (as shown on map 3) was subdivided into five different units according to land use, by using aerial photography of 1974 and 1984. For each unit an estimate of the actual evapotranspiration was prepared and the area measured from the map.
The evapotranspiration was determined seperately for the Town Area and the Downstream Area, as for both areas a water balance was established (section 7.8).

The calculations were carried out for the 9 months period of the dry season (September 15 - June 15) and for the 3 months period of the wet season (June 15 - September 15), see appendix A2.
The total annual waterloss by evapotranspiration from the wadi alluvial aquifer was estimated at 2.30×10^6 m^3 for the Town Area and 12.22×10^6 m^3 for the Downstream Area.

Table 3.5 Actual Evapotranspiration (AE) Estimate for the Alluvial Aquifer

	TOWN AREA			DOWNSTREAM AREA		
	Area (km^2)	AE (mm)	Volume (10^6 m^3)	Area (km^2)	AE (mm)	Volume (10^6 m^3)
Agriculture, irrigated	0.80	1330	1.06	0.7	1340	0.93
Agriculture, not irrigated	0.34	265-930	0.32	0.3	270-940	0.28
Man-made forest	0.02	930	0.02	1.2	940	1.12
Natural forest	-	695	-	8.5	705	5.91
Bare soils with bushes	0.62	150	0.09	1.7	150	0.26
Wadi	1.44	50	0.07	1.8	50	0.09
DRY SEASON TOTAL	3.22		1.56	14.2		8.59
Agriculture, irrigated	0.40	210	0.13	0.4	210	0.14
Agriculture, not irrigated	0.89	210	0.31	1.1	210	0.38
Man-made forest	0.02	210	0.01	1.2	210	0.41
Natural forest	-	155	-	8.5	155	2.21
Bare soils with bushes	0.47	130	0.10	1.2	130	0.26
Wadi	1.44	80	0.19	1.8	80	0.23
WET SEASON TOTAL	3.22		0.74	14.2		3.63
YEAR TOTAL	TOWN AREA		2.30	DOWNSTREAM AREA		12.22

4. SURFACE WATER RUNOFF

4.1 Introduction

The main recharge to the alluvial aquifer at Nyala is the infiltration of surface water runoff. The runoff appears in the wadi as floods of short duration and with high peaks. The runoff of Wadi Nyala has never been gauged before at Nyala. Salama (1971) provides an estimate of the total runoff during 1970. His estimate, 69 million m^3, was based on the observation of only one flood. Hunting (1974), estimated the Wadi Nyala runoff from data collected in the catchment of Wadi Bulbul. The estimate was revised to an average annual volume of 49 million m^3 by Humphreys (1983), who had a longer runoff record for Wadi Bulbul (6 years) available.

Downstream from Nyala, at approximately 75 km distance, the NWC operates a runoff station at Afindo. The project assisted there by supplying a waterlevel recorder and an automatic rain recorder. The relation between the runoff at Nyala and at Afindo is poor, probably mainly due to the extensive losses of runoff by infiltration, flooding of depressions between the stations and several tributaries adding runoff. The channel at Afindo is only 15 metres wide.

The WAPS-2 project started to gauge the Wadi Nyala flows in 1983. In order to analyse the flood events a runoff station was built about 1.2 km upstream from Texas Bridge. Here waterlevels in the Wadi were recorded continuously with a waterlevel recorder. The station consists of a well, which is connected by a small pipe with the wadi channel. The location, although not ideal because of the large width of the Wadi (80 metres) and the instability of the wadi bed, proved to give a satisfactory record of the flood events. From the bridge discharge measurements were carried out using a propellor with a 25 or 50 kg sinkerweight. The propellor was lowered from the bridge using a winch mounted on a landrover. In total 41 measurements were carried out in 1983, 10 in 1984 and 29 in 1985. For each flood the relation between stage and discharge was determined, providing the base for the calculation of total daily flows.

The measurement of the discharge during high stages was not possible, because of the strong turbulency of flow and the high flow velocities. Therefore discharges during the flood peak had to be estimated, by extrapolating the stage-discharge relation to higher stages. To check the estimated maximum discharge, data were used from two crest gauges installed at the runoff station and at the bridge. These provided the maximum waterlevel for each flood from which the maximum discharge was determined using the slope-area calculation method.

4.2 Description of Wadi Nyala

The runoff is generated by the rainfall in the catchment area, which extends about 90 km upstream of Nyala in north-north-west direction, with an area of approximately 1360 km^2 (see figure A.2). The upper limit of the catchment lies near the foot of the Jebel Marra. Thus the drainage system does not extend onto the slopes of the Jebel marra, in contrary to the neighbouring catchments of Wadi Amer and Wadi Bulbul, but is situated in the piedmont area. The highest elevation of the Wadi Nyala catchment reaches approximately 1100 m.

The slope is gentle, changing from 6 m/km in the upper reaches of the catchment to about 3.8 m/km in the lower reaches. The geology of the catchment is composed of the quartzite/gneiss formations belonging to the Basement Complex, which usually are at shallow depth. At some places intrusions, mostly granitic dykes are found, which form outstanding ridges trending in general between northern and north-eastern direction.

The vegetation is mainly composed of thorn bushes and low trees, but large areas are only sparsely covered. The degradation of the vegetation cover by the continuous cutting of trees and

overgrazing is a striking phenomenon. In large area's only tree stumps remain, the wood being used for firewood by local inhabitants or brought to Nyala to be sold.
It is clear that this process will enforce the extensive erosion of the already thin soil layer. Also it can be expected that flood volumes and flood peaks at Nyala will continue to rise, because of the decreasing capacity of the catchment to intercept and retain part of the rainfall.

The rainfall in the catchment area is governed mainly by the local thunderstorms, which are usually travelling across the area from north-east to south-west. The storms usually cover only part of the catchment area, but the high intensity of the rains still generate considerable volumes of surface runoff.
The infiltration capacity of the soil is low, due to the presence of a resistance surface soil cap. Soon after rain starts, the heavy impact of the raindrops closes the soil surface almost completely, by the forming of a thin surface pan or cap.
The interception capacity of the vegetation increases towards the end of the wet season. The area during this period changes from a dry and yellow to a green and pleasant landscape. On the parts where the best soils are found sorghum (dura) or millet (dukhn) is grown.
The surface runoff develops quickly, soon after rain has started. The water flows along small drainage channels, which are very densely distributed in a dendritic pattern. These join to form small wadi's which have a thin sandy bed, but no great lengths. Finally the water will reach one of the two main branches of the Wadi Nyala: the Wadi Kabris and the Wadi Domai (see figure A.1).
The bigger wadi's in the Wadi Nyala catchment usually have a bed composed of a few metre of coarse sands. In the beginning of the flood season infiltration into these sands will reduce the flood size. Later, after recharge has taken place this effect will be reduced.

The two main branches of Wadi Nyala join at Domai, about 8 km upstream from Nyala. The width of the wadi is never more than 100 metres, until Nyala is reached. There the width increases to a maximum of 400 metres. Downstream from Nyala the wadi flow is divided into several branches and the width is reduced; flooding of the banks occurs regularly. The runoff decreases because of the flooding, but also by the infiltration into the subsurface. In this area the course of the Wadi is sometimes changed after a big flood has passed. As a consequence the old channel receives less water or even remains dry during the next floods. The people rely for their water supply on dug wells in these old channels and sometimes have to shift to another location for water supply.

The present width of the wadi at Nyala and further downstream is in places larger than ten years ago. This can be deduced from aerial photography, which dates back to 1972. Also in other wadi's e.g. Wadi Bulbul, an increase in width is observed. The cause is probably that peak flows have increased, due to the advance of the denudation in the catchment area.
The increased width of the wadi bed occurs usually at the expense of valuable agricultural land. At Nyala the banks of the wadi have been flooded several times during 1983-1985. Depths were usually shallow but some wells were filled with sediment and a few were even destroyed. Also some orchards were damaged by erosion of the wadi banks (e.g. at dug well 103 and 105).
In 1983 BH 9 collapsed during a big flood. In 1985 BH 2 was severely damaged and BH 19 was destroyed. Also in 1985 damages occurred to the buried PEWC pipelines and to all the overhead electricity lines. It is clear that the continuing high flood peaks involve a risk of damage to the wells and gardens. Only measures in the catchment area to improve the vegetation cover will reduce this risk. In the meantime existing boreholes used by the PEWC need better protection (see section 9.4).

4.3 Discharge of Wadi Nyala

The discharge of Wadi Nyala was calculated using the continuous record of the surface water levels from the runoff station and the discharge measurements taken at the bridge. The method of calculation is described in appendix A3.

The daily discharges of 1983, 1984 and 1985 are presented in tables A.14 to A.16. The maximum daily discharge was 16.8 x 10^6 m^3 in September 1985. The maximum 24 hours discharge was 31 x 10^6 m^3, occurring during the same flood.
The total annual discharge is made up for a large part by a small number of big floods, and it varied strongly due to the variation in rainfall in 1983-1985 (see table 4.1). Also the dates of the first and last floods vary from year to year, but the main runoff period is concentrated between the beginning of July and the middle of September.

The number of runoff days was similar in 1983 and 1984, despite the difference in rainfall. But in 1985 the number was bigger, probably due to the higher groundwater levels in the wadi.
The longest consecutive period of runoff was in 1985: 92 days. However, the flow was smaller than 1 m^3/s during about half of these days.

Table 4.1 Wadi Nyala Discharge Data

	1983	1984	1985
Total runoff (10^6 m^3)	63.0	14.2	112.4
Days with runoff	47	43	103
Maximum peak discharge (m^3/s)	500	600	1500
Date of first flood	16 May	29 June	25 May
Date of last flow	17 Sep	28 Sep	5 Oct

The duration of the flood peaks is very short, usually not more than a few hours. The maximum discharge is often reached within one hour of the start of the flood.
During the big floods the recession starts about 3-6 hours after the start of flow. During the smaller floods even quicker. The recession from peak to a discharge less than 5 m^3/s takes usually less than 24 hours.
The flow velocities during peak flow are very high. Measurements with floats indicated velocities of 5 m/s.
The current metre propellor could only be used for velocities below 2.5 m/s because of the danger of damage due to the strong turbulency of the water.
Measurements of peak discharges were therefore not possible. They were estimated by applying the slope-area method (see table A.17). However, the estimate is complicated due to:

- a change in slope of the watertable at the bridge, because of the abrupt change in flow width;
- scouring of the wadi bed, which causes greater flood depths during the peak discharges.

The highest floodlevels occurred on September 10th, 1985. The peak discharge during this flood was estimated at 1500 m^3/s (the bridge was designed for a peak discharge of 1270 m^3/s!).
After the flood the elevation of the wadi bed surface was lowered by 0.5 to 1.0 metre along the whole length between Domai and Kundua.

4.4 Rainfall - Runoff Relationship

The runoff of Wadi Nyala is characterised by large flood peaks of short duration (few hours) and a short recession period. The localised storms often of high rainfall intensity, produce narrow, high peaks. This is clearly demonstrated in figure 4.1, showing two runoff and rainfall events of 1983. The discharge curve of Wadi Nyala at the Nyala gauging station is shown together with the hourly rainfall for each rainfall station in the

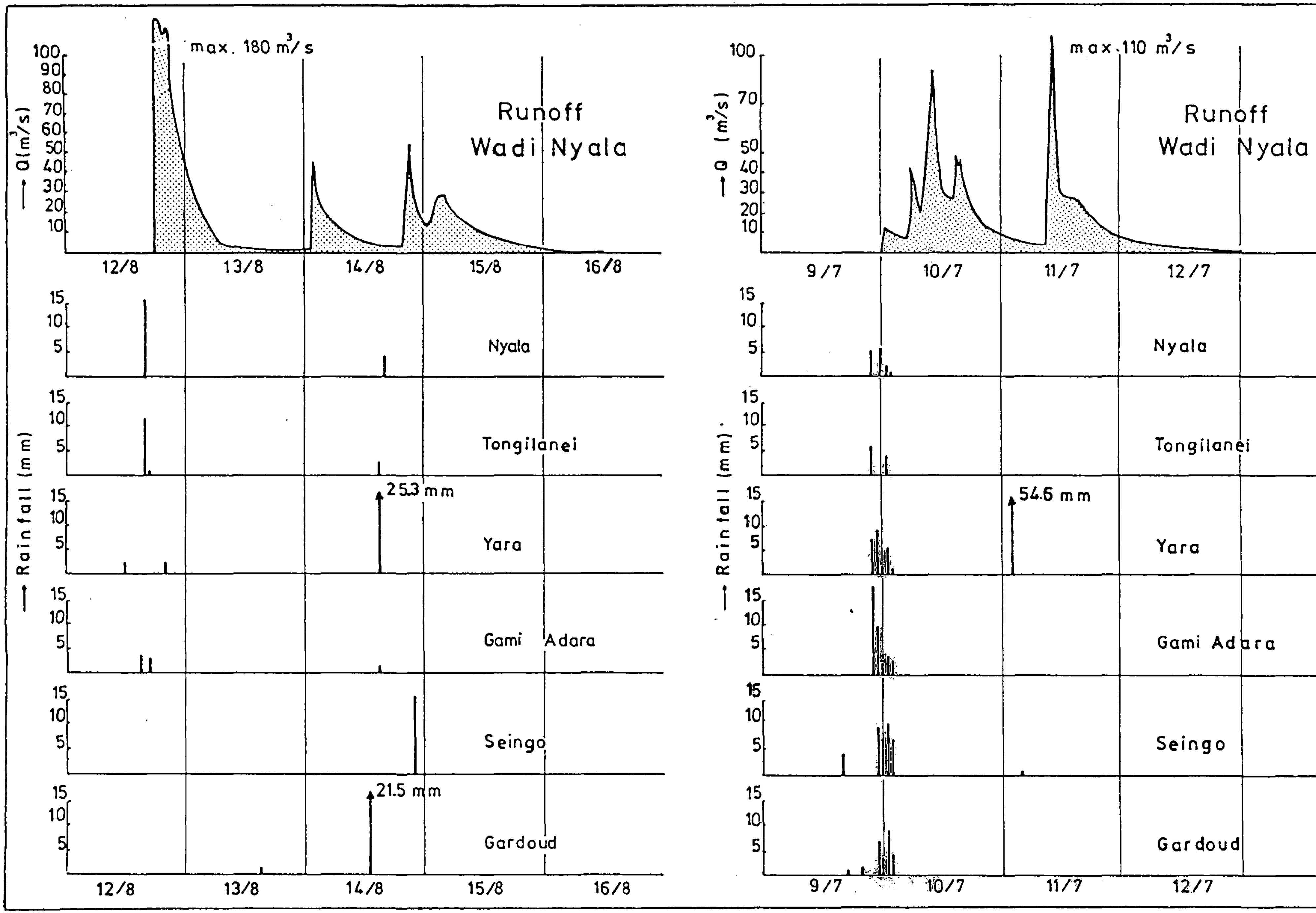


Figure 4.1

TWO RUNOFF EVENTS WADI NYALA 1983

catchment area.
The storms of high intensity often cover only part of the catchment area and rainfall is thus observed only in some of the stations (as on 11/7 and 12/8). The size of the flood peaks depends strongly on the location of the storm. Sometimes (e.g. on 14/8), a flood occurs without rainfall being observed in any of the stations. This shows the localized character of the rainstorms.

The percentage of the rainfall in the catchment area which reaches the wadi gauging station as surface runoff was determined. The catchment rainfall was calculated by constructing a so-called "Thiessen" net. The station rainfall is multiplied with a factor, which is determined by weighting the area assigned to each station, and the total catchment rainfall is the sum of all weighted station rainfall amounts. In table 4.2 the total catchment rainfall is shown for periods of 15 days. Also the runoff is shown expressed in mm and in percentages of the catchment rainfall.
In normal years the percentage reaches its maximum in the period of July, August and September, when rainfall events are most frequent, and the higher soil moisture content produces more surface runoff. The growth of the vegetation during the rain season seems not to have much effect on the percentage.
The annual percentage increases with a larger catchment rainfall. The runoff seems sufficient for recharge of the aquifer if rainfall is more than about 250 mm (see section 7.5).

To check the reliability of the relation between the rainfall observed at Nyala and the runoff of Wadi Nyala, correlation calculations were carried out with the 1983 and 1985 records. For each station in the catchment area, the individual rainfall storms were determined and correlated with the observed floods at Nyala. The result of the calculation is shown in table 4.3.

Table 4.2 Wadi Nyala Discharge at Nyala in Relation to Catchment Rainfall

		May	June		July		Aug		Sep		Oct	Total
1983	Catchment Rainfall (mm)	0.5	13.7	24.3	46.0	86.3	42.9	41.0	28.6	6.6	-	290.0
	Wadi Nyala Runoff (mm)	0.07	0.37	1.9	3.1	20.4	9.3	6.7	4.2	0.6	-	46.6
	Runoff in % of Rainfall	14	3	8	7	24	22	16	15	9	-	16
1984	Catchment Rainfall (mm)	3.6	3.3	23.2	33.4	46.6	31.3	9.5	22.9	30.8	10.8	215.4
	Wadi Nyala Runoff (mm)	-	-	0.29	3.31	1.03	1.47	1.54	0.44	2.35	-	10.43
	Runoff in % of Rainfall	-	-	1	10	2	5	16	2	8	-	5
1985	Catchment Rainfall (mm)	11.5	1.3	50.8	76.8	29.2	77.7	39.3	36.7	26.7	-	350.0
	Wadi Nyala Runoff (mm)	0.07	-	2.94	17.50	14.93	14.04	5.07	25.15	2.94	0.04	82.68
	Runoff in % of Rainfall	1	-	6	23	51	18	13	68	11	-	24

Table 4.3 Correlation between Station Rainfall and Wadi Nyala Runoff Events

Rainfall Station	Elevation (m asl)	1983		1985	
		Number of events	Correlation coefficient	Number of events	Correlation coefficient
Nyala	680	29	0.75	24	0.34
Tingilanei	775	30	0.73	26	0.44
Yara	830	35	0.70	27	0.57
Gardoud	980	35	0.34	19	0.15
Seingo	880	28	0.40	29	0.00
Gami Adara	800	26	0.28	19	0.48

The correlation between rainfall and runoff appears to be poor, especially for the upstream stations Seingo and Gardoud. It seems that runoff is generated mainly in the downstream part of the catchment. Rainfall in the upper part does not always reach Nyala as runoff, especially after storms of a small size.

The correlation between the rainfall at Nyala and the Wadi Nyala runoff at Nyala is also poor. The long rainfall record at Nyala therefore cannot be used to provide a probability analysis on the wadi runoff. Such an analysis would be complicated anyway, because of changes in the rainfall - runoff relation, due to continuing deforestation in the catchment area.

Already in previous years, it has been observed that flood volumes have increased, although rainfall continued to be low. It can be expected that also in future this rise in flood volumes will continue.

5. GEOLOGY

5.1 Geological setting

The geological description of Central Darfur Region in general and the Nyala area in particular, is based on Hunting (1974) supplemented with information of the area under study, which has been collected recently.

The general geology of Central Darfur Region is quite simple and consists of the Basement Complex (BC), which for the most part is covered by superficial deposits. These deposits include alluvium (mainly in wadi beds), residual deposits and goz sands, and are of Pleistocene to recent age.

In the project area the Basement Complex outcrops at Jebel Nyala and at some local places on the bank and in the Wadi Nyala-bed near Nyala Town and the upstream area. Exposures of rocks in the downstream area are scarce. The geological map (map 2) is based on approximately 1 : 45 000 scale aerial photography and field inspections.

5.2 The Basement Complex

The Basement Complex consists mainly of metamorphic rocks of sedimentary and igneous origin. They are of Pre-Cambrian to Cambrian age and are characteristic of the Sudan as a whole. The main rock types are strongly foliated gneisses and mica schists. Exposures are mostly of psammitic types, often quartzites (e.g. Jebel Nyala). Other rock types include a pink granite-gneiss with hornblende, and a fairly widespread pale unfoliated granite, which is probably one of the younger granites described by Vail (1972) and thought to be Cambrian in age.

In the project area the gneisses are of different compositions. At Wadi Kulkul, near the project office, a schist-gneiss rock of a grey colour is found. Several kilometres upstream along the same wadi, a coarse-grained quartz-feldspathic gneiss of a pink colour is observed. At some places near Wadi Nyala granitic-

gneiss rocks are found. Exposures of mica schists are found near Domai, about 8 kilometres upstream of Nyala Town, and at several places in the bed of Wadi Kulkul, near the WAPS-2 office. Quartzite is found at Jebel Nyala, which lies on the eastern side of Nyala Town, at scattered places near the banks of Wadi Nyala, at the western part of Nyala Town, and near Domai.
The gneisses and quartzite are intruded by granitic rocks, e.g. on the southern bank of the Wady Nyala at Texas and at the Town Wells site near the north bank of the wadi.
The Basement Complex rocks have been subjected to several phases of folding, followed by the intrusion of granites and quartz dykes, possibly of Cambrian age. The rocks were subsequently eroded to form a surface of subdued relief. Remnants of the old topography survive chiefly as narrow quartzite ridges like Jebel Nyala. In the Nyala region the dominant structural trend is northeast - southwest. This is also shown by pronounced lineaments on satelite images.
The Basement Complex is cut by a number of quartz dykes, several metres thick, which form prominent jagged ridges, the dominant features of the landscape. The trend of the dykes is usually 130^{o} to 150^{o}, but a subsidiary trend of 100^{o} to 110^{o} is also common, and some dykes have a forked outline. The dykes follow the general faulting pattern of the area (Vail, 1972).

The drainage pattern of the pediment is very distinctive. On a small scale, the pattern is dendritic with a high drainage density, but on a large scale it appears to be structurally controlled, with long narrow catchments conforming to the structural trend of the Basement Complex. Joints developed in granites are of a different trend, forming angular drainage systems which can be found at several places. On a relatively flat pediment these drainage patterns have led to considerable drainage instability, resulting in much overflow of floodwaters.
In the project area the Basement Complex is not regarded as an aquifer, although locally small quantities of groundwater can be stored in the weathered topzone of the Basement Complex or in fractures or faults within the Basement Complex.

5.3 Superficial deposits

5.3.1 Alluvial deposits

The type of alluvial deposit in the Central Darfur Region depends on the flow-regime of the wadi, and on its proximity to goz sands (more or less stabilized aeolian sands) and outcrops of Basement Complex rocks.
The Central Darfur pediment of the Basement Complex is drained by an intensive network of wadis which flow intermittently during the wet season. The main wadis flow NS and NNW-SSE (see figure 2.2) and have few major tributaries, but many minor ones which show a denditric pattern. After leaving the pediment, the major wadis converge on the Wadi Ibra flood plain. The flood plain is constricted between the major areas of goz sands, but to the east and south it opens out towards the flood plain of the larger Bahr el Arab, with which it merges.

The Wadi Nyala flows in a SSE direction upstream of Nyala, but changes direction to E along about 7 km at Nyala, due to a major structural fault in the Basement Complex. The floodwater is augmented from minor branches, but the water disperses in the flood plain SE of Nyala.

In the part of the Darfur Region, where the project area is situated, three stages can be recognized along the wadi profiles from north to south.
In the upstream stage the wadi flows in a recognizable, though very shallow valley with rocky side-slopes. In this stage, the wadi fill is generally coarse, but its thickness and width are quite variable, and in places the wadi channel may resemble a series of rocky basins.
The main wadis of this region on the Basement Complex pediment e.g. Wadi Nyala, are in the middle stage of wadi development in which a broad, shallow, sandy wadi channel is flanked by silty terraces which generally slope away from the wadi channel, over

low levees. In places two terraces can be seen; an inner terrace supporting stands of Haraz (Acacia albida) trees, flanked by an outer terrace of silty clay, covered by Heglig (Balantines aegyptiaca) trees. Rock outcrops are rarely seen near the wadi and the Basement Complex is hidden by residual soils, sheet wash deposits and thin flood alluvium. Boreholes and dug wells show that the wadi alluvium is variable both laterally and vertically and contains thick beds of clays, silts, and sands in close proximity. Also very coarse sands with some gravel and boulders are found. The sediments probably occur in lenticular deposits, which are generally hydraulically continuous. The depth of alluvium appears to be up to 12 m, though in Wadi Nyala, near Nyala Town, a depth of almost 20 m is known. There are indications that the depth to fresh Basement Complex is much the same beneath the wadi channel as it is beneath the residual soils and sheet wash on either side close to the channel. The width of the wadi near Nyala increases from 100 m upstream to more than 400 m near the Railway Wells. The clay content of the wadi alluvial fill increases downstream.

The third stage of wadi development occurs when the wadi leaves the pediment and flows over their flood plain. Here the wadi channel may change periodically. Downstream of Nyala Town, Wadi Nyala has changed position dramatically over a short time interval and as a result the flood plain sediments are being continually reworked. Evidence of the wadi channel changes can be seen by comparing aerial photographs from 1974 to 1984.

The entire flood plain is made up of alluvial sediments which have been laid down by relatively slow-moving rivers and is therefore generally fine grained, with narrow sandy strips close to the wadi channels. In many parts of the flood plain, the old abandoned channels of small wadis are marked by narrow, sinuous strips of sand, supporting stands of palm trees. The maximum depth of the alluvium in this area is 17 m, which is recorded in borehole NP015, near Umm Jakhokha Village.

5.3.2 Residual deposits

Much of the Basement Complex is covered with a mixture of residual deposits. They are known as the clays of the plains, as defined by Andrew (1948) and were formed during the Pleistocene. The thickness of this formation increases downstream. Residual deposits, a result of weathering of the Basement Complex formation, are composed of fine grained silts and clays, and are found in the lower parts outside the alluvial area.

5.3.3 Goz sands

Goz sands are aeolian deposits, formed during the Pleistocene. They are found overlying both the unconsolidated sediments and the Basement Complex rocks. The Nubian Sandstone formation is considered to be main source of dune sands in the Sudan. The goz sands are composed of medium to fine grained sands of quartz and a few feldspars and are brown to yellow in colour. The goz layer in the study area is probably only a few metres thick.

5.4 Geological Structure

The Basement Complex is the only outcropping formation in the area. Because of its complex tectonic history, many fault directions can be found, as well as several directions of foliation.

Structural planes (e.g. faults, foliation planes) are visible frequently on aerial photographs as lineaments. The lineaments near Nyala Town show many trend directions, reflecting the complex tectonic history of the geology of the area. Three major directions of lineaments can be distinguished. The orientations are: NW-SE, NE-SW and W-E. The lineaments which represent faults, are indicated on the geological map (map 2) as a dash-dot line; those of which the geological significance is uncertain are indicated by a dotted line.
In most cases, the wadi patterns reflect the structural features.

Using geophysics (EM method), three of the lineaments in the area near Wadi Nyala could be correlated with faults or fractured zones. They are shown as full lines on the geological map. One fault is located along the right bank of Wadi Nyala near the town; it runs W-E. Two faults or fractured zones are in the area downstream of Jebel Nyala; one lies along Kondua Forest and the second is located on the left bank of the wadi, in the area south of Wadi Buldanga. Their directions are NW-SE.

6. GEOPHYSICS

6.1 Introduction

The objectives of applying geophysics to the WAPS-2 water resources assessment study of Wadi Nyala are:

- to determine the geometry of the wadi aquifer;
- to find out the extension, depth and variation in thickness of less permeable layers within the aquifer;
- to trace faults and fractured zones in the Basement Complex which forms the lower boundary of the aquifer;
- to select locations for exploratory boreholes.

In general, the aim of geophysics is to reduce the number of (relatively expensive) exploratory borehole drilling operations to achieve the above mentioned objectives. No geophysical method will give a direct indication of the presence of groundwater.

The channel of Wadi Nyala in the catchment area is confined between banks, usually made up of rocks belonging to the Basement Complex. The width is generally narrow, not exceeding 100 metre. At a few places the wadi becomes wider, e.g. at Romalia, 13.5 km upstream from Mekkah Bridge, where the width of the wadi sediments reaches a maximum of 500 m but depths are most probably shallow, not exceeding about 6 metres (see section 11.2).
At Nyala Town the wadi channel widens along a longer stretch and the width of the wadi bed reaches up to 400 m. In the area downstream of Jebel Nyala, the wadi channel becomes less defined and at several places splits into different branches.

The geophysical survey was concentrated near Nyala Town, starting from the runoff station near Hai-el-Gir, where the wadi channel is still narrow (80 m) and rocks of the Basement Complex crop out on both banks of the wadi, and ending in the area of Bileil, where the wadi channel becomes narrow again. The total length of the survey area is about 18 km; the maximum width is about 3 km near Kundua Village.

The area of the wadi near the town center and west of the channel curve near Jebel Nyala is refered to as the Town Area; its length is about 6 km. The area east of Jebel Nyala is refered to as the Downstream Area; its length is about 12 km.

The hydrogeological setting of the area under study - a small thickness of the shallow aquifer, rapid lateral changes of the alluvial wadi fill together with an irregular topography of the top of the underlying Basement Complex - restricts the geophysical methods which can be applied successfully. During this study, an electromagnetic method and electrical resistivity methods have been applied to accomplish the geophysical objectives. Combined with exploration boreholes, these methods are considered to provide the optimum cost/benefit ratio for a small scale groundwater study.

The electrical resistivity method, especially the vertical electrical sounding (VES) technique, is a well known survey method for groundwater studies and has been applied successfully in many hydrogeological investigations in the Sudan and elsewhere.

The electromagnetic method of investigation in the Sudan, until now, has only been applied in the search for metallic ores. The EM technique has been used effectively in hydrogeological studies in different parts of the world, e.g. The Netherlands, Burkina Faso (formerly Upper Volta), the U.S.A.
Because of the flat topography of the survey area, no topographic reductions were applied for the geophysical interpretations.

The starting points of the geophysical survey of the Wadi Nyala aquifer were the available information from previous geological and hydrogeological studies of the area, data from existing boreholes and wells, and the results of previous geophysical investigations.

The results of the geophysical survey are presented in the form of an alluvial aquifer geometry map. The map shows a practically applicable division of the alluvial deposits for hydrogeological purposes.

6.2 Previous Investigations

Previous geophysical investigations in the Wadi Nyala aquifer near Nyala Town have been carried out by Salama (1977), Hunting (1970, 1974) and Abdul Razig Mukhtar (1979).

The seismic refraction surveys by Salama and Hunting gave an overestimated depth to basement in the Railway Wells site area. Their studies showed an alluvial fill thickness of 30 m. This turns out to be in error by at least 10 m, as was revealed by boreholes drilled afterwards. Furthermore, Hunting, on their seismic lines, made some debatable interpretations of a very thin, very low velocity top layer. Hunting also provided raw gravity profiles as an additional survey to support the seismic interpretations.

The electrical resistivity survey of Abdul Razig Mukhtar (1979), has been performed with equipment that was inadequate to overcome sufficiently the problems caused by the electrically high-resistant top layers. Hence the survey proved to be unsuccessful.

Geophysical surveys in the Downstream Area have never been carried out before.

The poor results of previous geophysical investigations in the wadi aquifer have been attributed to the small thickness and variability of the aquifer (Hunting, 1970).

6.3 Methods of Investigation

6.3.1 Electromagnetic (EM) method

For the EM survey of the alluvial aquifer, use was made of the EM 34-3 system of Geonics. The horizontal profiling technique was applied for the determination of lateral variations in electrical conductivity (or the reciprocal: electrical resistivity) of subsurface material. These are in many cases related to lateral variations like changes in lithology or groundwater quality.

In the beginning of the survey, 11 reconnaissance lines (total length: 45.9 km) were measured; the applied coil separation was 20 m, and the station interval 20 m. Later, measurements were carried out along 28 selected profile-lines.
The total length of these profiles is 66.5 km; the coil separation was again 20 m, the station interval 10 or 20 m, depending on the detail required. Figure 6.1 shows the locations of the EM profile lines; information about the stationnumbers is also indicated. A complete list with detailed information about the EM profile lines is given in appendix B, table B.4.

Near some borehole sites, detailed EM studies were carried out to correlate the lithology with the vertical electrical conductivity distribution of the subsurface. Because of the rapid vertical changes in lithology no satisfaying results could be obtained.

On some selected VES locations detailed EM studies were performed for the application of the combined use of the VES technique and EM 34-3 system; see section 6.3.4.

For investigating the wadi aquifer, the EM study has several advantages above other geophysical methods, especially when compared with electrical resistivity techniques; this is discussed

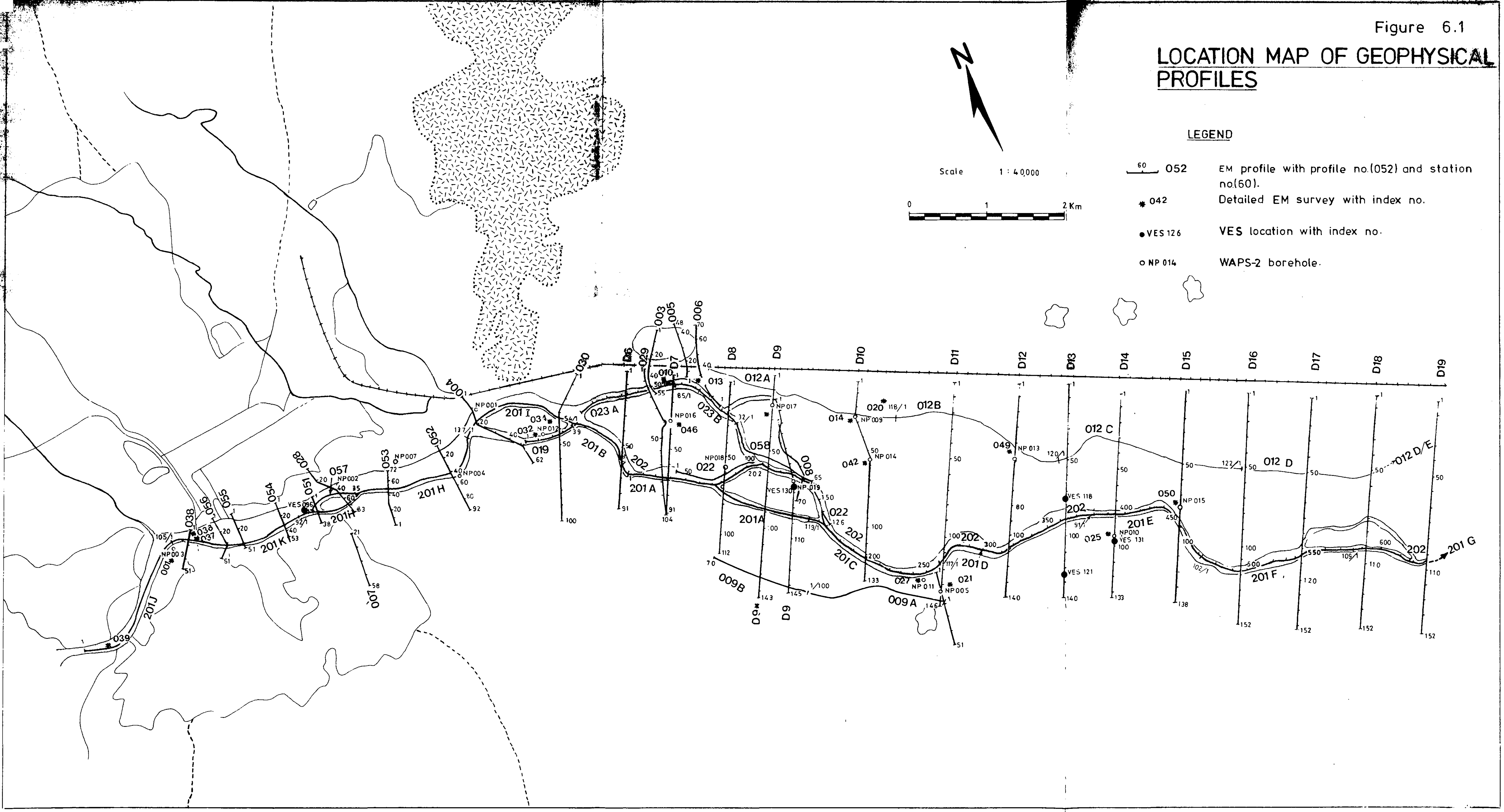


Figure 6.1

LOCATION MAP OF GEOPHYSICAL PROFILES

in appendix B. In the same appendix a detailed description is given of the principles of the EM 34-3 system, the instrumentation used, field techniques, data acquisition and processing, and interpretation techniques.

Despite the constraints in the resolving power of the EM technique, it proved to be a rapid and useful method of achieving several of the objectives of the geophysical survey.

6.3.2 Electrical resistivity method

The aims of applying electrical resistivity methods in the project area are:

- to obtain information about the depth to the Basement Complex which forms the lower boundary of the wadi aquifer;
- to delineate the presence and the extension of less permeable layers within the wadi aquifer;
- to determine the lateral extension of the wadi aquifer.

Use was made of the vertical electrical sounding (VES) technique. A total number of 120 VES's was carried out with a spread length ranging between 140 and 500 m. In addition horizontal electrical profiles were performed, with a total length of 6.6 km. The VES method is used to analyse the vertical electrical resistivity distribution to the subsurface, which in many cases can be related to the hydrogeological configuration of the underground.

The horizontal profiling technique is applied to delineate lateral changes of the electrical resistivity that can often be correlated with hydrogeological variations.
During the progress of the geophysical study, the horizontal electrical profiling method was replaced by the EM profiling technique. With the latter the same information was achieved considerably faster and less laboriously (see section B1 of appendix B).

The location map of the resistivity soundings is added to appendix C (see figure C.4).

During the survey it became clear that the electrical resistivity method as a quantitative method was less suitable than was originally expected. The reasons for this are:

- the topography of the Basement Complex underlying the aquifer is much more irregular than was expected;
- the lateral changes in the composition of the alluvial deposits occur in many places more rapidly than was expected.

Because of this, most soundings only could be interpreted qualitatively.

In appendix C, a description is given of the principles of the electrical resistivity methods, instrumentation used, applied field techniques, data acquisition and processing, and interpretation technique.

6.3.3 Combined use of EM 34-3 and VES

As mentioned in appendices B and C, the EM 34-3 exploration technique and the VES method have limitations and disadvantages of which the most important are:

- the EM 34-3 system only gives qualitative information;
- quantitative VES interpretation techniques are only applicable in case of a laterally homogeneous medium;
- non-uniqueness of VES interpretations, because of the principle of equivalence.

To reduce the above limitations and disadvantages, both methods were used in combination as per the following procedure (see Van Kuijk, 1984).

- From the EM-survey a map showing iso-resistivity contourlines was compiled (see appendix B, figure B.7). Those VES's, of which the spread did not cross large resistivity variations, were selected for quantitative interpretation. In most cases this was checked by additional EM measurements over the total VES spread length.

- With an option of the VES interpretation computer programme the EM 34-3 responses of the electrical resistivity horizontal layer models of each VES were calculated (see appendix B, section B1), and compared with the EM values as measured in the field. Where discrepancies with the EM data occur, the VES model interpretation was matched until a model was found that fitted both the electrical and the EM measurements.

An example of the above mentioned procedure is given in appendix C. Only a limited number of electrical soundings could be selected for a horizontal layer model interpretation. The locations are indicated on the map on figure 6.1, and they are listed in appendix C, table C.4.

6.3.4 Use of other methods

The seismic refraction method is not considered appropriate for the study of Wadi Nyala aquifer and other aquifers with comparable hydrogeological configurations, because of:

- the variations in the depth to the shallow lower boundary of the aquifer (max. 20 m), within relatively short distances;
- the lateral and vertical facies changes of the alluvium within short distances, which result in a heterogeneous complex of sandy and clayey layers and lenses.

The combined features of a shallow exploration target and highly heterogeneous aquifer will give rise to unreliable interpretations because of:

- velocity inversions of seismic waves, causing erroneous depth estimates;
- estimations of the correction factor for the seismic source depth (or shot depth) will be a precarious matter, especially in relation to the shallow survey target.

The penetration depth of a surface energy source (e.g. sledge hammer) will not be sufficient because of the very loose dry alluvial top layers. Previous seismic refraction studies proved to be unsuccessful (see section 6.2).

Gravity, magnetics and other surface geophysical methods are also considered inappropriate because of their constraints in resolving power for the area under study; they lack the detail and accuracy which are required to differentiate significant shallow hydrogeological changes.

During the Wadi Nyala water resources assessment study, a geophysical well-logging programme had to be cancelled because of a technical breakdown of the well-logging equipment in the first stage of the project.
In general, geophysical well-logs will give detailed information about the lithology and the quality of groundwater. Resistivity logs are used for simplified models of the vertical electrical resistivity distribution in situ which form the base for the quantitative interpretation technique of VES. It should be emphasized, however, that because of the rapid lateral facies changes within the alluvial deposits, the well-logs would have a very limited application for the interpretation of electrical soundings. Therefore, it was not tried to make the equipment operational again.

6.4 Results of the Geophysical Survey

6.4.1 Introduction

The results of the geophysical survey are presented in the form of a map on a 1 : 40 000 scale of the aquifer geometry (see map 3). The map shows the lateral extent of the alluvial wadi aquifer, the distribution of permeable and less permeable areas within the aquifer and where enough information is available contourlines of depth to the Basement Complex. Three faults (or

fractured zones) are also indicated.
The interpretation of the geophysical survey is mainly based upon qualitative analyses of the EM measurements carried out with a coil separation of 20 m in the HL mode of operation. In addition, boreholes data, analyses of electrical resistivity soundings, and EM data in the VL mode of operation (s = 20 m) have been used. No vertical distribution of the alluvial deposits can be given. A classification of the alluvium in three types is applied:

- S (sandy):
  This type mainly contains sand and gravel layers. Clay or clayey layers of importance are not expected to be found. This part of the aquifer is considered to contain sediments with a high transmissivity.

- CS (clayey/sandy):
  This type consists of a mixture of clay, clayey sand, and sandy clay layers together with sand and/or gravel layers of relatively small thickness. If the CS-type is adjacent to the S-type, the sandy intercalations may be in contact with each other. In that case this type can be rather productive.

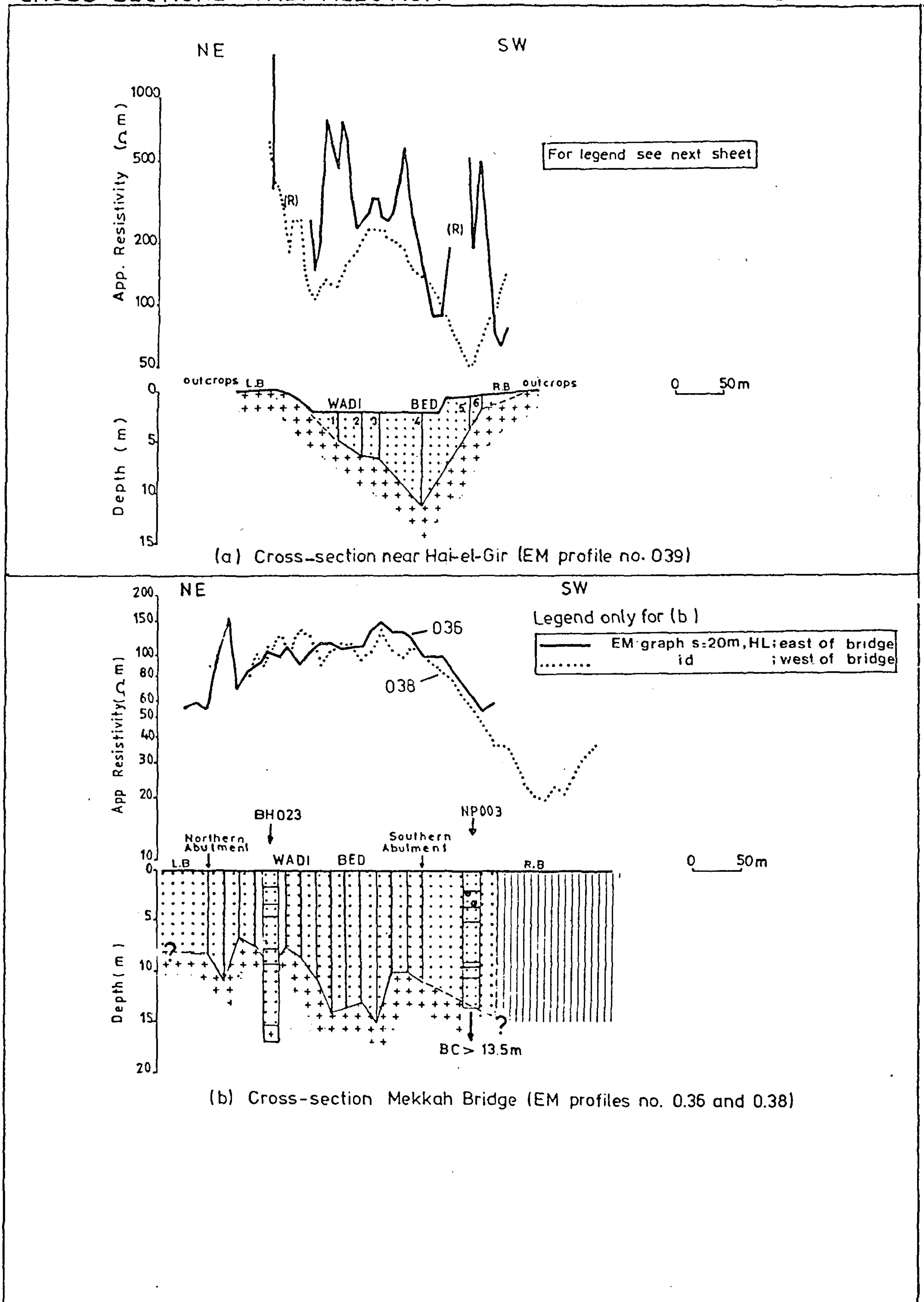
- C (clayey):
  This type consists mainly of clay or clayey layers. Although some minor sandy or sand layers may be present, it should not be considered as part of the aquifer.

For the major part, information about the thickness of the aquifer comes from borehole data. From the EM survey, only areas with a very shallow depth to the Basement Complex (considerable less than 10 m) can be inferred. At a few locations in the Downstream Area, VES interpretations offered estimates of the aquifer thicknesses.

In figure 6.2 four cross-sections of the wadi alluvium are

CROSS-SECTIONS WADI ALLUVIUM

Figure 6.2

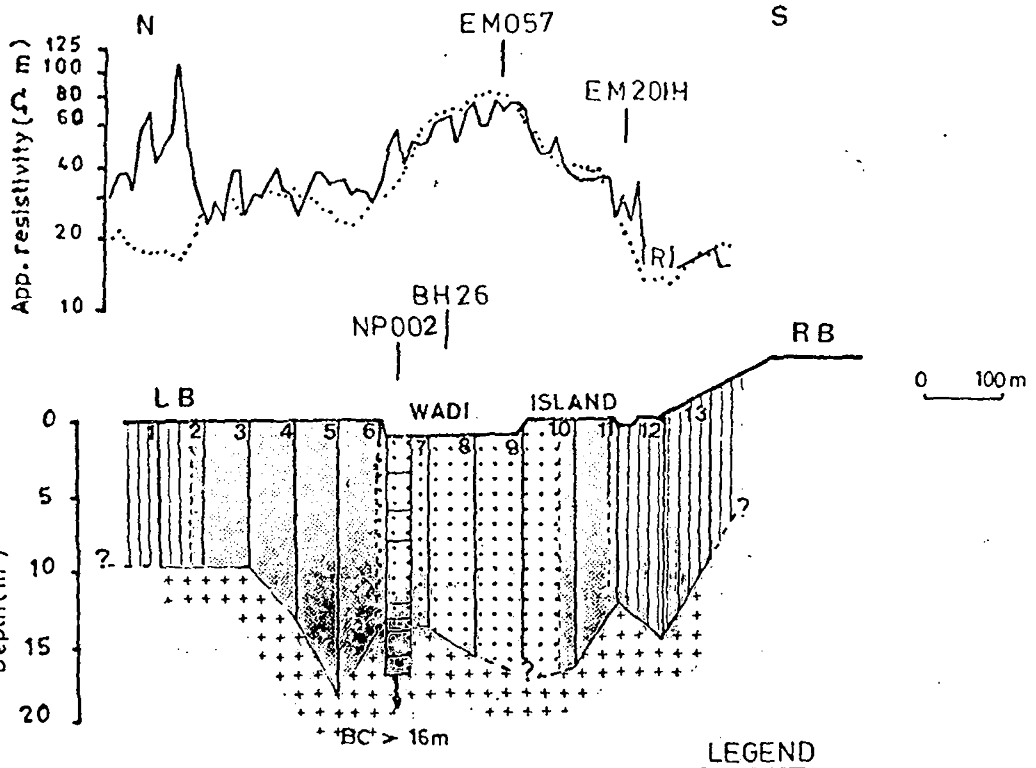


(a) Cross-section near Hai-el-Gir (EM profile no. 039)

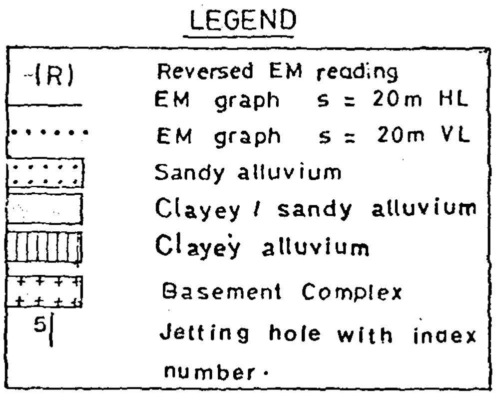
(b) Cross-section Mekkah Bridge (EM profiles no. 0.36 and 0.38)

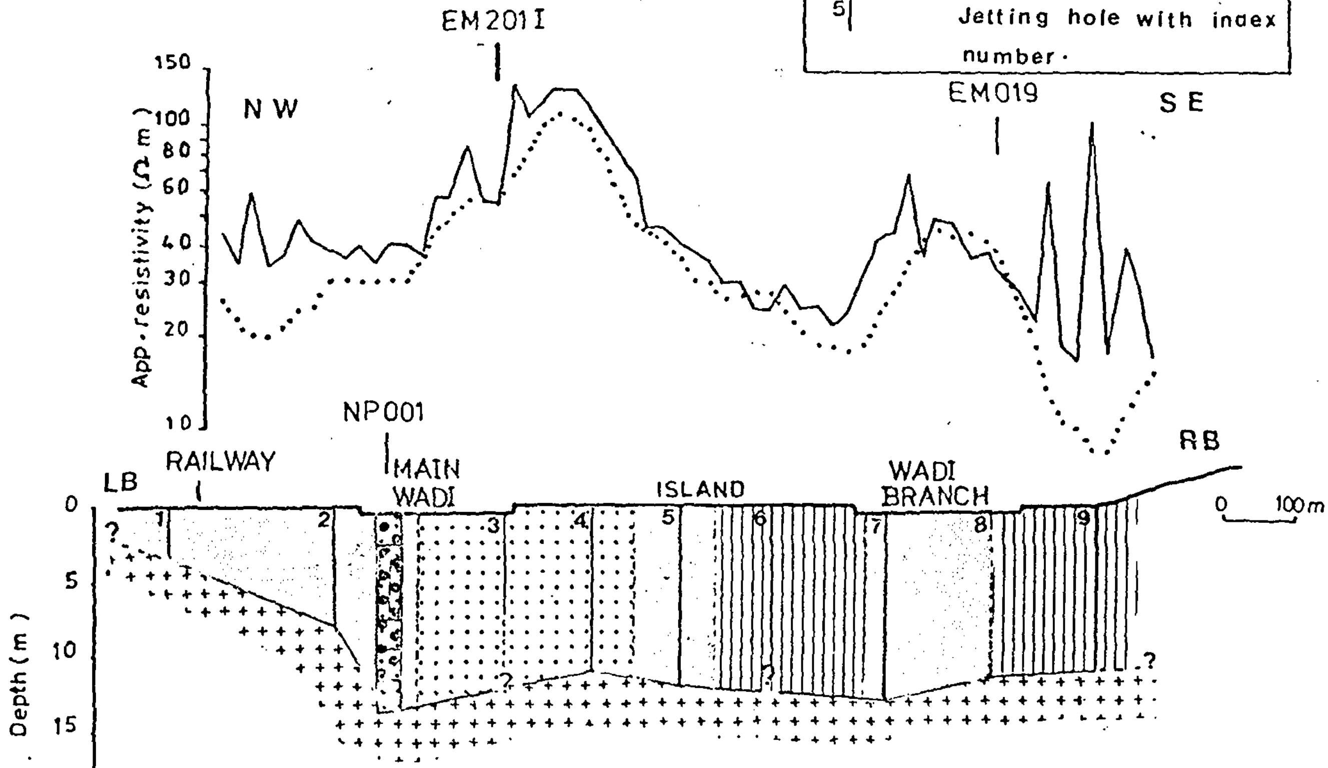
CROSS-SECTIONS WADI ALLUVIUM

Figure 6.2 (cont.)



(c) Cross section Zango Road
(survey line D1, EM profile no.028)





(d) Cross-section near Jebel Nyala (survey line D4; EM profile no. 004)

Note: for legend of boreholes see figure D.1

shown. Their location is indicated on the aquifer map. The profiles are the result of information from boreholes [the profiles (a), (c) and (d)], and from the construction of Mekkah Bridge [profile (b)]. No detailed information about the lithology of the alluvium can be given. Clayey deposits are absent in some boreholes on profile (c) [holes no. 8 (not completed), no. 9 (not completed) and no. 11] and on profile (d) [hole no. 4]. The profiles show the irregular surface of the Basement Complex, which underlies the alluvial aquifer. (Note: the information about the depth to the Basement Complex of borehole BH 26 [= 27.4 m] on profile (c) is from a doubtfull record). Above the cross-sections, the measured EM-profiles are plotted. They show considerable changes in apparent resistivity values, caused by the lateral facies changes of the alluvial deposits. The contribution of the underlying Basement Complex to the total measured apparent conductivity values is considered to be low because in general these rocks have a low range of values for electrical conductivity.

In the cross-sections also the type of alluvium (S, CS or C) is given, based upon borehole information and geophysical interpretations.

The effect of weathering of the top layers of the Basement Complex on the measured EM values and VES data cannot be fully assessed; however, in most cases the contribution to the total measured conductivity values (EM method) and to the apparent resistivity sounding curve (VES method) is low because of its limited thickness.

6.4.2 The aquifer geometry

6.4.2.1 Aquifer extent

For the delineation of the lateral extension of the alluvial aquifer next boundaries were taken:

- the clayey part of the alluvium (the C-type area);
- the area where the depth to the Basement Complex is supposed to be considerably less than 10 m.

In the Town Area the sedimentary deposits forming the alluvial aquifer are found in the wadi channel and in small zones along both wadi banks; these zones are sometimes interrupted by outcropping or very shallow Basement Complex rocks. The width of the aquifer varies between 200 m near the runoff station and 900 m in the area east of the Railway Wells. The width of the sandy part (S-part) of the aquifer ranges from 150 m (near borehole NP 02) to about 450 m (near the Railway Wells).

In the Downstream Area the aquifer does not always coincide with the present-day wadi channel. On a short stretch northeast of Kundua Villages and downstream of Umm Jakhokha Village the wadi channel lies outside the area belonging to the alluvial aquifer. In the downstream part of the study area, the aquifer is much wider, ranging from 0.7 to 1.2 km. The aquifer width reaches a maximum near Kundua Forest (1.7 km) and near Kundua Villages (about 2 km).

Just downstream of Jebel Nyala, the S-part of the aquifer is interrupted by a band of CS classified alluvium. Further downstream the width of the S-part of the aquifer varies between 150 m (near Kundua Forest) and about 800 m just north of borehole NP 05.

In general, the clay content of the alluvial deposits in the Downstream Area is higher than in the Town Area, especially in the near-surface levels of the alluvium. In small scattered areas within the aquifer zone, the clay content is very high; these patches appear as C-type on the aquifer map.

6.4.2.2 Aquifer thickness

On the aquifer map (map 3) the depths to the Basement Complex at the borehole locations are indicated as well as some depth contour lines. At many places the surface of the Basement Complex underlying the aquifer is irregular. This is reflected by the cross-sectional profiles of figure 6.2. In general, the thickness of the aquifer ranges from 0 to 20 m. A maximum thickness is reached at BH 19: 19.8 m.

In the Town Area, the depth contour lines are based on information from the many boreholes in this part of the aquifer. Near the Town Wells, outcrops of Basement Complex rocks are found inside the wadi channel. Dug well no. 1, previously a production well for the town water supply, has a depth to the Basement Complex of only 6 m.

In the Downstream Area, the maximum aquifer thickness is 17 m (at borehole NP 15). The 10 m depth contourlines which are indicated on the map are inferred from the EM survey. At one location in Kundua Forest the shallow depth was confirmed by hand-auger drilling; it revealed a depth to the Basement Complex of 6 m. The shallow depth to the Basement Complex in two boreholes located near the edge of the aquifer (no. NP 11 and NP 13, respectively 8 and 7 m) is not reflected by the EM survey. These are probably local elevations in the Basement Complex surface.

The thickness of the weathered top-layer of the Basement Complex varies from place to place; the maximum thickness found is 13 m at borehole NP 09, which lies in the C-part of the alluvium. In several places the weathered layer is absent (e.g. at boreholes Np 15, NP 16 and NP 17).

6.4.2.3 Faults and fractured zones

In the description of the geology of Nyala area (chapter 5) several lineaments are mentioned which are visible on the aerial photographs. They are shown on the geological map (map 2).

Some anomalies that show on EM profiles, especially on the graphs of the HL mode of operation, line up along a lineament on the aerial photographs, providing strong evidence for the presence of a fault or fractured zone.

Three faults are inferred from the EM survey:

- along the right bank of Wadi Nyala in the Town Area, running west-east;
- along and on the right bank of the wadi in the area of Kundua Forest and Kundua Villages, running NW-SE. Borehole NP 05 is probably located on the fault/fractured zone; borehole NP 11 is just outside this zone;
- in the most downstream area on the left bank, with also a NW-SE direction.

From the geophysical survey no conclusion can be drawn about the character of the faults or fractured zones. More drilling would be necessary for a better understanding. However, the hydrogeological study did not indicate the presence of significant water resources within these zones, and hence no more investigations were carried out.

6.5 Conclusions

1. The application of quantitative geophysical interpretation techniques were ultimately of very limited use because of the prevailing hydrogeological conditions: a very shallow Basement Complex with an irregular surface and an overlying alluvium with rapid lateral facies changes.

2. The EM 34-3 system proved to be a rapid and easy qualitative survey method for shallow (20 - 30 m) alluvial aquifers. By compiling an iso-resistivity map (s = 20 m; HL mode) of the alluvial area, zones with a high clay content could be outlined together with zones where the depth to the Basement Complex is very shallow (< 10 m). Furthermore the distribution of permeable and less permeable areas could be inferred. No vertical layering of the alluvial deposits can be given.

3. Only a few VES locations turned out to be suitable for layer model interpretation. As a quick method for checking the lateral homogeneity of the subsurface resistivity within a VES spread, the EM 34-3 system was used.

4. By combining the VES techniques with the EM 34-3 system in some cases the non-uniqueness of VES layer model interpretation could be reduced.

5. The horizontal electrical resistivity profiling technique (with a well selected electrode distance) and the EM method give similar qualitative information. However, the EM 34-3 is a considerably more rapid system and requires less manpower.

6. For the determination of the thickness of the alluvial aquifer, borehole information is indispensable.

7. GROUNDWATER QUANTITY

7.1 Introduction

At Nyala the alluvial deposits of Wadi Nyala comprise the only important source of groundwater. In the previous chapter the geophysical investigations of the wadi alluvium were disccused, and an aquifer geometry map was presented. In this chapter the results of the hydrogeological investigations are presented and used to establish the groundwater balance of the wadi alluvial aquifer.

The area studied covers a length of 18 km and is seperated in two parts:

- the Town Area containing the most developed part of the aquifer;
- the Downstream Area, not as developed at present, due to less favourable hydrogeological conditions.

A simulation by computer modelling of the alluvial aquifer was carried out for better understanding of the present conditions and to verify the estimates of aquifer parameters and of the groundwater recharge and discharge. Two groundwater models were prepared, one for the Town Area and one for the Downstream Area (section 7.7). The models were also used to predict the repercussions of an extended development of the alluvial aquifer (see chapter 9).

A water balance for the alluvial aquifer was prepared, reflecting groundwater flows under average rainfall conditions. The effects of the low rainfall conditions during the years 1983 and 1984 are described in section 7.8 (and also in 9.1).

The hydrogeological fieldwork carried out in 1983-1985 included:

- the drilling of 19 exploration boreholes (NP 01 - NP 19);
- the execution of 19 pumptests (7 steptests and 12 constant discharge tests);

- the monthly observation of groundwater levels in about 150 wells and boreholes;
- the operation of six groundwater level recorders;
- the inventory of all existing dug wells and boreholes, including an estimation of the pump discharges (see also appendix D).

7.2 The Alluvial Aquifer

7.2.1 Aquifer geometry

The boundaries of the alluvial aquifer have been determined according to the results of the geophysical survey (section 6.4). The alluvial deposits located outside the boundaries have a shallow depth and/or high clay content and therefore were not considered to be part of the aquifer. However, at some locations wells are found in these deposits, showing that locally favourable hydrogeological conditions may exist. This is the case along Wadi Kulkul in the area of Taybah, for example.

The alluvial aquifer was divided into two parts:
- a permeable part consisting of sandy sediments;
- a less permeable part consisting of sandy/clayey sediments.

The clayey alluvium was not considered part of the aquifer. This division was applied both in the Town Area and in the Downstream Area (see map 3).

The alluvial sediments are underlain by rocks belonging to the Basement Complex. The top of these rocks often are weathered and therefore have some hydrogeological significance. However, this was not taken into account in the model and the thickness of the aquifer was considered to be equal to the thickness of the alluvial deposits.

7.2.2 Aquifer lithology

The deposition of alluvial sediments depends mainly on the carrying capacity of the stream, which is directly related to the velocity of the runoff. The velocity of the runoff is controlled by the rainfall, the gradient of the stream and the degree of meandering. Because of variations in these factors, the sedimentation process, together with the ever recurring erosion, will produce sequences of clays and sands of limited extent. This can be illustrated from the borehole descriptions which show a large variation in the lithology (see tables D.3 and D.4).

In the Downstream Area the width of the wadi channel decreases, but the width of the floodplain increases. During high flood peaks often the wadi channel cannot accomodate the total runoff and flooding of the banks occurs. On the banks the flow velocity is reduced and fine sediments, like clay are deposited.

Lithological information is available from existing boreholes and from boreholes drilled by the WAPS-2 project:

- before the project started 29 boreholes had been drilled, 28 in the Town Area and 1 (BH 24) in the Downstream Area; from 13 lithological descriptions are available;
- under the supervision of the project 2 boreholes were drilled (BH 30 and BH 31) by the NWC in the Town Area;
- the WAPS-2 project drilled 19 boreholes (no. NP 01 - NP 19), 5 in the Town Area and 12 in the Downstream Area; 2 were drilled outside the study area.

In the Town Area sandy deposits dominate the lithology. The grainsizes range from fine to coarse sand. Some gravels are found interspersed or mixed with the sandy layers. Also clay layers of small thickness were found in some boreholes. In the clayey/sandy part of the aquifer often sandy deposits are found at the bottom of the aquifer (e.g. BH 19).

In the Downstream Area sands form also the main component of the sediments, but in general grain sizes are smaller. Also here gravels are found mixed with the sands. Layers containing clay are generally thicker than in the Town Area, but these were only found in the upper parts of the sediments. The lower parts contain often medium to coarse sands (NP 10, NP 15), showing that also in the Downstream Area good permeable layers do exist.

Mechanical analyses were carried out on samples from sediments taken at the depth of the screened part of the NP boreholes. The results of the analyses from those boreholes containing significant thicknesses of coarse grained material are presented in appendix D.
The uniformity coefficient, the quotient of the 40% particle size divided by the 90% particle size, shows a wide range from 1.8 to 5, with the average between 2.5 and 3.0. This indicates that generally the sediments (sands) are moderately sorted. In table D.6 of each sample the grainsize percentages are indicated. Generally it can be concluded that medium and coarse sands and gravel (particle size larger than 0.2 mm) comprise 90% of these samples. Only 10% consists of fine sands, clays or silts.

7.3 Hydraulic Properties of the Aquifer

7.3.1 General

The groundwater in the wadi alluvial aquifer is unconfined, the water-table forming the upper boundary of the aquifer. The hydraulic parameters of the aquifer are the transmissivity (T) and the specific yield (S). The transmissivity T is equal to the product of the permeability (k) and the saturated thickness (D) of the aquifer. The specific yield S is defined as the volume of water that the unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water-table (R.A. Freeze et al., 1979).

The transmissivity varies during the year as it depends on the saturated thickness of the aquifer. But also the values of k and S are not constant, because of the heterogeneous layered character of the aquifer. Therefore, from the value of T determined from a pumptest, only the average permeability of the aquifer for the existing water level at the time of the test can be inferred.

During the project, 7 steptests and 12 constant discharge tests were carried out. The objectives of the steptests were to check the quality of the well development and to obtain information on the efficiency and productivity of the well. The main objective of the constant discharge tests was to obtain data to estimate the parameters T and S. At BH 2 the chart of the water level recorder provides data as of a continuous steptest which allowes the analyses of the variation during the year of the mean permeability k.
The tests and the analysis results are presented in the following sections. The detailed data of each test is provided in appendix E.

7.3.2 Steptests

The drawdown observed in a pumped well is due to head losses caused by resistance to the groundwater flow:
- in the aquifer: the aquifer losses;
- at the entrance to and in the well: the well losses.

An estimate of the magnitude of these losses can be obtained from steptests, in which the well is pumped at different discharge rates. The relation between the drawdown s and discharge Q can be described as:

$$\text{Drawdown } s = \text{Aquifer losses} + \text{Well losses}$$
$$= BQ + CQ^2$$

This is an approximation of the actual relation, but it serves the purpose to estimate the well losses in the wells tested by the project.

The steptests were carried out in 4 or 5 steps of 0.5 to 1 hour duration. At the end of each step the pump discharge was increased. The following conclusions can be made from the test results:

- BH 16, BH 19 and BH 20
  These wells have considerable well losses; BH 16 (constructed in 1971) was used by the PEWC until it was abandoned in 1983; an attempt to clean the well with acids and salts failed.
  BH 19 and BH 20 were never used; corrosion and/or incrustation may have reduced the efficiency of these wells since the construction.

- BH 30 and BH 31
  These are wells with small well losses; they were constructed under the supervision of the WAPS-2 project; the Johnson screen used in these wells has a larger open area than the bridge slotted screen of BH 19 and BH 20.

- NP 07 and NP 015
  These wells have considerable well losses; they were constructed as exploratory boreholes drilled by the WAPS-2 rotary rig; the well losses may be due to insufficient development of the well, in which only part of the mud cake on the boreholewall was removed.

The transmissivity T from the steptest data was calculated according to the analysis method described in Birsoy and Summers (1980). The results are included in appendix E.
The steptests in BH 30 and BH 31 yielded acceptable results, which compared well with the results from the constant discharge tests. The other steptests did not provide accurate results,

Table 7.1 Step Test Data Wadi Nyala Aquifer

Borehole number	Date of test	Test duration (hrs)	Number of Steps	Maximum discharge (m^3/hr)	Maximum drawdown (m)	Remarks
<u>TOWN AREA</u>						
BH 16	02.05.84	2	4	19.9	4.25	Not suff. developed
BH 19	24.03.85	5	5	17.0	5.60	
BH 20	03.02.85	4	4	19.5	2.00	Unreliable data
BH 30	28.02.85	2.5	5	29.5	0.91	
BH 31	18.02.85	5	6	19.0	0.80	
NP 07	18.03.84	2	4	36.0	4.57	Unreliable data
<u>DOWNSTREAM AREA</u>						
NP 15	18.04.84	2	4	17.1	6.51	Not suff. developed

because of disturbances during the test due to:
- development of the well (BH 16 and NP 15);
- boundary effects (BH 19, BH 20 and NP 07);
- delayed yield effects (BH 19, NP 07 and NP 15);
- partial penetration (NP 07).

7.3.3 Constant discharge pumptests

The properties of the Wadi Nyala aquifer are not favourable for an accurate determination of the aquifer parameters T and S. The conditions under which groundwater flow to the pumped well takes place, deviate from the conditions for which the analysis methods of pumptests have been derived. These "unfavourable" conditions are:
- lateral heterogeneity of the sediments;
- difference in vertical and horizontal permeabilities (anisotropy).

Other conditions disturbing the pumptests were:

- effects of nearby boundaries;
- partial penetration effects, caused by short screen lengths;
- regional groundwater level changes during the test.

The Wadi Nyala alluvial aquifer contains groundwater under unconfined conditions. The methods of analysis available are "Jacob" and "Theis" and if delayed yield effects are encountered "Boulton". For a description of these methods reference is made to the literature (e.g. Kruseman & De Ridder, 1976).

The delayed yield conditions require long pumptest durations, if an accurate estimate of the specific yield S is required. The maximum test duration was three days.
The majority of the tests was carried out using 2 or 3 piezometers at distances of 5 and 10 meter. The data of each constant discharge test is summarized in table 7.2.

A short description of the analysis results is included in appendix E, a summary of the results is shown in table 7.3.

The transmissivity T was found to be high in many tests, which means large values for the hydraulic conductivity k: 80 - 160 m/day. These values seem very high, if compared with normal conductivities for sandy deposits.

A good estimate of T is obtained from tests in BH 20, BH 31 and NP 15. These tests indicate a T of 400 - 700 m^2/day. The corresponding value for k is 50 - 70 m/day.
The analysis of the recorder chart of BH 2 showed a mean value of k of 58 - 90 m/day at different groundwater levels during the year.

The specific yield S could not be determined from all the tests. Especially tests of short duration did not provide reasonable S-values. A good estimate of S was obtained from the tests in BH 19, BH 20, NP 15 en NP 16.

Table 7.2 Pumping Test Data Wadi Nyala Aquifer

Borehole number	Date of test	Duration of test (hrs)	Discharge of pump (m^3/hr)	Specific capacity (m^3/hr/m)	Saturated thickness (m)	Length of screen (m)
<u>TOWN AREA</u>						
BH 2	5/83-1/84	-	32.4	17-69	4.6-14.5	?
BH 7	05.01.84	23	32.7	27.3	8.3	8.20
BH 14	12.01.84	10	32	50	10.7	8.90
BH 19	30.03.85	73	14.7	3.0	14.0	?
BH 20	05.02.85	72	18.8	8.0	14.2	17.4
BH 30	30.05.84	2.5	36.0	26.5	6.3	12.2
BH 31	20.02.85	69	18.0	20.6	7.7	12.2
NP 04	01.11.83	12	20.0	7.2	9.9	5
NP 07	28.10.83	6	20	17.4	14.2	6
	15.03.84	6	32.7	11.4	8.6	6
<u>DOWNSTREAM AREA</u>						
NP 10	05.12.83	13	14.0	20.9	10.2	10.0
NP 12	23.11.83	10	21.0	27.6	8.5	7.0
NP 15	19.04.84	46	13.7	3.0	7.6	10.0
NP 16	13.12.83	12	14.0	21.9	6.0	7.0

Note: Specific capacity after eight hours pumping or if pumping period shorter, at end of test. Specific capacity of BH 2 indicates range in which the value varies during the year.

The value of S ranges between 15% for the clayey/sandy aquifer (BH 19, NP 15) and about 25% for the sandy aquifer (BH 31, NP 16).

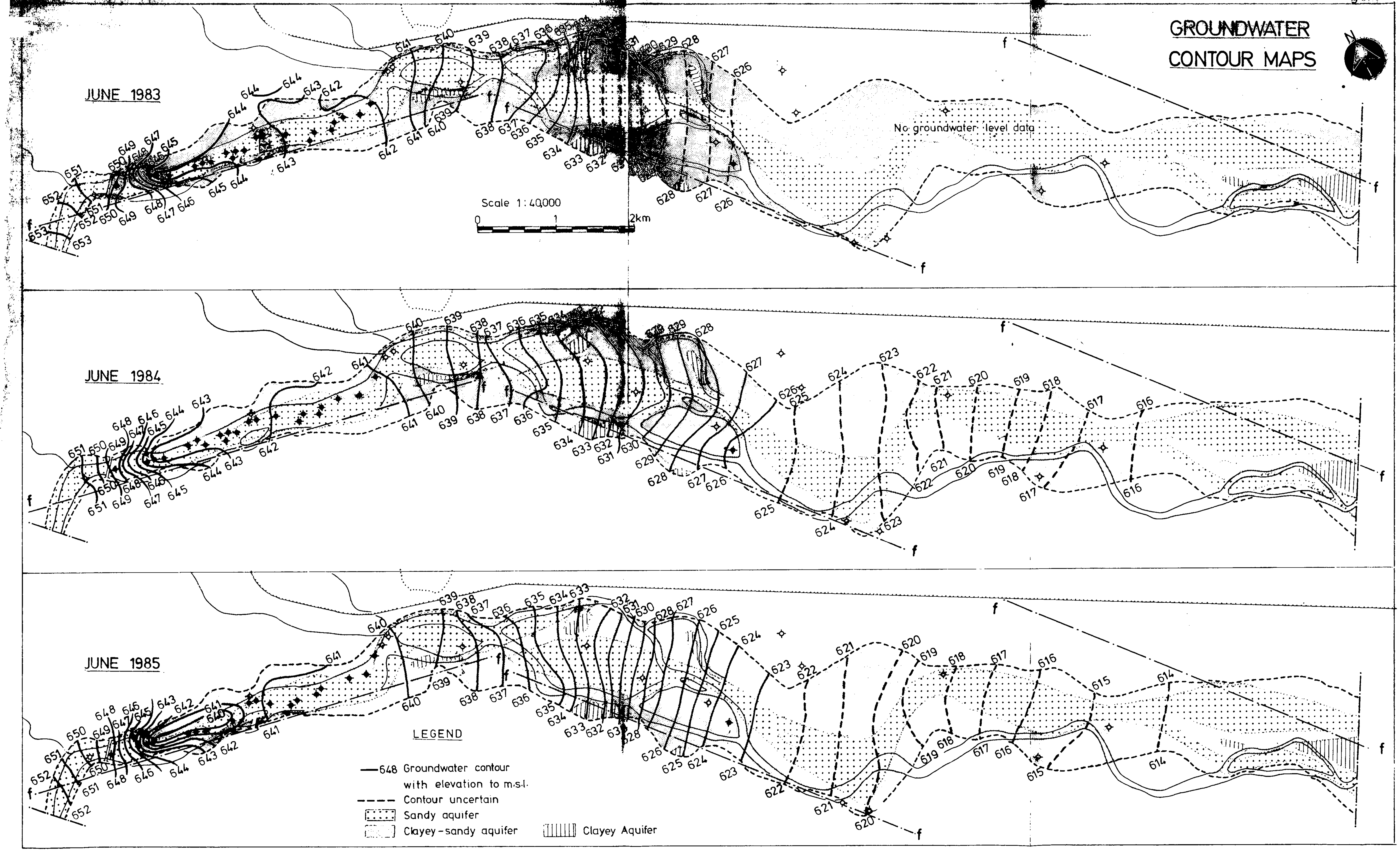
Table 7.3 Pumping Test Analysis Results

Well number	Transmis-sivity (m^2/day)	Hydraulic Conductivity (m/day)	Specific Yield (%)	Analysis Method
TOWN AREA				
BH 2	395-1200	58-90	-	Jacob
BH 7	850	100	-	Jacob
BH 14	(1300)	(120)	-	Theis
BH 16	(340)	(32)	-	Jacob
BH 19	1200	85	15-20	Boulton
BH 20	660	46	14	Jacob, Theis
BH 30	650	100	-	Jacob, Recovery
BH 31	520	70	28	Jacob, Theis
NP 04	(1000)	(100)	-	Boulton
NP 07	(1100)	(130)	-	Theis
DOWNSTREAM AREA				
NP 10	800	80	-	Boulton
NP 12	1400	160	-	Jacob, Boulton
NP 15	400	50	14	Theis
NP 16	800	130	21-27	Boulton

Note: Values between brackets are doubtful estimates.

The pumptests did not show differences in values for the permeability k and the specific yield S between the wells located in the Town Area and in the Downstream Area. But it should be realized that in the Downstream Area only the best wells were used, because several wells could not be tested, due to their insufficient productivity. The groundwater balance indicated that lower values for S should be used in the Downstream Area (see section 7.8).

Figure 7.1


GROUNDWATER CONTOUR MAPS
N
JUNE 1983
No groundwater level data
Scale 1:40,000
0 1 2km
JUNE 1984
JUNE 1985
LEGEND
—648 Groundwater contour with elevation to m.s.l.
- - - Contour uncertain
Sandy aquifer
Clayey-sandy aquifer
Clayey Aquifer
f

7.4 Groundwater Levels

The collection of groundwater level data at Nyala has been carried out in the past by Salama (1971). The water level data filed in the office of the NAW of Nyala, however, only covers the period since October 1979. The data was collected from about 70 index wells. Until April 1980 this was done monthly and from August 1980 until April 1982 every three months.

In 1983 the WAPS-2 project started recording water levels in February from the same 70 wells and boreholes. In April the number of index wells was raised to 150 and since then groundwater levels have been taken almost every month. All existing wells and boreholes were levelled and located by a survey team. Reference points were established as a rule on the top of the stone wall at dug wells and on the top of the casing at boreholes.

In figure 7.1 groundwater contour maps are presented, showing the minimum water levels of 1983, 1984 and 1985. The water levels were measured in June, before the start of the rainy season.

From these maps it is clear that water levels were much lower in 1985 than in 1983. This was mainly due to the smaller infiltration in the 1984 rainy season.

The maps show the effect of the water abstraction from the boreholes in the wadi on the groundwater-table. Especially in the area of the so-called Town Wells a large drawdown is present due to the concentration of three wells BH 2, BH 3 and BH 6. The extent of this drawdown can also be seen from the longitudinal profiles in figure 7.2. They show that the saturated thickness of the aquifer is reduced in June to only a few metres. At this time pumping has to be interrupted regularly, as the submersible pumps run dry, due to the large drawdowns in the wells.

The drawdowns in the area of the Railway Wells are smaller, because here the pumping from boreholes is less, and the sandy aquifer wider. The slope of the groundwater-table increases

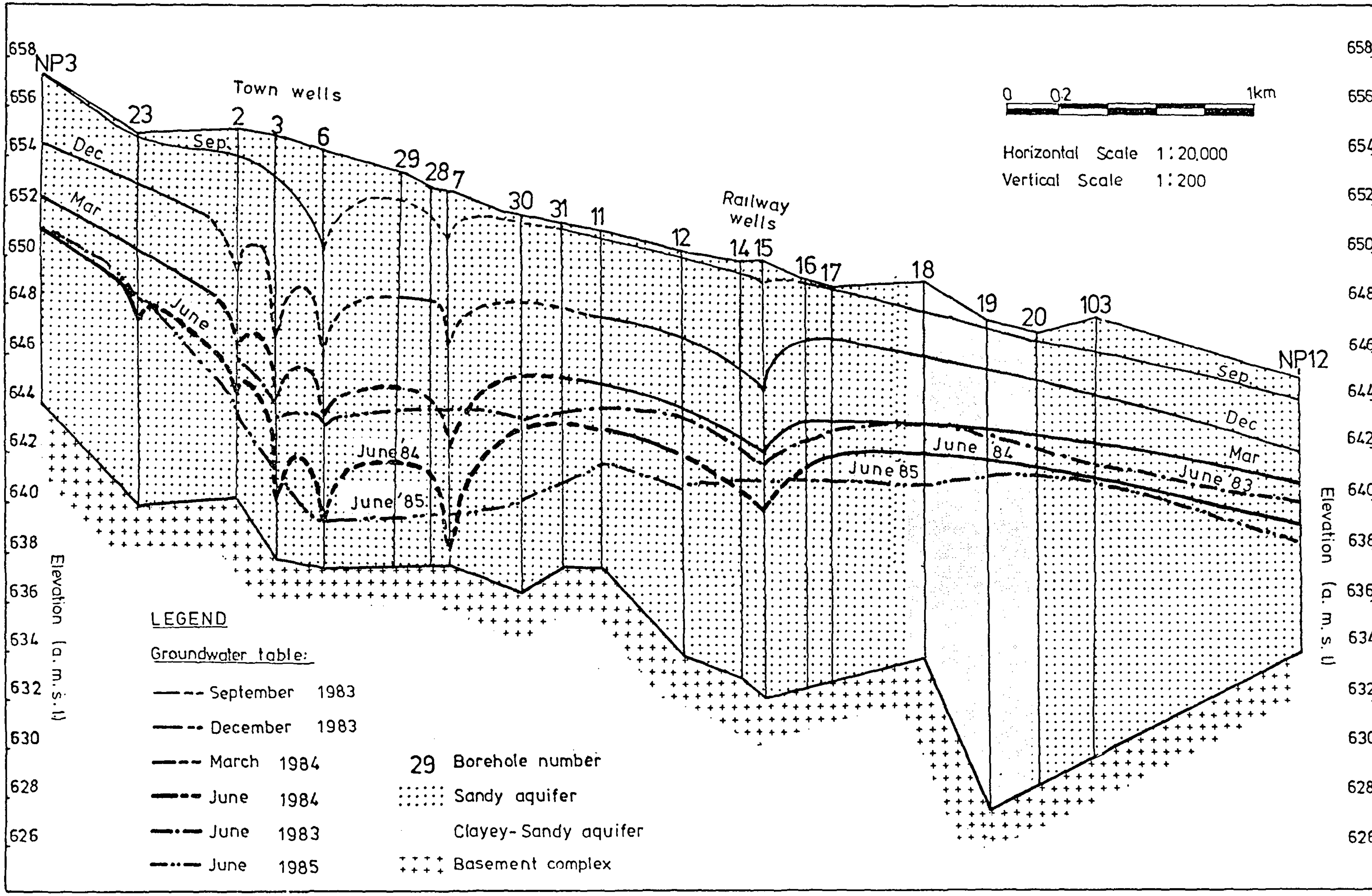


Figure 7.2 LONGITUDINAL PROFILE TOWN AREA

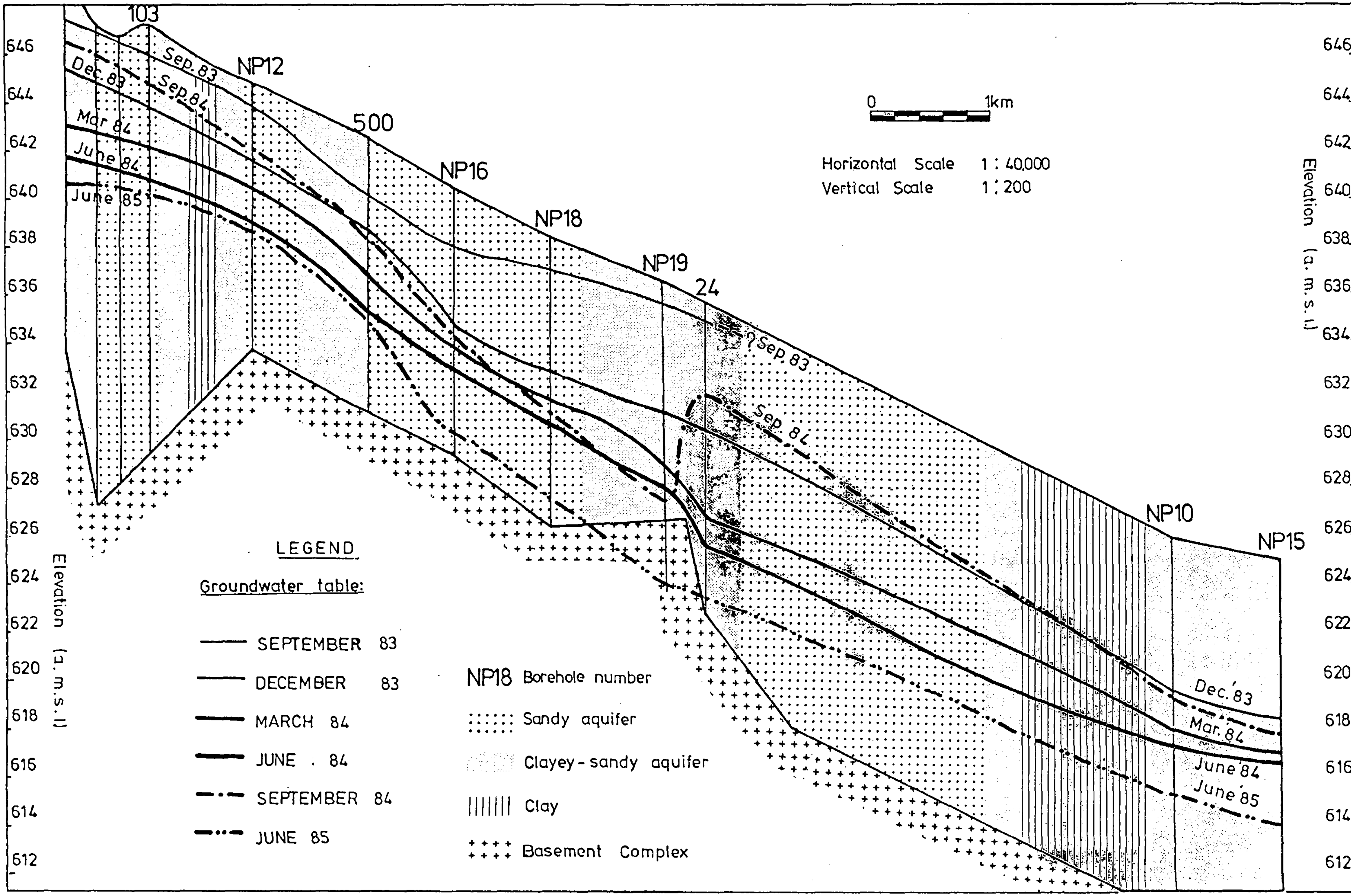


Figure 7.3 LONGITUDINAL PROFILE DOWNSTREAM AREA

downstream in the area of Kundua. The cause is not known but it could be related to a waterloss into a fractured zone in the Basement and/or the large evapotranspiration of groundwater by the man-made forest of Kundua. This could not be verified, however. The water-table slope is restored to its previous gradient further downstream in the Downstream Area (see figure 7.3).

7.5 Groundwater Recharge

The sources of recharge to the alluvial aquifer are:
- infiltration from surface water runoff in the wadi;
- infiltration from local rainfall;
- inflow of groundwater from the alluvial aquifer located upstream.

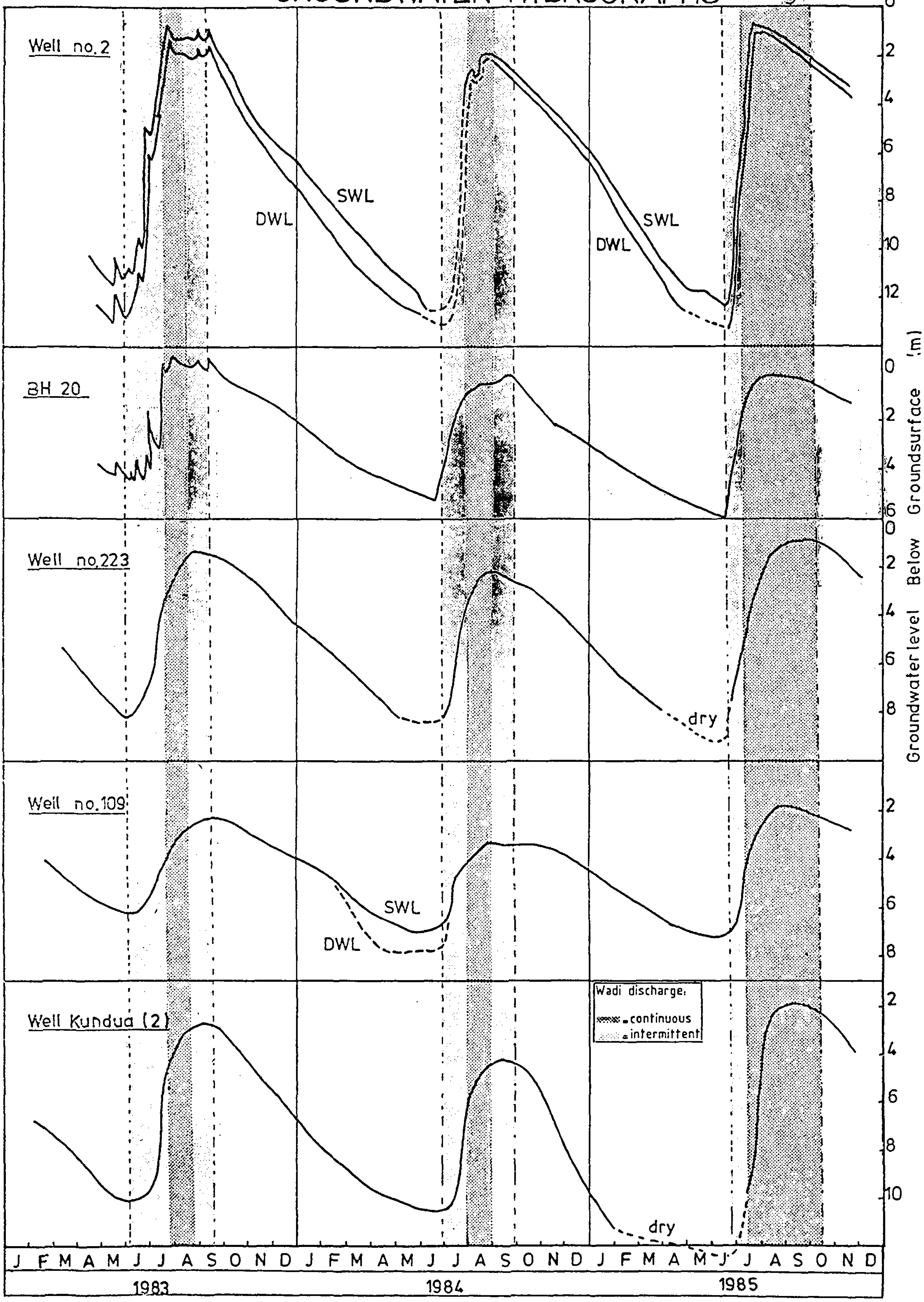
The most important source is the infiltration of surface water.

The rainfall on the study area has no direct effect on the groundwater levels. A change in level related to rainfall was never observed in the wells or in the boreholes equipped with recorders. Thus the direct infiltration from rainfall falling on the area under study must be small.

At the beginning of the rainy season the groundwater is at its lowest level. During the dry season groundwater levels have fallen continuously, due to water losses by evapotranspiration and pumping. The recovery of the groundwater levels starts as soon as surface water flow occurs in the wadi. The sandy deposits in the wadi possess a good permeability and infiltration of surface water takes place immediately (see the hydrographs of BH 2 and BH 20 in figure 7.4). The rise of the groundwater levels under the wadi results in a horizontal flow of groundwater to the banks. The recovery of the groundwater levels in the banks is thus later and slower. The hydrographs of well no. 223 and 109 show a delay of about one month (figure 7.4). In normal years full recovery is reached both in the wadi and in the

GROUNDWATER HYDROGRAPHS

Figure 7.4



GROUNDWATER PROFILES

Figure 7.5

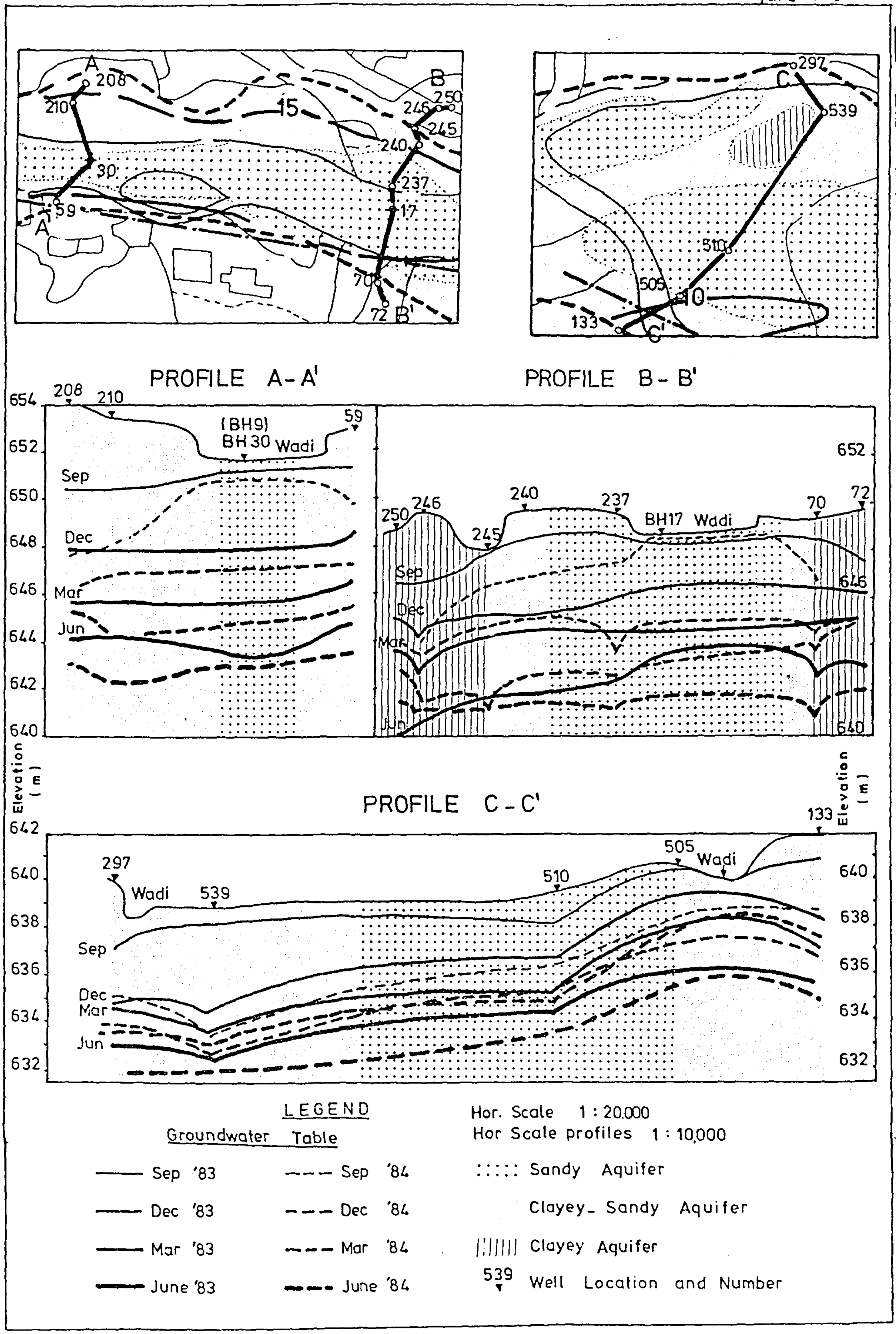
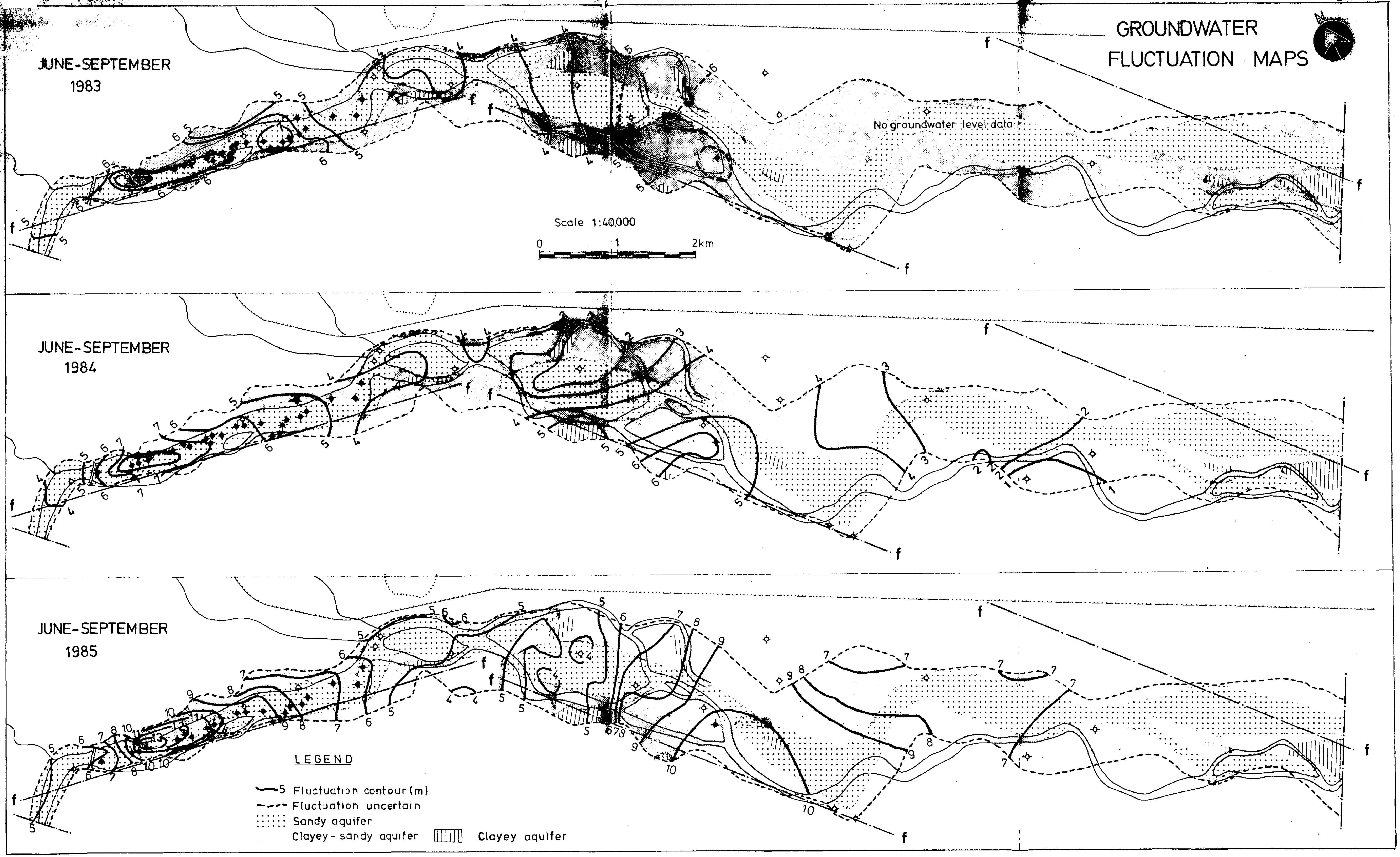


Figure 7,6


GROUNDWATER
FLUCTUATION MAPS
JUNE-SEPTEMBER
1983
No groundwater level data
Scale 1:40,000
0
1
2km
JUNE-SEPTEMBER
1984
JUNE-SEPTEMBER
1985
LEGEND
5 Fluctuation contour (m)
Fluctuation uncertain
Sandy aquifer
Clayey - sandy aquifer
Clayey aquifer

banks. Only in dry years, such as 1984 - and also 1983, but to a smaller extent - the groundwater levels in the banks do not recover fully. This is illustrated in figure 7.5, which shows that groundwater levels in the banks in September 1984 were 2 to 3 metres below the levels of September 1983. It can be seen also that this difference was reduced to 1 metre towards December.
In 1985 groundwater levels recovered fully due to the large wadi runoff. The recovery of the groundwater in the banks was helped by the extensive flooding.

The rise of the groundwater levels during the rainy seasons of 1983, 1984 and 1985 is indicated in figure 7.6, which shows the fluctuation contours. The maps show a distinct difference between the years, which is mainly caused by the much smaller recovery of the groundwater levels in 1984 and the big fluctuation in 1985.
In the Town Area the fluctuation is large near the Town Wells, but is smaller downstream.
In the Downstream Area the fluctuation was small in 1984, showing a small infiltration. The fluctiation in 1985 was bigger due to the better groundwater level recovery. The infiltration rate in years with low runoff is apparently small in the Downstream Area.
The volume of the net infiltration during the rainy season can be determined form the fluctuation map. The actual infiltration is larger, but part of the water is lost by pumping and evapotranspiration during the period of infiltration. The volumes involved are presented in section 7.8.

A continuous recharge of the groundwater takes place during the whole year by inflow of groundwater at the upstream end of the Town Area. The quantity involved, however, is very small. It was estimated at only 20 000 m^3/year.
The recharge of the Downstream Area by groundwater inflow from the Town Area was estimated at 210 000 m^3/year (see section 7.6.4).

7.6 Groundwater Discharge

7.6.1 Introduction

The groundwater volume stored in the alluvial sediments of Wadi Nyala is reduced to less than half of the original volume during the dry season. The water loss is caused by the following elements of discharge:

- evapotranspiration;
- pumping from wells and boreholes:
  - by the PEWC for water supply to the town;
  - from dug wells for irrigation purposes and for the supply to street water vendors;
  - from stock wells (temporary wells in the wadi) for domestic purposes and livestock watering;
- outflow of groundwater at the downstream boundary of the aquifer.

The water pumped for irrigation is mainly lost by evapotranspiration and therefore included in the estimate of evapotranspiration. Water pumped in excess of the water demand of the crops infiltrates and returns to the groundwater.

The groundwater flow across the boundary of the area considered, occurs only at the downstream end of the aquifer. Water losses to the underlying formation of the Basement Complex were assumed to be negligible.

7.6.2 Evapotranspiration from groundwater

The total evapotranspiration includes loss of water from:

- groundwater;
- soil moisture;
- water stored (temporarely) on the surface.

The evapotranspiration from the groundwater can be calculated by subtracting the evapotranspiration of soil moisture and surface water from the total evapotranspiration estimated in section 3.3. The evapotranspiration of surface water and soil moisture is concentrated in the wet season and in the beginning of the dry season. It consists of water from rainfall which evaporates before it reaches the groundwater. The amount of water involved (the net rainfall) was estimated at 75% of the total rainfall, assuming that under average conditions 25% of the rainfall is converted in surface runoff, and that recharge from rainfall to the groundwater is negligible. The average rainfall during the period 1971 - 1985 was 366 mm, which gives a net rainfall of 870 000 m^3 in the Town Area and of 3 830 000 m^3 in the Downstream Area. It was assumed that 80% of this amount evaporates during the wet season and 20% during the dry season. The evapotranspiration from the groundwater equals the estimated total evapotranspiration derived in section 3.3.3, minus the evapotranspiration from the (net) rainfall on the area and is presented in table 7.4.

Table 7.4 Average Annual Evapotranspiration Losses (m^3)

	Dry Season	Wet Season	Total Year
Total Evapotranspiration			
Town Area	1 560 000	740 000	2 300 000
Downstream Area	8 590 000	3 630 000	12 220 000
Total Area	10 150 000	4 370 000	14 520 000
Evapotranspiration Losses from Groundwater			
Town Area	1 386 000	44 000	1 430 000
Downstream Area	7 824 000	566 000	8 390 000
Total Area	9 210 000	610 000	9 820 000

The subdivision of the evapotranspiration according to land use is presented in the water balance in table 7.8.

7.6.3 Discharge from wells and boreholes

a. The PEWC
uses at present eight boreholes, all located inside the wadi (see also chapter 2). The total pump discharge is not known, because only the boreholes at the Town Wells site are metered (at the pumphouse). The other boreholes are not metered and are directly connected to the distribution net. Also there is no record of the pumping hours.
The estimate of the total PEWC water consumption was obtained, assuming that the variation in discharge observed from the metered wells, also occurs in the other wells and boreholes. The meter-data are available since September 1983. Maximum pumping occurs in October and November, the minimum is reached in August. The record shows that in 1984 and 1985 the pumped volumes were smaller than in previous years. This was probably caused by the combined effect of lower water levels and insufficient fuel to run the pumps.

b. The dug wells
are mainly located in the gardens along the wadi (see map 1).
A well inventory was carried out which comprised 346 wells. A summary of the data collected is included in appendix D, table D.1. The number of wells located inside the aquifer boundaries is for the Town Area 110 and for the Downstream Area 74.
The water is taken from many wells by diesel driven centrifugal pumps (total number 192) or otherwise by bucket. The water is used for irrigation and domestic purposes.
An estimate of the total water consumption was obtained by measuring the yield of the pumps installed and the number of hours per day the pump was said to be running. Some correction was needed to account for the overestimation by the farmers of their pumping hours (see table 7.6).

Table 7.5 Estimate of PEWC Water Consumption (m^3)

	PEWC Pumphouse (from meter)	Total PEWC Water Consumption
Dry season	700 000	1 650 000
Wet season	150 000	350 000
Total 1983	850 000	2 000 000
Dry season	480 000	1 160 000
Wet season	100 000	240 000
Total 1984	580 000	1 400 000
Dry season	490 000	1 170 000
Wet season	160 000	380 000
Total 1985	650 000	1 550 000

c. The stock wells

are small wood lined wells dug in the wadi bed. They are found in three sites: near the suq, near the wadi crossing at Kouria and at the outlet of wadi Kulkul in Wadi Nyala. The wells are only used in the dry season because in the wet season they are flooded by the wadi. The water from the wells is used for domestic purposes (transported on donkeys) and for livestock watering.

In 1983 24 of these wells were surveyed. The total abstraction was estimated at 170 m^3/day. The total annual abstraction (eight months) based on this estimate is 40 000 m^3.

7.6.4 Groundwater outflow

The groundwater flow across the boundary between the Town Area and the Downstream Area was calculated using estimates at the boundary of the permeability (k), of the water-table slope (i)

Table 7.6 Estimate of Discharge from Dug Wells

	Irrigation (m^3)	Domestic (m^3)	Total (m^3)
ALL WELLS			
+ Upstream Mekkah bridge	148 000	75 000	223 000
+ Between Mekkah bridge and Jebel Nyala	1 400 000	265 000	1 665 000
+ Haj El Jebel and Taybah area	50 000	75 000	125 000
+ Between Jebel Nyala and Kundua forest	1 106 000	5 000	1 111 000
+ Kundua and area downstream	135 000	27 000	162 000
ALL WELLS TOTAL	2 839 000	447 000	3 286 000
WELLS IN AQUIFER AREA			
+ Town Area	1 100 000	340 000	1 440 000
+ Downstream Area	1 000 000	25 000	1 025 000
TOTAL	2 100 000	365 000	2 465 000

and of the cross-sectional area of the saturated part of the aquifer (A). For k the value of 50 m/day was used. The other variables were estimated according to the seasonal variation of the groundwater levels at the boundary.

The total quantity involved is small and was estimated to be annually 210 000 m^3, divided in 50 000 m^3 during the wet season and 160 000 m^3 during the dry season.
The outflow from the Downstream Area to the alluvial aquifer downstream was not estimated, because the volume involved is small and negligible if compared with the error in estimation of the evapotranspiration losses in the Downstream Area.

7.7 Groundwater Model Simulation

7.7.1 General

The groundwater model applied for the aquifer of Wadi Nyala was developed for the project HP-85 microcomputer by TNO-DGV Institute of Applied Geoscience (Schoute and Swenker, 1984). A short description of the model is provided in appendix F.

The objectives of the groundwater model are:

- to simulate the fluctuation of groundwater levels and groundwater storage under the present conditions;
- to verify the permeability and specific yield of the aquifer and the estimates of the groundwater recharge and discharge;
- to study the repercussions on groundwater levels and groundwater storage of further development of the aquifer (see chapter 9.3).

Two models were designed, covering:

- the Town Area (2.8 km^2);
- the Downstream Area (14.1 km^2).

The boundaries of the aquifer model area were determined according to the aquifer geometry map (map 3).
The models were calibrated using data from the period October 1983 to May 1985, including one recharge period, the poor rainfall season of 1984, and two dry/discharge periods.

7.7.2 Town Area model

The Town Area model covers the area of the Wadi Nyala alluvial aquifer between Mekkah bridge and Jebel Nyala. The model does not include the shallow part of the aquifer between the runoff station and Mekkah bridge, which otherwise in this report is included in the Town Area. The description of the model lay-out, input data and calibration is included in appendix F 2. The calibration resulted in improved estimates of the aquifer parameters:

- The specific yield S was reduced to:
  - . 20% for the sandy part of the aquifer;
  - . 10% for the clayey/sandy part of the aquifer.
- The permeability k was determined at:
  - . 50 m/day for the sandy part of the aquifer;
  - . 20 m/day for the clayey/sandy part of the aquifer.

The discharge of groundwater from the aquifer is composed of water losses by:

- evapotranspiration;
- pumping for domestic use from boreholes and dug wells;
- groundwater outflow across the aquifer boundary.

The recharge to the aquifer is composed of:

- infiltration of surface water;
- groundwater inflow across the aquifer boundary.

The volumes of each of these discharge/recharge components were estimated based on calculations included in this report. The infiltration volume, however, was not used, because it depends on the groundwater storage depletion at the end of the dry season, which is not known beforehand. It was therefore decided to simulate the infiltration by introducing a fixed groundwater level at the wadi-nodes during the wet season. This simulates a sudden recovery of the groundwater table in the wadi-nodes, which corresponds well with the reality, because groundwater levels recover to near the ground surface within one month after surface runoff has started. During the remaining runoff season only small variations in the groundwater table occur in the wadi area. Recovery of the groundwater table in the nodes outside the wadi takes place by recharge from horizontal groundwater flow, which corresponds well with the actual situation.

The simulation results after calibration are shown in figures

F.2 and F.3. The simulated groundwater levels correspond well with the actually observed water levels. The simulated variation of the groundwater storage is shown in figure 7.7.

After calibration of the model, a sensitivity analysis was made of the simulation to test the effects of variations in the input data (see appendix F, section F2.3). The model result appeared to be sensitive to:

- the value of the fixed groundwater levels at wadi-nodes, which determines the infiltration during the rainy season;
- the value of S, the specific yield of the aquifer;
- the estimate of the discharge volumes.

The model result was found not to be sensitive to:

- the value of k, the aquifer permeability, except in areas where big drawdowns occur, e.g. the Town Wells area.

After a satisfactory simulation was obtained with the model, it was used to study the effects of increased pumping from boreholes for the town watersupply. This is discussed in section 9.3.

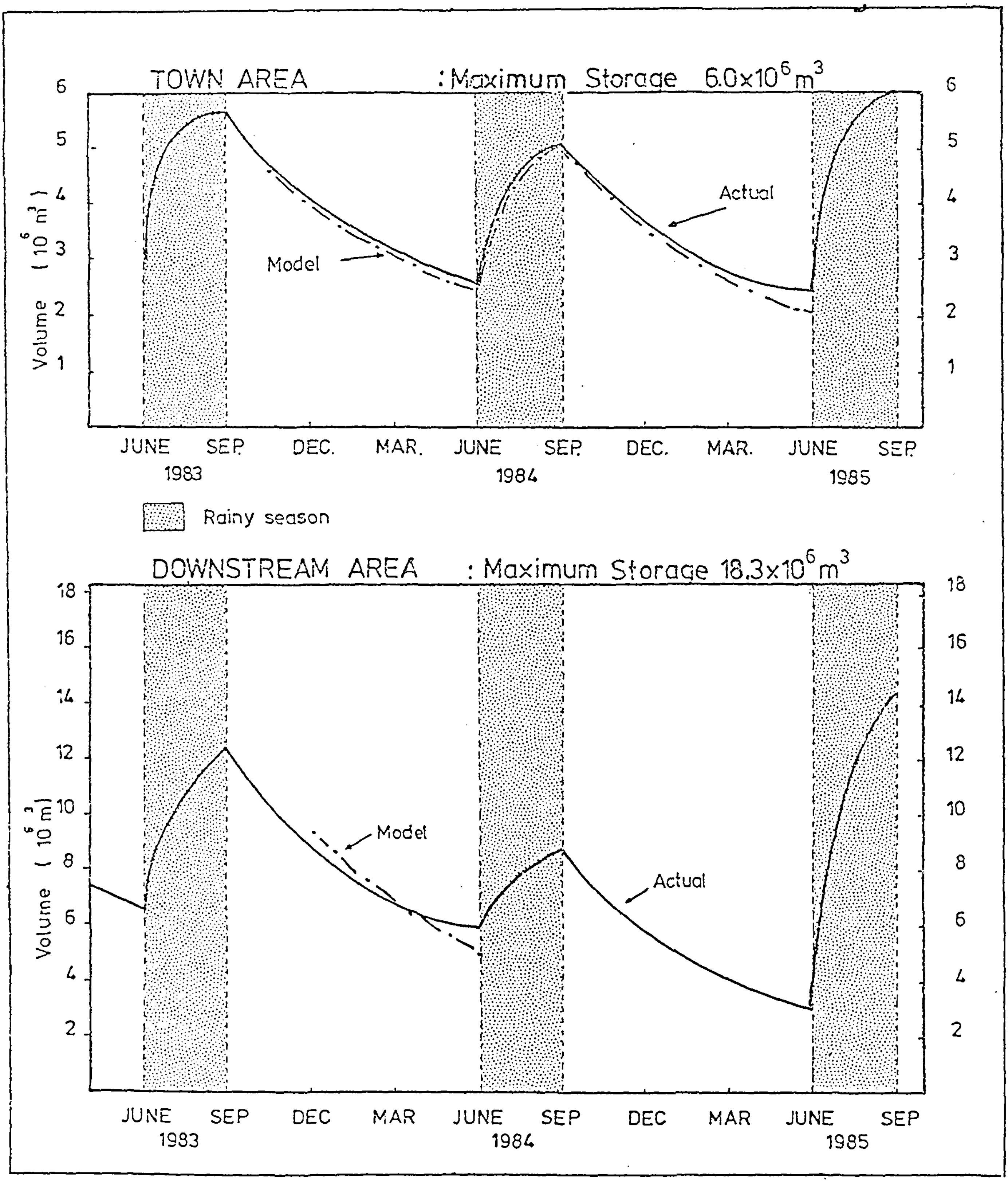
7.7.3 Downstream Area model

The Downstream Area model covers the aquifer area downstream of Jebel Nyala to the downstream boundary of the study area, near Bileil, an area of 14.1 km^2. A description of the model is included in appendix F.3. This model is not as detailed as the Town Area model, because of the limited availability of groundwater level data. The recovery of the water levels after the rainy season was not simulated due to insufficient data in the area of Kundua (see section 7.4). The simulated period was therefore limited to one dry season. Large nodal areas were used because of the small number of data. This has two disadvantages:

- horizontal groundwater flow is not well simulated;
- the value of S, the specific yield, cannot be calibrated satisfactorily (see appendix F, section F3.3.).

VARIATION OF GROUNDWATER STORAGE IN 1983-1985.

Figure 7.7



The pumptests in the area did not show a significant difference in results with those in the Town Area. However, from water balance analysis it appeared that a lower estimate of S should be used (see section 7.8):

- 16% for the sandy part of the aquifer;
- 8% for the clayey/sandy part of the aquifer.

The development of the groundwater resources in the Downstream Area for the town water supply seems possible only in the area upstream of Kundua forest. The effect on the groundwater levels in this area was simulated with the model and is discussed in section 9.3.

7.8 Groundwater Storage and Groundwater Balance

7.8.1 Groundwater storage

The alluvial aquifer of Wadi Nyala is a groundwater reservoir, which is recharged every year during the rainy season and from which water is discharged throughout the year. The geometry of the reservoir corresponds with the boundaries of the alluvial aquifer as indicated on map 3.
The aquifer was subdivided schematically in two parts, sandy aquifer and clayey/sandy aquifer, as described in section 6.4. For the Town Area the amount of water which can be released from the aquifer, expressed as specific yield, was determined at 20% and 10% respectively. This was based on the results of the groundwater model simulation. The water balance of the Downstream Area aquifer showed that average S-values of 16% and 8% respectively should be used.

The maximum groundwater storage capacity for the aquifer in the Town Area and the Downstream Area is presented in table 7.7. The volumes were determined assuming an unsaturated zone of 1.0 metre below the ground surface in the sandy/clayey aquifer and of 0.5 metre in the sandy aquifer.

The groundwater storage fluctuation during the wet season in the years 1983, 1984 and 1985 was determined from the groundwater fluctuation map (figure 7.6). This fluctuation equals the total recharge to the groundwater minus the groundwater consumption during this period.

Table 7.7 Size of Alluvial Wadi Aquifer, Groundwater Storage Capacity and Groundwater Storage Fluctuation

	TOWN AREA	DOWNSTREAM AREA	TOTAL AREA
Surface area (km^2)	3.2	14.2	17.4
Gross volume (10^6 m^3)	38.5	157.5	196.0
Storage capacity (10^6 m^3)	6.0	18.3	24.3
Storage fluctuation (10^6 m^3):			
Year 1983	2.9	5.7	8.6
Year 1984	2.5	2.8	5.3
Year 1985	3.6	11.3	14.9

The variation of the aquifer storage in the years 1983 - 1985 is presented in figure 7.7:

- In the Town Area recharge in 1984 was less than in the other years, but the storage capacity was filled to more than 80%. In the other years the aquifer was recharged almost to maximum capacity.

- In the Downstream Area storage has been depleted during the years 1983 - 1985, mainly due to the small recharge in the dry year 1984. In June 1985 the stored volume had dropped to 16% of the total storage capacity.

7.8.2 Groundwater balance

The groundwater balance of the alluvial aquifer in the Town Area and Downstream Area was derived for one whole year. The duration of dry and wet season was determined at 9 and 3 months respectively, the wet season lasting from mid-June to mid-September. The water balance specifies the volumes of flow in a year of average conditions. This average year has a rainfall of 366 mm, which is the average of the period 1971 - 1985.

For the water balance an estimate of the total average recharge from infiltration is needed. Based on the fluctuation which was observed in the years 1983 - 1985, it was estimated that in an average year the recharge equals 3.98×10^6 m^3 in the Town Area and 8.21×10^6 m^3 in the Downstream Area.

This recharge does not include infiltration from rainfall on the aquifer area. As described in section 7.5 recharge from rainfall is negligible. The rainfall which does not leave the area as surface runoff, is stored temporarily on the surface and in the unsaturated zone and evaporates before it reaches the groundwater. The estimates of the losses through evapotranspiration (or consumptive use) and domestic consumption are all valid for average conditions.

In the Town Area on average 3.5×10^6 m^3 is consumed out of a total storage capacity of 6.0×10^6 m^3 during the dry season. The major loss of groundwater is from the pumping for domestic consumption. (In 1984 and 1985 domestic consumption from boreholes was less, mainly because of fuel shortages, table 7.5). It is clear that in the Town Area only a limited possibility exists for additional groundwater use.

In the Downstream Area the major loss of groundwater is from the consumptive use of the forest. The forest covers a large part of the area, but it is at present not productively used. The forest has a function in stabilizing the wadi channel.

Table 7.8 Water Balance of Wadi Nyala Aquifer (volumes in $10^6 m^3$)

	TOWN AREA			DOWNSTREAM AREA		
	Dry Season	Wet Season	Total Year	Dry Season	Wet Season	Total Year
IN: 1. Infiltration	-	3.98	3.98	-	8.21	8.21
2. Groundwater inflow	-	-	-	0.16	0.05	0.21
IN Total	0.00	3.98	3.98	0.16	8.26	8.42
OUT: 1. Consumptive use* of:						
irrigated agriculture	0.94	0.01	0.95	0.85	0.02	0.87
not irrigiated agric.	0.29	0.02	0.31	0.25	0.06	0.31
forest	0.02	-	0.02	6.40	0.41	6.81
bare soils	0.14	0.01	0.15	0.32	0.08	0.40
2. Domestic consumption:						
from boreholes	1.65	0.35	2.00	-	-	-
from dug wells	0.29	0.05	0.34	0.03	-	0.03
3. Groundwater outflow	0.16	0.05	0.21	-	-	-
OUT Total	3.49	0.49	3.98	7.85	0.57	8.42
Change in storage	-3.49	+3.49	0.00	-7.69	+7.69	0.00

*Note: Consumptive use only includes groundwater losses.

8. GROUNDWATER QUALITY

8.1 Introduction

The quality of the water used for the supply of drinking water needs close monitoring at Nyala. The source of the water, the wadi aquifer, is inside the town and therefore vulnerable to pollution. The wadi, with its permeable sand deposits is crossed continuously by people and animals at several places. It is used for dumping of waste and before 1985 even the suq extended into the wadi.

Water analysis carried out in the past, did not show any contamination, but tests carried out by the WAPS-2 project showed that at present many wells are contaminated.

The field programme on water quality included:

- surveys measuring EC, pH and temperature in approximately 50 wells and boreholes;
- chemical analysis with a Hach Kit (field laboratory) of samples from boreholes and dug wells;
- in October 1983, sampling of the same boreholes and dug wells, for analysis in the chemical laboratory in Khartoum (Ministry of Health);
- tests on bacteriological quality of the water in wells and boreholes used for drinking water supply.

From previous studies, some information was available on water quality, but results of full tests were only found in Hunting (1974) and Humphreys (1983).

8.2 Chemical Quality

8.2.1 Electrical conductivity, pH and temperature surveys

During the project period, surveys were carried out to monitor

the electrical conductivity (EC), the pH and the temperature of the groundwater. The surveys were carried out before, during and after the wet season.
The objective of the surveys was to indicate any existing variation of groundwater quality in place and in time. The measurements were carried out directly in the field, using portable Hach EC and pH meters. The results are presented in table 8.1 (see also table D.1, Well Inventory).

The pH of the groundwater at Nyala ranges generally from 6.9 to 7.8; this means that the water is slightly alkaline to neutral.

The EC ranges in general between 250 and 700 µS/cm, the lower values being found in and near the wadi. In a few wells higher values were measured, up to 1100 µS/cm.
In figure 8.1 an Electrical Conductivity Map is presented based on the results of the October 1983 survey. From this map, it is clear that EC-values increase going away from the wadi into the banks.
The water infiltrating from surface runoff has a low conductivity: about 100 µS/cm. The conductivity of the groundwater in the alluvial deposits becomes higher due to ion exchange with the clay minerals and with the weathered Basement underlying the deposits. In the banks, the deposits contain generally more clay, thus causing higher EC-values of the groundwater. The recharge with water of a low conductivity gives a reduction in the conductivity of the water in the wells. In general, low EC-values were measured in July and September. However, in most of the wells the values have been restored to the pre-wet season values by October.

The temperatures of the groundwater are fairly high, ranging between 26°C to 28°C in general. It should be noted, however, that temperature measurements are not accurate in dug wells.

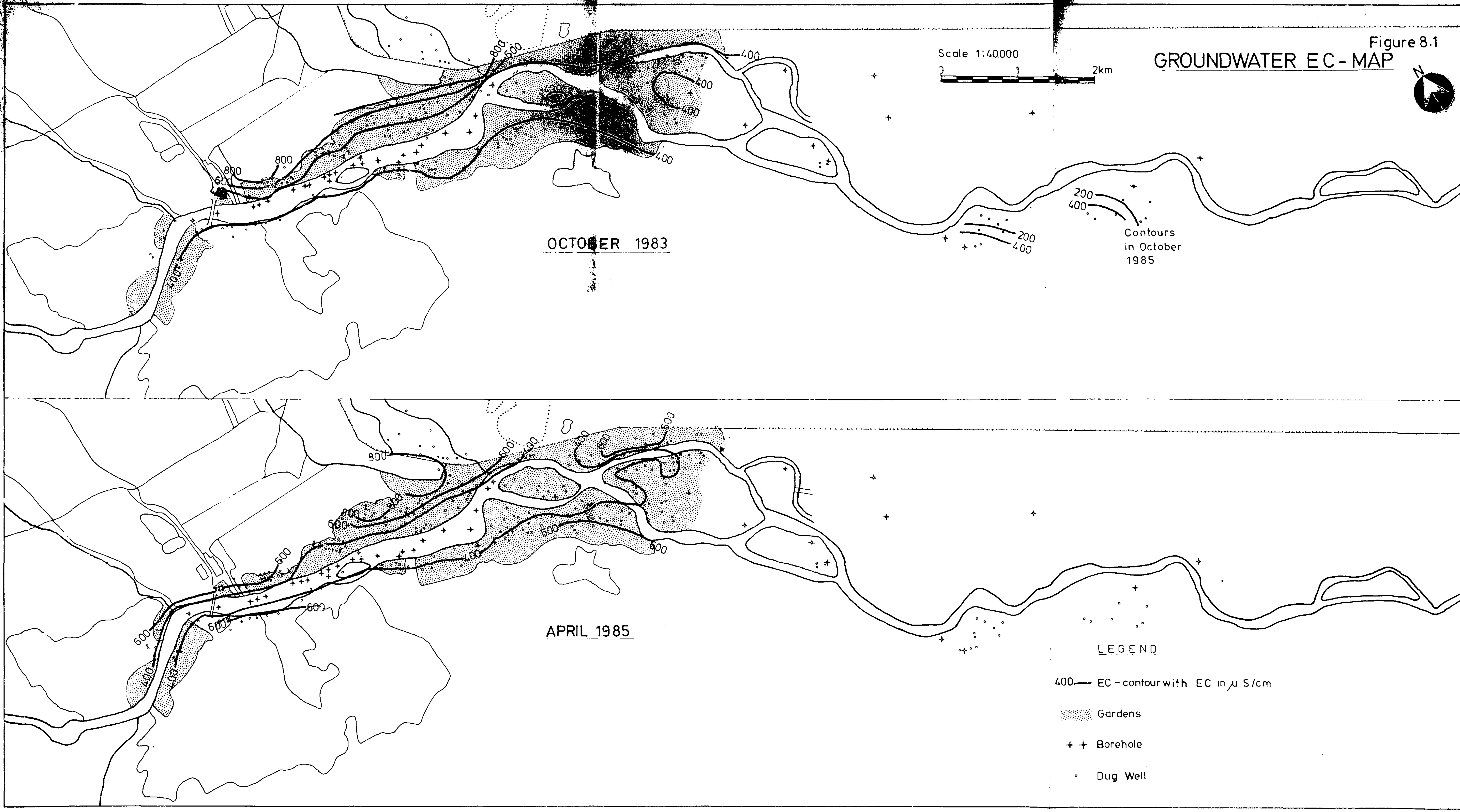


Figure 8.1
GROUNDWATER EC-MAP

Table 8.1 Electrical Conductivity, pH and Temperature Measurements

Well no.	Electrical Conductivity (μS/cm)							pH		Temp°C
	1983				1984		1985	1983		1983
	May	Jul	Sep	Oct	May	Oct	Apr	Jul	Oct	Oct
2	370	375	220	320	350	200	230	7.5	7.9	28.6
BH19	300	250	destroyed		-	-	-	7.8	-	-
14	-	400	-	400	-	-	330	7.2	7.3	28.5
BH15	-	250	-	245	225	220	230	7.4	7.6	28.0
16	-	440	-	550	420	-	260	7.2	7.5	-
19	325	235	320	355	375	300	230	6.9	7.5	28.3
BH24	-	-	480	510	520	540	290	-	7.4	25.0
31	-	860	580	1000	520	860	630	7.1	7.5	27.5
48	600	500	-	590	-	-	dry	7.1	7.5	27.4
59	-	325	280	420	-	-	550	7.2	7.3	26.0
69	375	320	-	460	-	-	310	7.4	7.5	27.7
75	-	280	-	250	-	-	250	7.4	7.9	26.0
93	580	-	600	540	-	400	290	-	7.4	25.0
103	300	-	-	190	-	-	240	-	7.3	24.5
106	380	340	340	310	-	-	220	7.0	7.5	27.0
109	-	440	-	450	-	-	240	7.0	7.4	27.8
113	-	160	300	380	-	-	150	7.8	7.5	27.8
129	400	-	-	350	-	-	240	-	7.6	27.5
133	620	-	-	180	-	-	590	-	7.9	26.0
518	-	360	-	360	-	-	310	9.0	7.6	27.7
517	275	320	-	300	-	-	280	8.3	7.3	27.9
513	-	-	-	330	-	-	460	-	7.5	25.6
512	-	280	-	400	-	-	330	7.8	7.3	27.9
523	-	530	-	340	-	-	440	7.1	7.9	27.6
525	-	320	440	410	-	-	180	7.3	7.4	27.9
537	-	-	-	330	-	-	dry	-	7.5	28.0
208	815	-	-	510	420	400	350	7.3	7.5	28.2
221	320	240	285	340	350	-	230	6.3	7.5	27.2
223	-	-	-	400	-	-	380	-	7.5	26.8
228	800	-	-	660	-	-	dry	-	7.4	26.9
230	-	-	-	1100	-	-	1400	-	7.4	26.8
234	-	300	-	250	-	-	dry	7.6	7.7	27.2
245	-	-	-	450	-	-	440	-	7.5	28.4
246	-	720	640	790	-	-	390	7.4	7.5	27.0
256	-	450	-	430	-	-	320	7.5	7.7	27.2
266	-	1100	-	800	-	-	810	7.5	7.6	30.0
269	-	840	245	870	860	-	600	7.4	7.3	26.4
271	-	520	-	400	-	-	490	6.8	7.8	26.0
280	660	-	-	510	-	-	560	-	7.4	27.5
282	-	-	-	390	-	-	290	-	7.5	28.0
286	-	260	345	270	-	-	390	7.3	7.4	27.3
289	-	780	-	540	-	-	760	7.1	7.5	28.7
295	680	220	-	-	-	-	440	7.6	-	-
297	-	420	-	480	460	-	370	7.3	7.4	28.5
299	-	620	-	490	-	-	450	7.1	7.5	28.0
300	-	300	440	480	-	-	dry	7.2	7.6	22.5

8.2.2 Chemical water analysis

The project selected about 18 wells and boreholes from which water samples were taken in September 1983, October 1984 and in April 1985.
The analysis was carried out in the field and in the project office using a Hach DR-EL/4 field kit. The analysis included pH, conductivity, hardness, alkalinity, calcium, iron, chloride, nitrate, sulphate, phosphate, colour and temperature.
The concentrations of sodium and potassium could not be determined with this kit and an accuracy check with the cation-anion balance was therefore not possible.
In October 1983 samples were sent for analysis to the chemical laboratory of the Ministry of Health in Khartoum. From these analyses cation-anion balances could be established, which showed a low level of accuracy of the analysed concentrations.
Two test results are available from samples (May 1981) analysed in the UK (Humphreys, 1983). These can be compared with the test results obtained in Nyala and Khartoum. Most striking is the large difference in concentration of the anions.
It appears that the analyses carried out in Sudan are not accurate. The Hach field kit has its limitations, also because of the unfavourable conditions at Nyala (too high room temperatures). But unfortunately also the laboratory in Khartoum provided inaccurate data. A summary of the results is provided in table 8.2.

The groundwater in the wadi alluvial aquifer is generally of the calcium-carbonate type. The hardness varies from moderate to very hard. The analysis results indicate no seasonal variation in the concentrations.

8.3 Bacteriological Quality

The water from dug wells and boreholes which are used for drinking water supply, was tested for bacteriological quality.

Table 8.2 Results Chemical Analyses Groundwater Wadi Nyala

Well number	19				31			59		93			525			
Date of sampling	1983 July	1983 Oct	1984 Oct	1985 Mar	1983 Oct	1984 Oct	1985 Mar	1983 Oct	1985 Mar	1983 Oct	1984 Oct	1985 Mar	1983 Oct	1984 Oct	1985 Mar	
Conductivity	370	-	300	230	-	860	650	-	550	-	400	250	-	300	180	μS/cm
pH	6.4	7.2	7.8	-	7.7	7.1	-	7.6	-	7.4	7.2	-	7.4	7.6	-	
TDS	-	230	-	-	640	-	-	250	-	330	-	-	440	-	-	mg/l
Total hardness	179	165	136	153	330	165	200	210	210	270	216	189	190	155	123	mg/l
Total alkalinity	-	140	-	154	380	274	212	240	140	300	-	272	190	-	140	mg/l
Excess alkalinity	-	Nil	-	-	50	-	-	30	-	35	-	-	Nil	-	-	mg/l
Calcium (Ca)	54	60	54	58	100	109	-	70	59	95	170	94	55	50	43	mg/l
Magnesium (Mg)	11	5	0	2	20	14	-	10	15	10	-	2	15	7	4	mg/l
Sodium (Na)	-	10	-	-	90	-	-	10	-	25	-	-	15	-	-	mg/l
Potassium (K)	-	5	-	-	10	-	-	5	-	10	-	-	5	-	-	mg/l
Total Cations	-	3.96	-	-	10.80	-	-	4.90	-	6.90	-	-	4.75	-	-	me/l
Chloride (Cl)	-	25	12	11	50	-	-	15	19	35	16	18	30	19	14	mg/l
Sulphate (SO_4)	-	80	5	12	130	-	-	55	31	85	4	19	45	3	16	mg/l
Nitrate (NO_3)	-	Nil	3	12	80	-	-	Nil	15	Nil	3	9	Nil	1	11	mg/l
Nitrite (NO_2)	-	Nil	-	-	0.01	-	-	Nil	-	Nil	-	-	Nil	-	-	mg/l
Fluoride (F)	-	0.50	-	-	0.50	-	-	0.80	-	0.70	-	-	0.50	-	-	mg/l
Total Anions	-	5.15	-	-	13.03	-	-	6.35	-	8.75	-	-	5.95	-	-	me/l
Ammonia (N)	-	Nil	-	-	Nil	-	-	Nil	-	Nil	-	-	Nil	-	-	mg/l
Albuminoid-Nitrogen	-	Nil	-	-	Nil	-	-	Nil	-	Nil	-	-	Nil	-	-	mg/l
Arsenic (As)	-	Nil	-	-	Nil	-	-	Nil	-	Nil	-	-	Nil	-	-	mg/l
Lead (Pb)	-	Nil	-	-	Nil	-	-	Nil	-	Nil	-	-	Nil	-	-	mg/l
Iron (Fe)	-	Nil	0.1	0.1	0.3	-	0.1	Nil	Nil	Nil	Nil	0.4	Nil	0.1	0.2	mg/l
SAR	-	0.3	-	-	0.3	-	-	2.1	-	0.6	-	-	0.5	-	-	

Table 8.2 Results Chemical Analyses Groundwater Wadi Nyala (cont'd)

Well number	113		221			266		269			BH 24		316		
Date of sampling	1983 Oct	1985 Mar	1983 Oct	1984 Oct	1985 Mar	1983 Oct	1985 Mar	1983 Oct	1984 Oct	1985 Mar	1983 Sep	1985 Mar	1984 Oct	1985 Mar	
Conductivity	–	150	–	280	230	–	810	–	800	600	480		400	580	μS/cm
pH	7.9	–	7.6	7.9	–	7.9	–	7.8	7.3	–	7.5		7.4	–	
TDS	230	–	360	–	–	365	–	680	–	–	–		–	–	mg/l
Total hardness	160	167	150	112	126	190	168	330	241	314	150		177	323	mg/l
Total alkalinity	200	173	140	142	153	390	343	440	414	320	250		216	168	mg/l
Excess alkalinity	40	–	Nil	–	–	215	–	120	–	–	–		–	–	mg/l
Calcium (Ca)	45	56	45	42	46	50	36	70	84	84	58		68	86	mg/l
Magnesium (Mg)	15	7	10	2	3	15	19	35	7	25	1		2	26	mg/l
Sodium (Na)	20	–	10	–	–	95	–	70	–	–	–		–	–	mg/l
Potassium (K)	5	–	5	–	–	5	–	5	–	–	–		–	–	mg/l
Total Cations	4.53	–	3.63	–	–	7.99	–	9.79	–	–	–		–	–	me/l
Chloride (Cl)	26	6	30	23	19	35	16	30	31	45	7		15	29	mg/l
Sulphate (SO_4)	60	13	80	0.2	13	75	90	65	4	58	2		5	23	mg/l
Nitrate (NO_3)	Nil	8	Nil	1	9	Nil	8	Nil	3	9	1		2	8	mg/l
Nitrite (NO_2)	Nil	–	0.01	–	–	0.03	–	0.01	–	–	–		–	–	mg/l
Fluoride (F)	0.60	–	0.50	–	–	1.20	–	0.80	–	–	–		–	–	mg/l
Total Anions	5.95	–	5.32	–	–	10.35	–	11.00	–	–	–		–	–	me/l
Ammonia (N)	Nil	–	Nil	–	–	Nil	–	Nil	–	–	–		–	–	mg/l
Albuminoid-Nitrogen	Nil	–	Nil	–	–	Nil	–	Nil	–	–	–		–	–	mg/l
Arsenic (As)	Nil	–	Nil	–	–	Nil	–	Nil	–	–	–		–	–	mg/l
Lead (Pb)	Nil	–	Nil	–	–	Nil	–	Nil	–	–	–		–	–	mg/l
Iron (Fe)	Nil	0.1	Nil	0.4	0.3	Nil	0.1	Nil	Nil	0.2	0.5		Nil	0.2	mg/l
SAR	0.7	–	0.3	–	–	3.0	–	1.7	–	–	–		–	–	

Table 8.2 Results Chemical Analyses Groundwater Wadi Nyala (cont'd)

Well number	PEWC Waterworks			2				BH 15			Stock Well			Wadi Nyala	
Date of sampling	1981 May	1984 Oct	1985 Mar	1983 July	1983 Oct	1984 Oct	1985 Mar	1983 Oct	1984 Oct	1985 Mar	1981 May	1983 Oct	1985 Mar	1983 Sep	
Conductivity	295	360	310	375	-	200	230	240	220	230	280	-	230	86	µS/cm
pH	7.4	7.4	-	6.8	7.1	7.6	-	7.1	7.6	-	7.4	7.6	-	8.2	
TDS	210	-	-	-	120	-	-	120	-	-	205	600	-	-	mg/l
Total hardness	138	139	182	172	90	83	158	90	99	93	140	440	153	88	mg/l
Total alkalinity	145	-	192	-	80	97	148	100	102	100	142	520	160	75	mg/l
Excess alkalinity	-	-	-	-	Nil	-	-	10	-	-	-	85	-	-	mg/l
Calcium (Ca)	44	46	61	62	30	37	60	30	32	32	46	145	56	12	mg/l
Magnesium (Mg)	7	6	7	4	5	3	2	5	4	3	6	15	3	14	mg/l
Sodium (Na)	12	-	-	-	10	-	-	5	-	-	7	30	-	-	mg/l
Potassium (K)	5	-	-	-	5	-	-	2	-	-	4	25	-	-	mg/l
Total Cations	3.40	-	-	-	2.47	-	-	2.18	-	-	3.20	10.41	-	-	me/l
Chloride (Cl)	4	-	62	23	20	32	21	25	12	12	2	40	26	9	mg/l
Sulphate (SO_4)	5	3	17	-	-	Nil	8	55	Nil	16	5	60	21	3	mg/l
Nitrate (NO_3)	18	1	6	-	Nil	3	20	Nil	3	3	12	Nil	25	-	mg/l
Nitrite (NO_2)	Nil	-	-	-	0.04	0	-	Nil	0.1	-	Nil	0.66	-	-	mg/l
Fluoride (F)	0.19	-	0.70	-	0.50	-	-	0.50	-	-	0.1	0.70	-	-	mg/l
Total Anions	3.40	-	-	-	4.14	-	-	3.85	-	-	3.20	12.78	-	-	me/l
Ammonia (N)	Nil	-	-	-	Nil	0.2	-	Nil	0.1	-	Nil	2.50	-	-	mg/l
Albuminoid-Nitrogen	0.07	-	-	-	Nil	-	-	Nil	-	-	0.07	Nil	-	-	mg/l
Arsenic (As)	-	-	-	-	Nil	-	-	Nil	-	-	-	Nil	-	-	mg/l
Lead (Pb)	Nil	-	-	-	Nil	-	-	Nil	-	-	Nil	Nil	-	-	mg/l
Iron (Fe)	Nil	Nil	0.1	-	Nil	3	0.1	Nil	Nil	Nil	0.16	Nil	0.7	Nil	mg/l
SAR	0.4	-	-	-	0.2	-	-	0.6	-	-	0.3	0.4	-	-	

Surveys were carried out during 1983, 1984 and 1985 by the project using Millipore coli-count samplers. These samplers must be incubated at 35°C for 24 hours.
Total coliform is determined by counting the number of colonies appearing on the samplers and multiplying it by 100, to obtain the total number of coliform per 100 ml.

In cooperation with the veterinary laboratory, samples were also tested by making a plate count using an aselective medium (MacConkey). The results from these compared reasonably well with the results from the Millipore samplers (May 1984 survey).
In November 1984 samples were taken from a number of wells and boreholes and analysed in El Fasher (Water Analysis Laboratory).

The results of all surveys are presented in table 8.3.

The coliform bacterial count is used as an indicator for the presence of pathogenic bacteria, e.g. salmonellae and shigellae which cause typhoid. However, specific tests are necessary to prove the presence of these pathogenic bacteria.
The Water Analysis Laboratory in El Fasher carried out these tests in November 1984. They showed no salmonellae or shigellae bacteria. E-coli (or faecal coliform) was found in some native wells near the wadi crossing at Kouria, in the water from dug well 1 and in a combined sample from boreholes 7 and 30. However, some doubt exists about the reliability of the last result, because bacterial contamination was never found by the WAPS-2 project on other occasions.

8.4 Groundwater Pollution

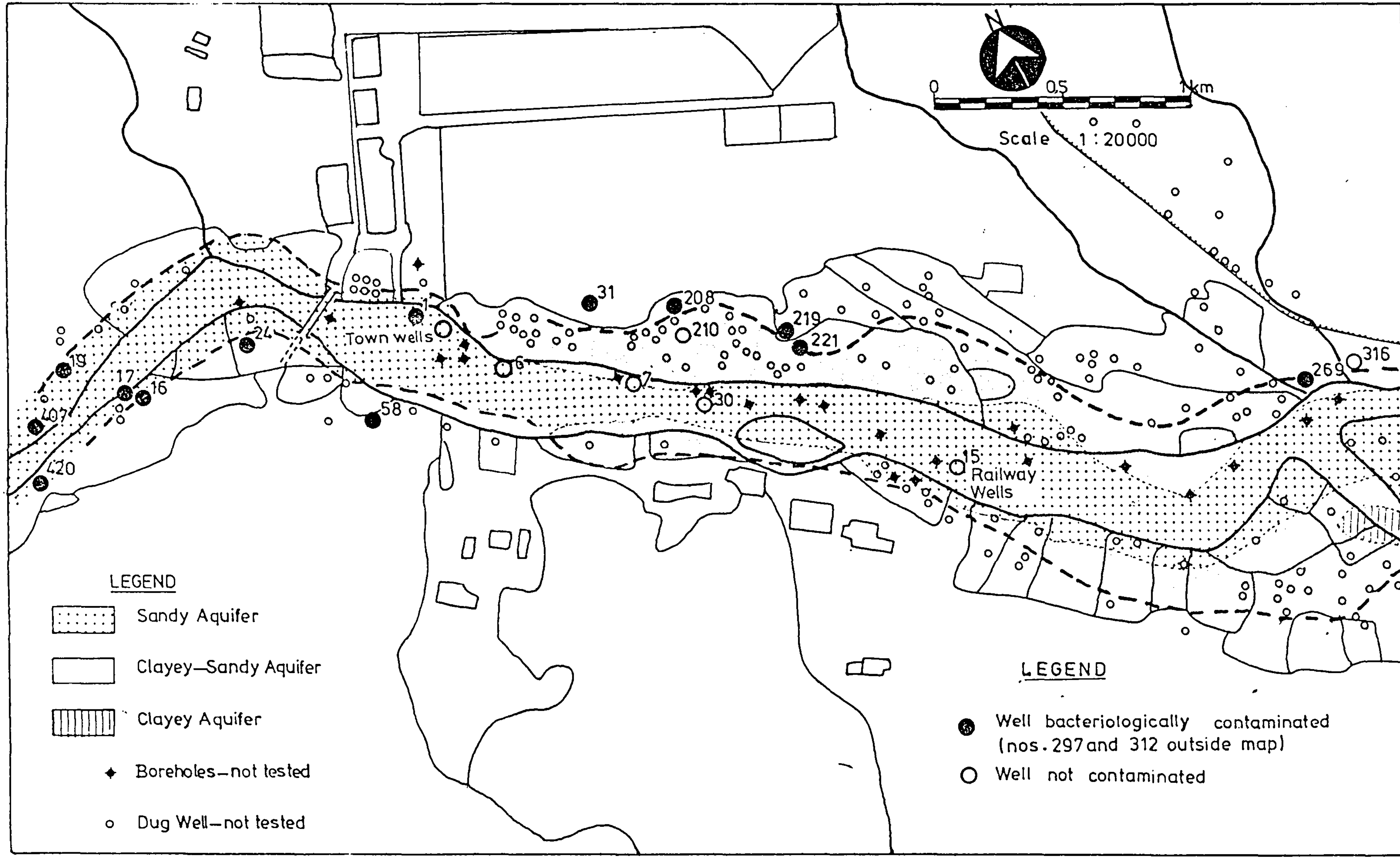
The location of the main water resource of Nyala, the groundwater in the wadi aquifer, makes it very vulnerable to pollution. The houses of the town reach to the edges of the aquifer and the wadi itself is crossed at many places by humans and animals. The aquifer in the wadi is not covered by any less permeable layers

Table 8.3 Results of Bacteriological Tests

Well no.	Total Coliform / 100 ml 1983 Dec	1984 May	1984 Oct	1985 Apr	Bact/ml 1984 Nov	Remarks
1	100	-	700	-	68 500	E-coli present in Nov 1984
2	300	-	-ve	-	29 400	
BH 6	100	-	-	-	-	
BH 7	-ve	-ve	-ve	-ve	12 400	E-coli present in Nov 1984
BH15	-ve	-ve	-ve	-ve	51 500	
BH30	-	-	-	-ve	-	
16	-ve	2 700	-ve	+ve	-	
17	-	1 200	-	100	-	
19	300	400	-ve	200	-	
24	-	3 000	-ve	700	-	
31	100	10 000	+ve	-	-	
58	-	3 000	+ve	200	-	
208	-ve	600	600	200	19 200	
210	-	400	-ve	-	-	
219	-	400	1 100	800	-	
221	-	1 000	-ve	+ve	-	
269	-ve	1 400	+ve	200	-	
297	-	200	+ve	1 400	-	
312	-	-ve	+ve	+ve	-	
316	-	200	+ve	-ve	-	
407	-	100	-	800	-	
420	-	600	-	300	-	
Pumphouse PEWC	-	-ve	-ve	-ve	15 400	

Notes:

1. 1984 Nov tests by water analysis laboratory El Fasher, all other tests by WAPS2
2. -ve = negative, no coliform bateria present
3. +ve = positive, but count of bacteria not possible
4. - = not tested



LOCATION MAP BACTERIOLOGICAL WELL TESTS Figure 8.2

and therefore, if water is available, diluted contaminants quickly reach the groundwater.

The main danger to pollution at present is:

- the use of pit latrines in the town;
- the dumping of waste at random in the town and in the wadi;
- the absence of protection for boreholes and dug wells used for drinking water supply;
- the trucks entering the wadi to quarry sand.

The drinking water supplied through the piped distribution net by the PEWC is pumped from boreholes and wells located in the wadi. Three boreholes: 6, 7 and 15, and two dug wells, 1 and 2, were tested bacteriologically. E-coli was found in 1 and 7 but in the others high numbers of bacteria were also found.
In 1984 dug well 1 was closed on the advise of the project. It was poorly protected and was only covered with badly fitting pieces of corrugated zinc sheets. The location near the market (suq) meant a continuous hazard from people and animals moving nearby. BH 2 is also located too close to the suq, but is still in operation. Continuation of this well should only be allowed if the authorities are able to contain the suq at some distance from the wadi. Attempts to achieve this had been made, but without much success, until a large section of the suq was cleared in 1985.
The E-coli present in the combined sample from borehole 7 and 30 might be due to waste dumped at the site of the boreholes. Both boreholes are located near the much used wadi crossing at Kouría. This result shows that continuous monitoring of the bacteriological quality of the water from the boreholes is necessary.

People whose houses are not connected to the distribution system mainly rely for their water supply on water vendors. These receive their water either from water kiosks connected to the distribution system or from dug wells located near the wadi.
Sixteen dug wells used for this purpose were checked and the

majority was found to be contaminated. Several of these wells are located very near to the town. Drainage water from the town might make the water from these wells unreliable. Well 31, which is located between the houses, was highly contaminated and was closed by the authorities after the first water test in 1983.
Another problem of the dug wells is the absence of a drainage system for excess water. The water which is spilt when the 1 m^3 tanks of the water vendors are filled, floods the area surrounding the wells. Part of it will return to the water in the wells by percolation and transport diluted excrements from horses and donkeys. This most probably is the cause of the contamination in many wells. This situation can be improved simply by paving an area around the well and surround this with a concrete drainage ditch to discharge the excess water.

8.5 Groundwater Suitability

8.5.1 Suitability for domestic use

Groundwater in general used as a water source has the advantage that, except at open wells, no direct contact is possible with human activities or animals. Because it is stored underground, the quality is more or less constant and also the temperature does not vary much. The filtering effect of the aquifer sediments and the long retention times provide the groundwater self-purification properties.

At Nyala the main recharge of the groundwater is by infiltration of wadi runoff, which is of good quality. The wastes left by people in the wadi endanger this quality but the large flood peaks usually remove them, before too much water has infiltrated. The location of the groundwater source, partly inside the town of Nyala, implies a continuous pollution hazard.
To ensure a safe water supply for domestic use, preventive measures should be taken to remove the sources of pollution, as described in the previous section.

Meanwhile it is advisable to add chlorine to the water supplied by the PEWC, to kill bacteria which might be present in the pumped water. Also regular checks on the water quality should be carried out at the PEWC office in Nyala.
The water from the aquifer is, at present, generally of good chemical quality. The salinity is generally low and concentrations of constituents are within the drinking water standards. The hardness of the water, however, is in many places hard to very hard. This might be problematic in the case of industrial use, where water heating equipment is required.

8.5.2 Suitability for agricultural use

The salinity levels in the groundwater at Nyala are generally acceptable, except at the boundaries of the aquifer. There values of 800 to 1100 μS/cm are found, which might have some effect on crop yields if the water is used for irrigation. In such cases, over-irrigation should be applied to obtain leaching of the salts from the soils. The low yields from the wells near the aquifer boundary, however, shows that this leaching requirement cannot always be achieved.
The suitability of water for irrigation can be indicated with the Sodium-Absorption-Ratio (SAR).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

High values of SAR imply a hazard of sodium replacing absorbed calcium and magnesium and this replacement damages the soil structure (Hem, 1970).

SAR-values were calculated for the samples collected in October 1983 and are included in table 8.2. Suitability of the water is indicated if the SAR-value is below 8, which is the case for all wells.

9. GROUNDWATER DEVELOPMENT

9.1 Present Situation

In the Town Area an average 3.5 x 10^6 m^3 groundwater is used during the dry season out of the total storage capacity of 6.0 x 10^6 m^3, the majority for domestic consumption. Large drawdowns occur in the area of the Town Wells, due to a concentration of wells. In the Downstream Area not much groundwater is used productively. The majority of the water is lost by the consumptive use of the forest.

Every year the groundwater stored in the Wadi Nyala alluvial aquifer is largely used up.
The wadi runoff is sufficient to provide recharge for recovery of the groundwater levels in years with normal rainfall. The total wadi discharge is then far in excess of the required infiltration. However, the infiltration potential has been reduced in recent years, because of a reduction in the runoff duration, due to the degradation of the vegetation cover in the catchment area.
In years with low rainfall, infiltration is insufficient, especially in the Downstream Area.

The events during the period from the wet season of 1983 until the wet season of 1985 have shown the effects of low rainfall:
- In the Town Area the water levels were generally 1 metre lower in 1984 than in 1983 and many dug wells dried up during the last months of the dry season in 1985.
- In the Downstream Area groundwater levels did not recover much in the area of Kundua. The saturated thickness in this area was shallow and varied between only 3 and 5 metre. Further downstream the recovery in 1984 was still 3 to 5 metre below that of 1983 (see figure 7.3).

The authorities have no established policy to use the available groundwater resouces efficiently. The volume of abstraction by the PEWC for the town water supply is not controlled (on many wells not even metered) and groundwater levels are not observed.

9.2 Water Demand

9.2.1 Present situation

Presently the PEWC supplies about 50 000 to 60 000 people (Humphreys, 1983) with the distribution net. The supply varied in recent years between 1.4×10^6 m³ and 2.0×10^6 m³ (table 7.5), indicating a consumption per capita of 64 to 110 litres/day (the actual consumption per capita is lower because water losses through pipe leakages are included in this estimate).

The total population of Nyala is estimated at 205 407 people, including 24 798 displaced persons (source: Town Council, July 1985). Of these about 150 000 rely on water from dug wells, which is sold by street water vendors. The discharge from dug wells for domestic purposes is about 0.4×10^6 m³ (table 7.6), indicating a consumption per capita of 7 litres/day. This consumption is below the absolute minimum water requirement as adopted by the World Health Organization.

The present water consumption by irrigation was estimated in the Town Area at 0.95×10^6 m³ and in the Downstream Area at 0.87×10^6 m³ (table 7.8).

9.2.2 Future water demand

The water demand from domestic and industrial users in the near future was analysed by Humphreys (1983). In their study they used a 1981 population figure of 136 000 for Nyala and based the projection of the demand for drinking water on expected population growth rates of 6% for the period 1981 - 1985, 5.5% for 1986 - 1990 and 5% for 1991 - 1995.

Using a water consumption estimate of 2.5×10^6 m^3 for 1981, they estimated the total water demand in 1995 at 6.4×10^6 m^3 (table 9.1).

Table 9.1 Domestic and Industrial Water Consumption (after Humphreys, 1983)

Year	Population Estimate	Total Consumption (m^3/year)	Consumption per capita (l/day)
1983	152 000	2 400 000	43
1985	172 000	3 400 000	54
1990	224 000	4 900 000	59
1995	286 000	6 400 000	61

The future water demand for domestic use depends strongly on the type of water supply system that will be implemented. As definite plans for the future increase of the system have not yet been established, the demand projections of Humphreys have been used in this report.

In the Town Area any increase in irrigation in the future is not advised, because the water resources in the alluvial aquifer are limited and should be reserved for the drinking water production.

In the Downstream Area pumping for irrigation purposes could be increased from present rates, especially if water losses by evapotranspiration from the forest are reduced. It is very important that any extension of the gardens is evenly spread to avoid an inefficient use of groundwater for irrigation. This process should be controlled by the Authorities. Water levels are low in dry years, resulting in small saturated thicknesses and hence low water production rates. The choice of the crop types should take this into account.

9.3 Future Groundwater Exploitation

9.3.1 Town Area

The possibility of increasing the groundwater abstraction for the town water supply was analysed using the groundwater model. Six development options were designed, increasing the pump capacity from the 1984-level of 1.4×10^6 m^3 to between 1.9×10^6 m^3 and 4.0×10^6 m^3.
The maximum pump capacity from one borehole was determined at 30 to 35 m^3/hour. The simulation of the development options was run for 20 months, comprising the conditions of an average year and of a dry year. Other groundwater requirements (for irrigation etc.) were kept unchanged from the present situation.

A detailed description of the simulation results is included in appendix F, section F2.4. A summary of the results is provided in table 9.2.

The simulation of the development options shows that the increase in groundwater exploitation in the Town Area should be found in the downstream part of this area. The area of the Town Wells contains already many wells and only one more well between BH 6 and BH 7 is acceptable (see figure 7.4). A maximum production of 4.0×10^6 m^3 is possible from the alluvial aquifer, but at the end of the dry season some wells may have to be shut due to excessive drawdowns. This may introduce shortages in water supply because the demand is high in this period.
In dry years big shortages are expected to occur at the end of the dry season if the pumping is more than 3.0×10^6 m^3/year.
Not included in this quantity is the present abstraction from dug wells for domestic use, being 0.25×10^6 m^3/year.

Table 9.2 Summary Development Options Town Area

Option	Required Exploitation Rate (10^6 m³/year)	Number of Wells Old	New	Average year Actual Exploitation Rate (10^6 m³)	Dry year Actual Exploitation Rate (10^6 m³)	Minimum Required Infiltration (10^6 m³)
1	1.9	8	-	1.8 *	1.8 *	3.4
2	2.0	8	2	2.0	2.0	3.6
3	2.5	8	5	2.5	2.5	4.1
4	3.0	9	6	3.0	3.0	4.6
5	3.5	9	10	3.5	3.4 *	5.0
6	4.0	9	11	4.0	3.8 *	5.5

* In option 1, 5 and 6 the total required exploitation cannot be achieved, due to excessive drawdowns in a dry year (in option 1 also in an average year). The drawdowns cause interruptions in pump operation because minimum groundwater levels are exceeded.

The infiltration required at maximum development of the Town Area aquifer is 5.5 x 10^6 m³ (see option 6). This is a minimum, because it creates the dry year conditions as simulated. For average conditions an infiltration of about 6.2 x 10^6 m³ is required. Considering the large flood volumes observed in 1983 and 1985, this infiltration will probably be achieved. However, in the event of a dry year the infiltration potential might be insufficient for full replenishment of the aquifer.

The drawdown caused by the increased pumping from deep boreholes in the wadi, will affect the groundwater levels in the banks, where the gardens are located. This will occur especially in the area of the Railway Wells and further downstream where the extended development of groundwater is planned. The conditions

under option 3 (2.5 x 10^6 m³ pump capacity) will entail an extra drawdown of about 2 metre in the garden area. Under full development (4.0 x 10^6 m³ pump capacity) the extra drawdown can be about 4 to 5 metre.
Due to the variation in lithological conditions no detailed picture can be drawn, but generally wells located near the wadi will be more affected.

It is clear that the development of the wadi aquifer for domestic purposes cannot be undertaken without planning the necessary measures to continue to provide for the irrigation needs of the area.

9.3.2 Downstream Area

The groundwater model of the Downstream Area is not detailed due to a lack of groundwater level data in the area. The simulation of several development options was therefore not relevant (see appendix F, section F3.4).

The exploitation of the groundwater resources in the Downstream Area for the town water supply seems possible only in the area upstream of Kundua forest. A total annual abstraction of 750 000 m³ might be obtainable from this area. To achieve this quantity six boreholes located in the wadi course with an average capacity of 20 m³/hour will be necessary (see figure F.12).
The exploitation of the groundwater in the Town Area will probably not affect the available quantity in the Downstream Area very much.

In a dry year groundwater levels will be generally one metre lower in the area upstream Kundua forest. The pumping of the same quantity of 750 000 m³ may then still be possible.

As explained in section 7.4 a loss of groundwater may take place in the area of Kundua, due to a fractured zone in the underlying

Basement. If this is correct then some exploitable water may be stored in this zone. The drilling facilities of the project did not allow this to be verified, however, and the quantification of the water availability was therefore not possible.
The alluvial aquifer area is crossed at many places by fault systems in the Basement (see section 5.4). If in the future the groundwater potential of the alluvial aquifer is used to near its capacity, then an additional exploration of these fault systems may be justified.

Downstream of Kundua forest the alluvial aquifer appears to have a reasonable saturated thickness. Considering the distance of this area from the town it seems impractical to reserve the groundwater resources for the town water supply. However, the resources could be used for an increased agricultural development.

9.3.3 Conclusions

The water resources from the alluvial aquifer at Nyala, available for domestic and industrial use are:

in the Town Area	3.5 to 4.0 x 10^6 m^3
in the Downstream Area	0.75 x 10^6 m^3
Total	4.25 to 4.75 x 10^6 m^3

The water demand in 1995 as estimated by Humphreys (1983) for domestic and industrial use is 6.4 x 10^6 m^3. This means a shortfall of 1.65 to 2.15 x 10^6 m^3, which in dry years increases to 1.85 to 2.25 x 10^6 m^3.

If the water demand by the town approaches the available water resources then investigations should be carried out to verify the possibility of additional supply from:

- the Kundua Area, if water losses from the consumptive use of the forest are reduced;
- the fractures in the Basement underlying the alluvial aquifer.

The small groundwater resources in areas outside Nyala (see chapter 11) are not feasible for the town water supply due to the large distances and the small quantities involved.
Surface water is not an alternative at Nyala, because storage facilities, like a reservoir, do not seem feasible. Good locations for a dam do not exist, the only area suitable for a reservoir could be Buldanga, east of Jebel Nyala.

The groundwater resources for agricultural purposes are very limited near Nyala.
In the Town Area pumping for domestic supply should have priority. The present consumptive use of 0.95 x 10^6 m^3/year in irrigated agricultural areas should not be increased.
In the Downstream Area some additional development of the groundwater resources is possible for agricultural purposes. However, the groundwater levels in this area are sensitive to the infiltration potential of the surface water.

The use of the limited groundwater resources in the Wadi Nyala alluvial aquifer requires the introduction of a proper water management plan and the establishment of an executing authority. Especially in years of low rainfall the need for water management will be critical (see also chapter 10).

9.4 Methods of Aquifer Exploitation

The alluvial aquifer of Wadi Nyala has a small thickness and is of limited width. The groundwater table is near the surface and traditionally water is pumped from shallow wells by centrifugal pumps driven by a diesel engine.

The first deep borehole was drilled in 1960, but only in recent years has the number of boreholes increased.
The boreholes are all located in the wadi, where the depth to Basement is greatest.

The design of the older PEWC boreholes (BH 3, BH 6 and BH 7) is not known, but most probably the screens are of the bridge slotted type. The more recently constructed boreholes (BH 14, BH 15 and BH 30) were installed with Johnson screens. The efficiency of the wells is still good, as is expressed by the values of their specific capacity (table 7.2): 25 to 50 m³/hour/m.

The efficiency of other boreholes is much lower, except for the new borehole BH 31. Therefore, additional boreholes have to be constructed, if groundwater exploitation is to be increased.
The location of additional boreholes with respect to the required abstraction rate and available groundwater storage was analysed with the groundwater model of the Town Area (see appendix F, section F2.5). A minimum well spacing of 200 metre was used. As discussed before, the boreholes should be located in the area of the Railway Wells or further downstream.
The total number of boreholes required varies from 10 to 20, for a total groundwater production of 2.0 to 4.0 x 10^6 m³/year.

The pump yield from one borehole should not exceed 30 to 35 m³/hour. This discharge can easily be achieved, except at the end of the dry season when water levels are low. Then pumps might run dry if pumped continuously at this discharge, and therefore pumping has to be interrupted daily during some hours to let the water-table recover. Also a well design is required which minimizes well head losses.

New boreholes should be constructed according to the following requirements:

- The depth of the screen should be as large as is feasible, to enable the continuation of pumping if large drawdowns exist in the aquifer. The borehole has to penetrate the top of the Basement below the weathered zone, to enable the deep placement of pumps, as far as engine cooling requirements allow.
- The top of the screen should be at least 5 metre below the ground surface to provide some safeguard against contaminants.

- The diameter of the screen and casing need not be larger than 200 mm (compare table D.7 for maximum possible discharge).
- The screen should be of the wire-wound type. The size of the slots should be 1.5 to 2.0 mm, using a gravel pack consisting of uniformly sorted gravel with D 90 = 1.5 to 2.0 mm (see table D.7). This combination will lead to small well head losses.
- The protection against damage of the borehole-casing, exposed above the wadi surface, has to be improved, because in future more large floods can be expected. This protection can be achieved by placing a barrier of loose stones around the casing or by burying the well head and discharge pipe.

Humphreys (1983) suggested radial collector wells, to reduce the number of boreholes needed. They estimated the yield from one such well at 60 to 80 l/s. However, this yield will lead to unacceptable large drawdowns, and especially at the end of the dry season the yield from such a well will be much reduced.
Furthermore the construction of radial collector wells requires special skill, knowledge and equipment, which is not available in Sudan. Also the maintenance of such a unit will be problematic.

For the irrigation of gardens, brick lined dug wells are used exclusively at present. A great number exist in the area, but the individual yield is small and the depth of the wells seldom exceeds 8 metre.

In future, the use of dug wells for irrigation should be continued because it is the best method to abstract groundwater from the shallow aquifer of Wadi Nyala. Increase of the total yield should not be allowed in areas where groundwater is pumped for the town water supply.

10. WATER MANAGEMENT

10.1 Introduction

In the past, when there was no groundwater legislation, disputes and disagreements about the use of water resources were solved according to the traditional customs (Ajawid). Nowadays the growth of the population, the increase in the human activities and the effects of severe drought necessitate the set up of legal measures to control the water resources.

As (ground)water is a scarce and valuable commodity, it is obvious that water resources development must be controlled, both quantitatively and qualitatively. Clearly such a controlled development can only be achieved through an adequate and competent management.

Water management deals with the relation between water demand, natural water resources and the required technical and administrative measures. The water demand consists of demand for domestic use, industrial use, agricultural use and cattle watering. It can only be fulfilled by the natural water resources: rainfall, surface water and groundwater. To divide these resources between the different users, determine their priorities and rights, technical administrative measures are needed such as: legislation, establishment of taxes and water fees, of distribution systems and the control of water resources and their permanent monitoring.

Water management is required because of the limited (ground)-water resources and the lack of alternatives. Pollution (water-borne diseases) and overuse of water (dry wells, loss of investments) are considered to be serious risks.

Implementation of the water management should be achieved through the institution of:

- A Regional Water Authority (the policy makers), which task it is to set priorities, to make plans for water development, to set rules and to settle disputes.
- A Technical Committee (the technical advisers), which should monitor groundwater levels, groundwater quality and groundwater abstractions, monitor surface water resources, carry out investigations and research and which is to advise the Regional Water Authority.

Legal provisions in the form of a Water Act are required to realize an optimal functioning of the above institutions.

10.2 Historical Background

Presently the Sudanese laws do not include general legislature on the management of water resources. The only existing legal arrangements are those concerning the River-Nile System (surface water) and the recently passed Water Act for the Gash Basin.
In 1981 Presidential Decree number 838 was issued to establish a board to look after drinking water, sanitary and sewage affairs. The board was headed by the former Ministry of Energy. One of the main tasks of the board is to arrange the utilization of different water resources and their protection. To be able to perform well, the board divided itself into three committees:
- drinking water committee
- sanitary sewage committee
- legislative committee.

The board considered the following as important duties:
- to regulate the rates of discharge from different water resources;
- to adopt standards for drinking water;
- to protect drinking water from contamination hazards;
- to investigate the processes of filtration, distribution and supply of drinking water to consumers;
- to control the drainage of the used water from sewages and

other drainage systems so as to reduce the environmental pollution;
- to find methods to tackle and get rid of the already contaminated water.

The board has the right to derive and/or approve certain regional acts or regulations concerning the drinking water in all regions.
The board has a free hand to select specialists for advice and to conduct necessary visits to any place in the country.

The board presently confines itself:
- to study the existing water acts, evaluate them and give advice on their validity;
- to compare these with similar water regulations in other countries (e.g. Egypt, Kenya and India) for correlation;
- to compare the existing Sudanese standards for water quality with what is found internationally in the same field (e.g. WHO, Unicef, etc.).

In 1984 the Regional People Council of the Eastern Region was the first in Sudan to pass a water act to control and manage a groundwater basin. The act was prepared by WAPS and NWC under the name "The Gash Basin Act". According to this act a Regional Water Council and a Technical Committee were established at Kassala.

10.3 Water Act and Regional Water Authority

As mentioned previously a legal basis is required for an executive water management body with authoritative power. It is therefore proposed to have a Water Act passed by the regional authorities focussed on adequate use and management of the Nyala water resources.
The Water Act should include regulations and instructions regarding the establishment of a Regional Water Authority and its

duties, the establishment of a Technical Committee and its duties, as well as the financial aspects involved. An example of a Water Act (adapted from the Kassala Gash Basin) is given in annex H.

The Regional Water Authority, responsible for the management of the Nyala water resources should be composed of representatives of the regional government, representatives of the water users and groundwater specialists of the National Water Corporation.

The duties of the Regional Water Authority should include:
- the formulation of short and long term plans for the water resources development;
- the setting of priorities for the exploitation of the groundwater in the area;
- the issuing of licenses concerning the drilling of boreholes, the construction of wells and the permissible discharge;
- the planning and supervision of required research;
- the securing of the necessary financial means.

10.4 Technical Committee

In order to provide the Regional Water Authority with the required information a Technical Committee should be established by the National Water Corporation in consultation with the Regional Water Authority.

The tasks of the Technical Committe should include:
- advising of the Regional Water Authority;
- continuation of the hydrogeological investigations near Nyala;
- evaluation of the groundwater resources and preparation of annual water balances;
- recording of all wells and boreholes and their abstractions;
- supervising of the drilling activities near Nyala, including site location and construction of the wells.

The activities to fulfill the above mentioned tasks include:

- monitoring of the groundwater network. Monthly the groundwater levels in about 75 wells have to be measured;
- collection of water samples. Twice a year (May and October) samples will be taken from about 75 wells. From the samples the EC will be measured; from about 10 samples chemical analysis will be made after the sampling in May;
- monitoring of bacteriological contamination. From suspected wells samples have to be taken and checked on the occurrence of E-coli. If severe contamination is found a complete bacteriological analysis has to be done;
- execution of Wadi Nyala discharge measurements. During the flow period of the wadi, daily measurements have to be made at Mekkah Bridge;
- execution of well discharge measurements four times a year (May, August, November, February). An estimation has to be made of the total groundwater abstraction;
- continuous updating of the well inventory;
- yearly set up of a water balance;
- advising on the location of new wells and boreholes and supervision of drilling activities;
- carrying out special investigations into the different aspects of the water development according to arising needs;
- offering technical advice for government units and third parties.

11. ALTERNATIVE RESOURCES

11.1 Introduction

At Nyala the water resources from the wadi alluvial aquifer are limited. This might hamper the future increase in water supply for domestic and industrial purposes and might also limit the possibilities for further agricultural development. Therefore, investigations need to be carried out to identify alternative sources.

Surface water resources are ample at Nyala, but cannot be utilized, because storage facilities, like a reservoir, are not feasible. Good locations for a dam or hafir do not exist.

Additional groundwater resources near Nyala exist upstream and downstream along Wadi Nyala. The area downstream of Kundua has prospects for an increase in groundwater development as was already pointed out in previous chapters.
Upstream from Nyala, at Romalia, a small aquifer is at present exploited for irrigation. Also at Buldanga, east of Jebel Nyala, groundwater is used for irrigation. Short preliminary studies were carried out to assess the groundwater resources in these areas.

Water resources at a larger distance from Nyala have been indicated by Humphreys (1983). These are the Umm Ruwaba aquifer of the Baggara Basin, some 70 to 100 km south of Nyala and the wadi alluvial aquifers of Delal el Angara and Timbusku along Wadi Bulbul, at 30 to 40 km southwest from Nyala.

The sandstone aquifer seems too far from Nyala to be of interest as an alternative for the water supply of Nyala. The aquifer at Wadi Bulbul might provide possibilities for a small increase in irrigated agricultural land in this area and is therefore of more interest.

11.2 Area Upstream along Wadi Nyala

11.2.1 General description of the area

Upstream of the town of Nyala, at several places along the wadi, the groundwater from the wadi alluvium is being used. Not far from Nyala, near a place called Romalia, the wadi alluvium reaches a reasonable width and several gardens are found in this area.

These extend for about 7.7 km, from Shadida to Domai, along the Wadi Kabris, the northern tributary of Wadi Nyala. The area is composed of an upstream part, called Taronga (Upper Romalia) and a downstream part, called Romalia (see figure 11.1).
The wadi flows from north to south, the slope of the bed is approximately 2.5 m/km. The total surface area of wadi alluvial deposits is estimated to be 4.5 km^2. Some outcrops of granitic gneiss and quartzite dykes are found at different locations along the wadi channel.

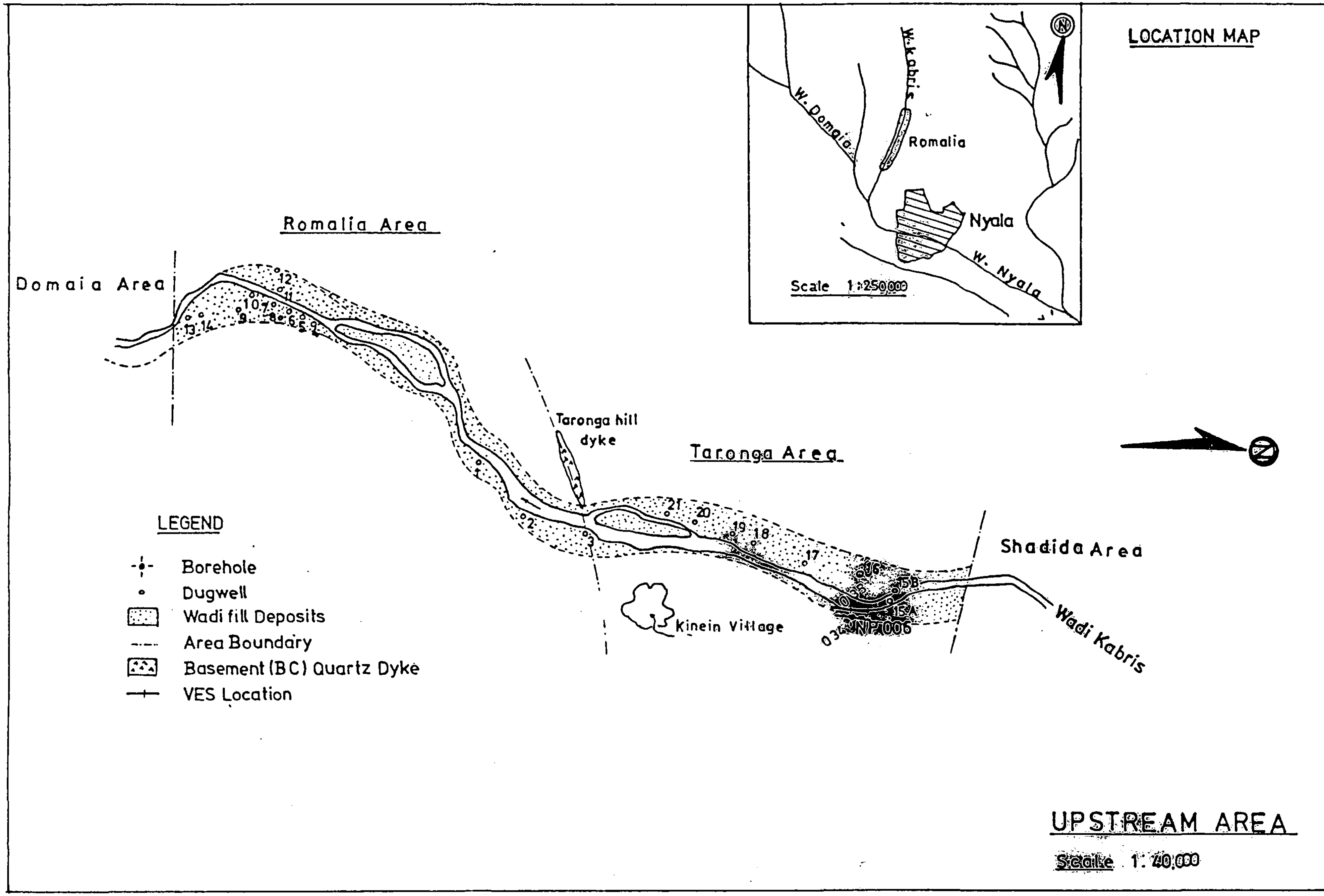
11.2.2 Investigations at Romalia

A preliminary survey was carried out at Romalia, comprising:
- a well inventory, including 21 open dug wells;
- two VES-measurements (the EM-equipment was not yet available at the time of the survey);
- one exploratory borehole NP 06.

The fieldwork was carried out in December 1983.

11.2.3 The alluvial aquifer

During the well inventory, 21 open dug wells were located in the area. In the upstream part, all the wells are located on the right bank of the wadi; in the downstream part, most of them are located on the left bank. Inside the wadi channel, many native



LOCATION MAP
W. Kabris
W. Domaia
Romalia
Nyala
W. Nyala
Scale 1:250,000
Romalia Area
Domaia Area
Taronga hill dyke
Taronga Area
Shadida Area
Kinein Village
Wadi Kabris
NP 006
LEGEND
Borehole
Dugwell
Wadi fill Deposits
Area Boundary
Basement (BC) Quartz Dyke
VES Location
UPSTREAM AREA
Scale 1:40,000

Figure 11.1.

dug wells are found. The water extracted from the dug wells is mainly used for irrigation, while the water from the native dug wells is used for domestic purposes. The project drilled an exploratory borehole in the Taronga Area (NP 06), but the Basement was already encountered at a depth of only 3.5 metres.

The wadi alluvial deposits composing the aquifer are mainly medium to coarse sands and gravels. The water bearing formation lies directly on the impermeable bed of the Basement Complex. There are some clay lenses in the aquifer body, as can be seen from the presence of brick manufacturing sites. The aquifer is annually recharged by the wadi during the flood season. According to information provided by local farmers, the groundwater level rises to ground surface during the flood season and drops for about 2.5 metres during the remainder of the year.

11.2.4 Groundwater quantity

The well inventory included 21 dug wells. The discharge of each well was measured. The total discharge is indicated in table 11.1.

Table 11.1 Annual Discharge from Wells in Romalia Area

Area	Number of wells	Annual Discharge (m^3)
Taronga	7	0.23×10^6
Romalia	14	0.18×10^6
	Native wells	0.08×10^6
	Total Discharge	0.49×10^6

The total discharge from the aquifer was estimated by assuming that the average fluctuation of the groundwater table amounts to 2.5 metres. Using an estimate for the specific yield of 20%, the total volume involved can be calculated at 2.25 x 10^6 m^3. As the pumped discharge is estimated at 0.49 x 10^6 m^3, the remainder of 1.76 x 10^6 m^3 is lost mainly by evapotranspiration from phreatophytes.

The total storage for both areas was estimated using an average depth to Basement of 6 metres for the Taronga Area and of 5 metres for the Romalia Area. Table 11.2 shows that the volume not used at present is 2.4 x 10^6 m^3. Part of this volume can be pumped and utilized for irrigation, but the saturated thicknesses towards the end of the dry season will make the extraction increasingly more difficult. Exploitation should preferably be from large diameter dug wells.
The present consumption of 0.5 x 10^6 m^3 for agricultural purposes may be extended to 1.5 x 10^6 m^3, especially if also the evapotranspiration by phreatophytes is reduced. The exploitation of additional water for the town water supply, seems economically not feasible, because of the small quantity and the large distance to the town.

Table 11.2 Water Balance Romalia Area

Area	Total Storage (m^3)	Discharge Pumping (m^3/year)	Discharge Evapotransp. (m^3/year)	Water not used (m^3/year)
Taronga	2.4 x 10^6	0.23 x 10^6	0.85 x 10^6	1.3 x 10^6
Romalia	2.3 x 10^6	0.26 x 10^6	0.91 x 10^6	1.1 x 10^6
Total	4.7 x 10^6	0.49 x 10^6	1.76 x 10^6	2.4 x 10^6

11.3 Buldanga

11.3.1 General description of the area

Buldanga is a small basin at some 10 km east of Nyala, beyond Jebel Nyala. It is crossed by Wadi Buldanga which has a catchment area of about 200 km². The geology of the area is Basement Complex rocks covered by thin superficial deposits.

The Basement outcrops on the banks disappear near the village of Buldanga, as they are covered by alluvial deposits, which become thicker in downstream direction. The wadi channel also changes to a large width and a smaller depth in this area, and Wadi Baba branches off on the left side.

Further downstream the wadi channel again becomes narrower and the flood waters overflow the wadi banks extensively. Finally the wadi channel disappears into a flat clayey flood plain. The channel does not reach the course of Wadi Nyala.

The studied area measures about 17.0 km² of which the irrigated gardens occupy less than 2.0 km². The gardens are found mainly along Wadi Baba and Wadi Buldanga. Most of the gardens are owned by people from Nyala and the fruits and vegetables are sold in the Nyala market. In the rest of the area rainfed agriculture is practised in farms.

11.3.2 Investigations at Wadi Buldanga

The hydrogeological study at Buldanga was concentrated in an area, 7 km long, between the wadi channels of Buldanga and Baba. Most of the dug wells are found in this area. The field work included:

- a well inventory
- an electro-magnetic survey
- drilling of hand auger holes

- surveying and levelling of wells and geophysical profiles
- groundwater level measurements
- pumptests
- groundwater quality analysis.

The work was carried out in April and May 1985. A detailed report will be included in the Wadi Buldanga Technical Bulletin.

11.3.3 The alluvial aquifer

The main aquifer in the area is composed of alluvial sediments. The depth of these sediments does not exceed 15 metres. They are characterized by rapid facies changes and clays are present not only in the flood plains, but also in the active wadi beds. The sandy sediments form the water yielding parts of the aquifer and these are usually covered by a thick clay layer.

Some wells are dug into the weathered top zone of the Basement Complex, which has a sufficient porosity and permeability to yield groundwater. The area is crossed by several faults, but it is not clear whether these will yield any water, if wells or boreholes are constructed in them.

The location of the dug wells indicates that:
- better aquifer permeabilities exist near the wadi courses;
- groundwater recharge occurs mainly along the wadis by the infiltration of surface runoff.

The well inventory indicated 78 dug wells in the study area. About 50 of these are equiped with a diesel driven centrifugal pump and used for irrigation.
Pumptests were executed in three dug wells (no. 6, 48 and 62). The test duration was short, due to the low productivity of the wells and the large pump capacity (about 20 m^3/hour). The pumptest analysis (method Papadopulos - Cooper) indicated an aquifer permeability of 70 m/day, which should be considered a maximum, because the wells rank among the most productive in the area.

The specific yield could not be determined from the pumptest analysis. But it is expected that the value of S ranges between 10 and 15%.

11.3.4 Groundwater storage fluctuation

The main recharge to the alluvial aquifer is the infiltration of surface water from the wadis. The infiltration potential is limited due to:

- the short duration of the floods;
- the low permeability of the alluvium.

The water levels observed in May 1985 were affected by the preceding period of dry years. The groundwater storage at this time therefore has to be considered a minimum.
The wet season of 1985 was characterized by a rainfall total equal to the average of the last 15 years. But the floods reached higher levels due to the denudation of the catchment area and extensive flooding of the area occured. Therefore the infiltration conditions in 1985 were better than normal, although the flood duration probably did not differ much from flood durations in normal years. The groundwater fluctuation volume observed during the rainy season of 1985 was about 5×10^6 m^3, which is more than the normal average. The total storage of the aquifer in the surveyed area was not yet determined and for an estimate of this reference is made to the Wadi Buldanga Technical Bulletin.

11.3.5 Groundwater quality

The electrical conductivity (EC) of the groundwater generally ranges between 400 and 700 µS/cm, but in some wells also higher values up to 2000 µS/cm were measured. As it is usually observed in this type of alluvial aquifers, the EC increases going away from the wadi course. Three water samples were analysed (table 11.3). The analysis shows low concentrations of chloride and nitrate. The hardness is moderate in two of the wells.

Figure 11.2

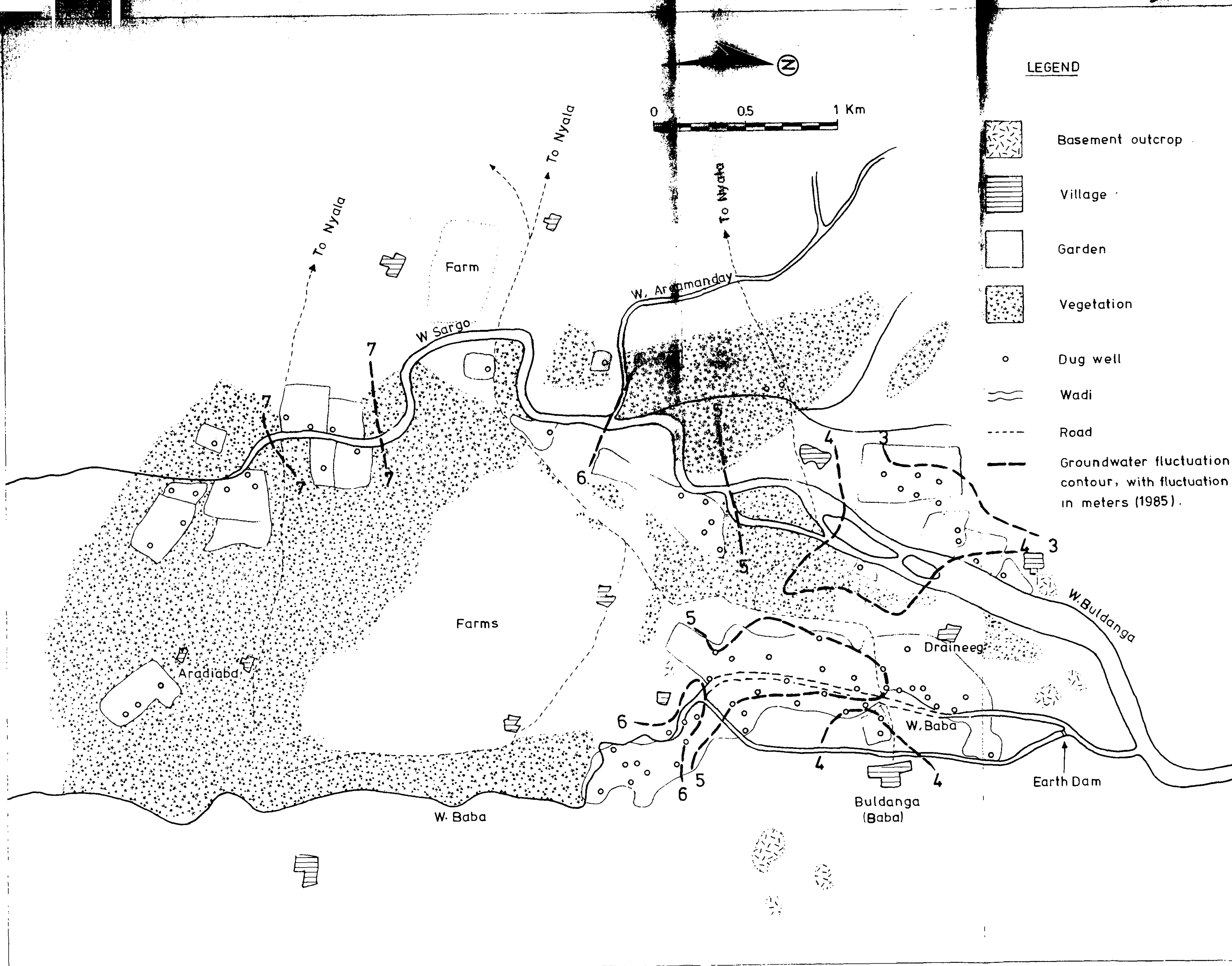

LEGEND
Basement outcrop
Village
Garden
Vegetation
Dug well
Wadi
Road
Groundwater fluctuation contour, with fluctuation in meters (1985).
0
0.5
1 Km
To Nyala
To Nyala
To Nyala
Farm
Farms
W Sargo
W. Buldanga
W. Baba
W. Baba
Aradiaba
Draineeg
Buldanga (Baba)
Earth Dam
7
7
7
7
6
6
6
5
5
5
5
4
4
4
4
3
3

Table 11.3 Results Chemical Analysis Groundwater Buldanga

	Well number		
	25	45	49
Conductivity (μS/cm)	380	1090	380
Total hardness (mg/l)	176	53	149
Alkalinity (mg/l)	208	228	227
Calcium (mg/l)	66	17	27
Iron (mg/l)	0.3	0.2	Nil
Chloride (mg/l)	29	18	26
Nitrate (mg/l)	9	12	8

11.3.6 Conclusions

The alluvial aquifer at Buldanga contains only small thicknesses of sand and generally the permeability is low due to the large clay content. The yield of the present dug wells is small, and due to recharge conditions wells are located along the wadi courses.
The survey indicated that the area of Buldanga only has a limited potential for groundwater development, which is already largely utilized. For the construction of new wells there only seems to exist good sites along Wadi Buldanga. The area cannot provide additional water for the water supply of Nyala.

The wadis flood the area extensively during the rainy season, due to an increase of flood levels, which is caused by the denudation of the catchment area. The agricultural practises therefore should be adapted to make use of this water. The construction of storage reservoirs for surface water may be possible due to the presence of thick clay layers.

11.4 Wadi Bulbul

11.4.1 General description of the area

The catchment area of Wadi Bulbul borders the western side of Wadi Nyala catchment. It extends on to the slopes of the Jebel Marra and the runoff reaches the Bahr al Arab in the south in contrast to Wadi Nyala. Two areas along the wadi course, near Nyala, have been identified as containing a reasonable groundwater aquifer.

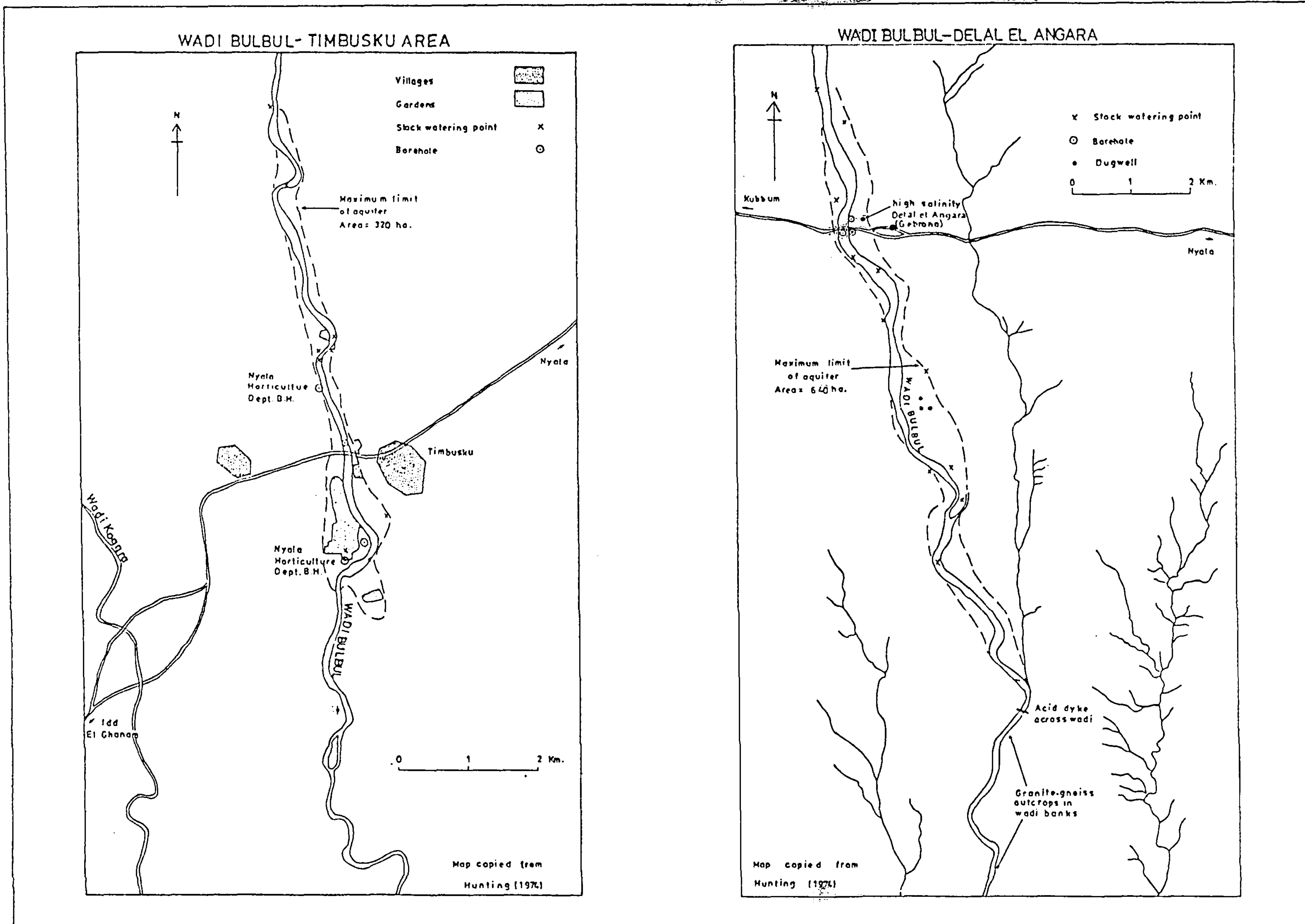
- The upstream area, called Gebrona or Delal el Angara, has a total area of 640 ha, is 11 km long and on average 600 metres wide (see figure 11.3).
- The second area, Timbusku, is about 5 km long and on average, also 600 metres wide, with a total area of 320 ha (see figure 11.3). The lateral limits of the alluvial aquifer are less clear than at Delal el Angara.

11.4.2 Investigations at Wadi Bulbul

The areas at Delal el Angara and Timbusku were surveyed by Hunting (1974) to determine the groundwater resources, with a view to the planning of small irrigation schemes. The survey included seismic refraction along traverses, drilling of two boreholes at Timbusku and three at Delal el Angara, groundwater level observations and water quality measurements.

The WAPS-2 project started to update and improve the hydrogeological data in November 1985. The WAPS-2 survey included an electro-magnetic survey along traverses, a well inventory, water level measurements, etc.

The data is not yet available and therefore not included in this report. The survey will be presented in the Wadi Bulbul Technical Bulletin.



WADI BULBUL ALLUVIAL AQUIFER

Figure 11.3

11.4.3 The alluvial aquifer

The alluvial deposits of Wadi Bulbul are mainly sands ranging from fine to coarse, with a lot of gravels distributed within the sand layers. Generally the deposits at Timbusku contain more clay than at Delal el Angara.
Pumptest results are available from two boreholes at Timbusku and one at Delal el Angara. Drainage tests were carried out on several sand samples. From the tests Hunting (1974) estimated the hydraulic characteristics as shown in table 11.4.

Table 11.4 Hydraulic Properties Alluvial Aquifers at Wadi Bulbul (after Hunting 1974)

Area	Hydraulic Conductivity m/day	Transmissivity m^2/day	Specific Yield %
Delal el Angara	75	600	20
Timbusku	50	450	20

11.4.4 Groundwater quantity

The wadi aquifer shows a marked seasonal fluctuation in water-tables due to the short period of recharge in the wet season.
Table 11.5 gives gross aquifer, groundwater storage and groundwater fluctuation volumes of both aquifers. The maximum amount of water which might be abstracted can be estimated at 2/3 of the total storage, thus some scope for an increase in groundwater abstraction exists.

Table 11.5 Groundwater Storage Alluvial Aquifers at Wadi Bulbul (after Hunting, 1974)

Area	Gross volume (10^6 m^3)	Storage volume (10^6 m^3)	Volume fluctuation (10^6 m^3)
Delal el Angara	48.5	10	3.3
Timbusku	26.4	5.3	1.5

11.4.5 Groundwater quality

The salinity of the groundwater increases from the wadi channel into the banks. Hunting (1974) indicated values of 140 to 450 µS/cm. During a short field trip in 1983 by members of the WAPS-2 team, higher EC-values were observed. In one dug well at Delal el Angara 1900 µS/cm was measured. It should, therefore, be investigated as to what extent the water quality forms a constraint to groundwater development.

11.4.6 Conclusions

The alluvial aquifers at Timbusku and Delal el Angara are at present not yet sufficiently investigated. There seems more groundwater available in the areas for an extension of the irrigated areas. But the total volume of groundwater is limited.
The use of the groundwater for the water supply of Nyala is not feasible, due to the large distance and small resources.

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APPENDIX A

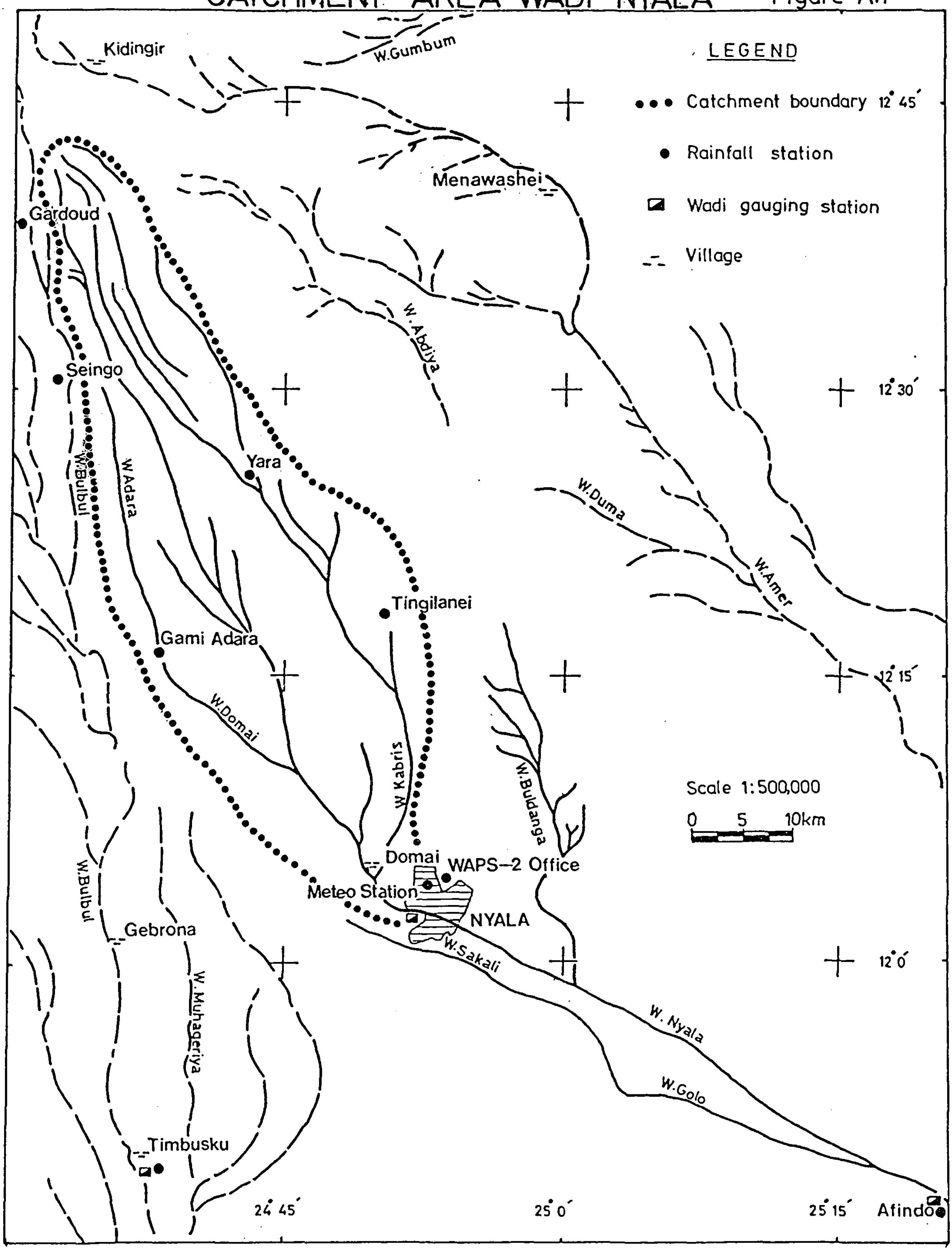
HYDROLOGICAL DATA

A1. Rainfall Data

A2. Evapotranspiration Calculations

A3. Discharge Measurements Wadi Nyala

CATCHMENT AREA WADI NYALA
Figure A.1



APPENDIX A1 RAINFALL DATA

TABLE A.1 Nyala Rainfall Data 1921-1985 (mm/month)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL TOTAL
1921	0.0	0.0	0.5	0.0	19.3	17.7	87.0	122.6	68.9	0.0	0.0	0.0	316.0
1922	0.0	0.0	0.0	0.0	9.1	35.6	218.5	213.2	237.5	64.5	0.0	0.0	778.0
1923	0.0	0.0	0.0	1.1	29.2	114.9	186.3	186.7	77.5	29.4	0.0	0.0	625.1
1924	0.0	0.0	8.0	1.5	3.3	88.1	86.2	189.3	155.4	6.0	0.0	0.0	537.8
1925	0.0	0.0	0.0	0.0	12.0	13.4	52.0	275.0	22.7	26.6	10.0	0.0	412.3
1926	0.0	0.0	0.0	18.8	8.0	15.5	162.5	134.3	45.7	11.5	0.0	0.0	396.3
1927	0.0	0.0	0.0	0.0	64.0	58.3	164.0	135.9	94.8	17.3	0.0	0.0	534.3
1928	0.0	0.0	12.2	68.5	63.6	68.9	147.6	187.0	38.9	1.0	0.0	0.0	557.7
1929	0.0	0.0	0.0	0.0	64.7	44.4	200.3	132.0	130.3	8.8	0.0	0.0	580.5
1930	0.0	0.0	2.7	10.9	134.7	39.8	290.7	18.2	82.8	0.0	0.0	0.0	579.8
1931	0.0	0.0	0.0	0.0	7.5	102.4	125.0	277.4	109.5	4.5	0.0	0.0	626.3
1932	0.0	0.0	0.0	0.0	0.0	76.5	56.9	192.3	121.8	106.5	0.0	0.0	554.0
1933	0.0	0.0	0.0	0.0	32.6	188.7	119.6	76.6	140.1	1.0	0.0	0.0	558.6
1934	0.0	0.0	0.0	5.0	35.3	52.9	84.8	98.1	135.2	30.2	0.0	0.0	441.3
1935	0.0	0.0	0.0	6.0	57.5	124.6	29.4	244.8	33.9	2.8	0.0	0.0	499.0
1936	0.0	0.0	0.0	0.0	70.2	48.2	68.6	146.9	43.6	26.5	0.0	0.0	404.0
1937	0.0	0.0	0.0	0.0	38.5	36.2	123.8	215.2	83.7	21.1	0.0	0.0	518.5
1938	0.0	0.0	0.0	1.9	40.3	65.4	146.9	145.4	206.6	0.0	0.0	0.0	606.5
1939	0.0	0.0	0.0	17.2	25.1	38.3	143.5	133.3	133.2	8.0	0.0	0.0	498.6
1940	0.0	0.0	0.0	0.0	1.7	65.5	66.3	132.6	21.6	6.3	0.0	0.0	294.0
1941	0.0	0.0	0.0	7.1	41.6	63.1	4.8	78.8	11.5	0.5	0.0	0.0	243.4
1942	0.0	0.0	0.0	0.0	49.5	37.0	154.8	231.9	11.5	17.5	0.0	0.0	502.3
1943	0.0	0.0	0.0	0.0	3.0	9.4	154.0	232.1	63.9	15.8	0.0	0.0	478.2
1944	0.0	0.0	8.6	0.4	32.6	18.0	145.8	205.9	62.6	2.4	0.0	0.0	476.3
1945	0.0	0.0	0.0	4.6	70.6	12.4	174.1	92.8	74.6	66.9	0.0	0.0	496.0
1946	0.0	0.0	0.0	0.0	0.0	151.1	164.0	182.9	107.1	5.5	0.0	0.0	610.6
1947	0.0	0.0	0.0	2.7	33.1	54.7	50.7	-----	------	----	---	---	-----
1948	0.0	0.0	0.0	1.3	16.2	41.6	113.8	115.2	19.0	0.0	0.0	0.0	307.1
1949	0.0	0.0	0.0	0.0	9.3	8.8	116.2	116.0	49.7	19.5	0.0	0.0	319.5
1950	0.0	0.0	0.7	13.0	28.0	52.5	167.0	176.8	103.9	0.0	0.0	0.0	541.9
1951	0.0	0.0	0.0	0.0	27.8	38.7	72.3	107.9	137.5	72.2	0.0	0.0	456.4
1952	0.0	0.0	0.0	0.0	2.4	56.9	77.0	124.9	73.1	34.0	0.0	0.0	371.3
1953	0.0	0.0	0.0	0.0	36.8	15.0	178.7	207.5	69.8	12.0	0.0	0.0	519.0
1954	0.0	0.0	0.0	0.0	22.5	40.0	164.0	202.5	57.0	27.0	0.0	0.0	513.0
1955	0.0	0.0	0.0	15.0	22.0	52.5	191.0	149.5	122.5	17.0	0.0	0.0	569.5
1956	0.0	0.0	0.0	0.0	4.0	8.0	85.2	329.3	141.0	0.0	0.0	0.0	567.5
1957	0.0	0.0	0.0	0.0	21.2	36.0	225.5	126.4	57.9	19.0	0.0	0.0	486.0
1958	0.0	0.0	0.0	0.0	0.9	39.4	195.9	189.2	48.8	5.8	0.0	0.0	480.5
1959	0.0	0.0	0.0	6.0	8.0	40.6	137.0	210.0	66.7	0.0	0.0	0.0	468.3
1960	0.0	0.0	0.0	0.0	16.0	50.0	104.0	129.0	121.0	9.0	0.0	0.0	429.0
1961	0.0	0.3	0.0	0.0	0.0	86.0	134.0	172.0	52.0	13.5	0.0	0.0	457.8
1962	0.0	0.0	1.0	0.0	0.0	71.5	118.1	164.4	47.7	46.2	0.0	0.0	448.9
1963	0.0	0.0	0.0	17.0	47.9	51.5	203.8	196.5	79.7	23.6	0.0	0.0	620.0
1964	0.0	0.0	0.0	1.2	7.2	33.0	177.0	246.0	112.0	45.0	0.0	0.0	621.4
1965	0.0	0.0	0.0	0.0	19.0	78.0	124.0	54.0	56.0	4.0	0.0	0.0	335.0
1966	0.0	0.0	4.0	3.0	63.0	31.0	116.0	151.2	81.0	21.5	0.0	0.0	470.7
1967	0.0	0.0	0.0	6.5	0.0	55.4	128.2	171.7	47.3	13.0	0.0	0.0	422.1
1968	0.0	0.0	0.0	0.0	25.8	57.4	104.2	160.6	52.2	0.0	0.0	0.0	400.2
1969	0.0	0.0	1.0	21.0	14.9	101.4	103.4	204.0	48.2	1.7	0.0	0.0	495.6
1970	0.0	0.0	0.0	0.0	0.0	10.0	143.0	116.0	199.0	41.0	0.0	0.0	509.0
1971	0.0	0.0	0.0	0.0	13.0	41.5	67.5	110.5	126.3	9.6	0.0	0.0	368.4
1972	0.0	0.0	0.0	0.0	56.4	64.8	86.4	32.6	95.8	11.5	0.0	0.0	347.5
1973	0.0	0.0	0.0	15.6	27.0	20.0	194.0	38.0	34.5	33.3	0.0	0.0	362.4
1974	0.0	0.0	0.0	0.0	30.0	29.5	175.0	171.0	-----	----	0.0	---	-----
1975	0.0	0.0	0.0	0.0	2.7	61.3	134.4	116.2	98.3	----	0.0	0.0	-----
1976	0.0	0.0	0.0	1.6	0.5	0.2	100.0	46.6	75.4	46.4	0.0	0.0	270.7
1977	0.0	0.0	0.0	0.0	21.9	66.4	70.8	196.9	9.1	18.2	0.0	0.0	383.3
1978	0.0	0.0	0.0	0.0	27.4	50.3	74.6	217.9	33.1	76.3	0.0	0.0	479.6
1979	0.0	0.1	0.0	1.6	19.1	50.5	56.2	106.0	58.8	26.0	0.0	0.0	318.3
1980	0.0	0.0	0.0	0.0	31.5	106.5	217.0	81.3	97.1	0.0	0.0	0.0	533.4
1981	0.0	0.0	8.6	TR	3.3	42.1	158.3	56.2	29.5	41.0	0.0	0.0	339.0
1982	0.0	0.0	TR	TR	TR	45.6	45.5	82.9	89.6	8.8	0.0	0.0	272.4
1983	0.0	0.0	TR	TR	4.6	84.0	123.7	53.4	74.5	0.0	0.0	0.0	340.2
1984	0.0	0.0	0.0	0.0	20.9	0.8	86.4	49.1	38.7	1.4	0.0	0.0	197.3
1985	0.0	0.0	11.0	1.6	3.0	19.6	125.3	103.2	88.7	0.0	0.0	0.0	352.4
MEAN	0.0	0.0	0.6	3.3	25.1	52.4	129.7	149.5	79.8	19.4	0.2	0.0	459.7

Table A.2 Monthly Rainfall Data Stations WAPS-2 Project (mm)

		Nyala	Tingilanei	Yara	Gardoud	Seingo	Gami Adara	Afindo	Timbusku
1983	Jan	-	-	-	-	-	-	-	-
	Feb	-	-	-	-	-	-	-	-
	Mar	-	-	-	-	-	-	-	-
	Apr	-	-	-	-	-	-	-	-
	May	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	June	84.0	20.2	30.8	11.1	51.6	38.8	61*	27.1
	July	145.6	92.9	184.3	122.1	93.8	155.4	121.4	74.2
	Aug	45.5	124.3	89.2	66.2	49.1	87.4	44*	102.8
	Sep	42.9	59.7	38.2	15.2	12.0	27.5	47.0	58.6
	Oct	0.0	-	-	-	-	-	-	-
	Nov	0.0	-	-	-	-	-	-	-
	Dec	0.0	-	-	-	-	-	-	-
1983	Total	322.6	297.1	342.5	214.6	206.5	309.1	273.4	262.7
1984	Jan	0.0	-	-	-	-	-	-	-
	Feb	0.0	-	-	-	-	-	-	-
	Mar	0.0	-	-	-	-	-	-	-
	Apr	0.0	-	-	-	-	-	-	-
	May	23.6	0.0	3.9	0.0	0.0	0.5	0.0	0.0
	June	4.7	6.2	35.9	4.0	8.4	13.4	24.0	11.9
	July	62.5	84.6	97.8	58.7	68.0	88.0	53.1	43.0
	Aug	33.2	48.1	36.9	55.5	46.7	29.8	37.5	44.0
	Sep	28.5	60.7	70.4	45.5	44.6	54.1	88.4	37.9
	Oct	1.8	7.6	14.5	23.9	8.0	12.0	9.7	3.2
	Nov	0.0	-	-	-	-	-	-	-
	Dec	0.0	-	-	-	-	-	-	-
1984	Total	154.3	262.2	259.4	187.6	175.7	197.8	212.7	140.0
1985	Jan	0.0	-	-	-	-	-	-	-
	Feb	0.0	-	-	-	-	-	-	-
	Mar	8.0	-	-	-	-	-	-	-
	Apr	1.0	-	-	-	-	-	-	-
	May	0.0	14.9	10.9	0.0	20.9	13.1	0.0	0.0
	June	3.1	40.3	33.6	76.0	138.9	38.3	28.4	48.8
	July	151.1	105.8	119.2	89.3	83.4	92.9	123.7	205.8
	Aug	103.3	163.4	112.1	113.2	114.4	80.8	151.5	89.9
	Sep	83.7	100.0	50.3	28.3	20.7	69.3	39.0	73.2
	Oct	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Nov	-	-	-	-	-	-	-	-
	Dec	-	-	-	-	-	-	-	-
1985	Total	350.6	424.4	326.1	306.8	378.3	294.4	342.6	417.7
3 years average		275.8	327.9	309.3	236.3	253.5	267.1	276.2	273.5

* Record incomplete

Table A.3 Number of Raindays Stations WAPS-2 Project

		Nyala	Tingilanei	Yara	Gardoud	Seingo	Gami Adara	Afindo	Timbusku
1983	Jan	-	-	-	-	-	-	-	-
	Feb	-	-	-	-	-	-	-	-
	Mar	-	-	-	-	-	-	-	-
	Apr	-	-	-	-	-	-	-	-
	May	1	-	-	-	-	-	-	-
	June	7	4	4	4	10	7	x	2
	July	8	12	16	16	17	x	11	5
	Aug	10	10	15	15	14	13	x	12
	Sep	7	8	6	8	4	9	9	10
	Oct	-	-	-	-	-	-	-	-
	Nov	-	-	-	-	-	-	-	-
	Dec	-	-	-	-	-	-	-	-
1983	Total	33	37	41	43	45	(29)	(20)	32
1984	Jan	-	-	-	-	-	-	-	-
	Feb	-	-	-	-	-	-	-	-
	Mar	-	-	-	-	-	-	-	-
	Apr	-	-	-	-	-	-	-	-
	May	1	-	1	-	-	1	-	-
	June	4	6	7	1	3	5	5	5
	July	7	10	11	12	12	13	7	10
	Aug	11	11	9	14	8	8	9	12
	Sep	8	11	6	12	10	6	8	11
	Oct	1	2	2	3	3	2	2	4
	Nov	-	-	-	-	-	-	-	-
	Dec	-	-	-	-	-	-	-	-
1984	Total	32	38	33	39	33	33	29	42
1985	Jan	-	-	-	-	-	-	-	-
	Feb	-	-	-	-	-	-	-	-
	Mar	1	-	-	-	-	-	-	-
	Apr	3	-	-	-	-	-	-	-
	May	-	1	3	-	2	2	-	-
	June	1	8	8	5	8	5	2	7
	July	7	9	12	x	9	x	x	10
	Aug	7	8	9	8	8	10	x	12
	Sep	6	x	5	4	6	6	8	8
	Oct	-	-	-	-	-	-	-	-
	Nov	-	-	-	-	-	-	-	-
	Dec	-	-	-	-	-	-	-	-
1985	Total	25	(26)	37	(17)	33	(23)	-	37
3 years average		30	-	37	-	37	-	-	37

APPENDIX A2 EVAPOTRANSPIRATION CALCULATIONS

A2.1 Determination of Penman's Evaporation

The Penman equation applied for Nyala is identical to the one used in the Kassala Gash Basin Project (1982), except for some coefficients related to sunshine duration (see table A.5.).

In the following sections the meteorological data required as input to the equation is described seperately.

The data used as input to the equation are summarized in table A.4 together with the results of the calculation.

Table A.4

Evaporation Estimate (Penman) and Relevant Climatological Data

Month	(1) Bright Sunshine (%)	(2) Mean Daily Temperature (^{o}C)	(3) Wind Velocity (m/s)	(4) Relative Humidity (%)	Net Radiation (W/m^2)	Evaporation Estimate (mm/day)
Jan	90	23.3	1.6	17	96	4.8
Feb	88	25.3	1.6	15	114	5.5
Mar	83	28.5	1.6	13	129	6.2
Apr	79	30.3	1.6	15	143	6.7
May	75	30.9	1.3	27	168	6.8
Jun	68	29.7	1.3	45	183	6.6
Jly	58	27.1	1.3	63	184	5.9
Aug	58	26.3	1.3	68	187	5.8
Sep	68	27.5	1.3	57	187	6.2
Oct	81	28.3	1.6	36	161	6.3
Nov	90	26.5	1.9	21	113	5.6
Dec	89	23.7	1.9	20	95	4.9
Mean	77	27.3	1.5	27	147	5.9

(1) Average data El Fasher and Ghazala Gawazat 1971 - 1980

(2) Nyala 1951 - 1980

(3) Nyala, visual estimates 1971 - 1980

(4) Nyala 1941 - 1970.

Table A.5:

The Penman Equation as used for Nyala

The PENMAN EQUATION is usually written as follows:

$$E_o = \frac{E}{L} = \frac{\frac{\Delta}{\gamma} R + LE_a}{(1 + \frac{\Delta}{\gamma})\ L}$$

Where:

E_o	= evaporation from an extended water surface	($mm.day^{-1}$)
E	= energy used for evaporation	($W.m^{-2}$)
L	= evaporation energy: 1 mm x $1m^2$ water at 25 ^oC requires 585 kcal = 2450 KJ = 28.4 W.day	($W.day.mm^{-1}.m^{-2}$)
Δ	= slope of the saturation vapour pressure curve	($mb.^oC^{-1}$)
R	= net radiation = $(1-r)\ R_{sk} - R_{long}$	($W.m^{-2}$)
r	= reflection coefficient for water surface: 0.06	
R_{sk}	= short wave incoming radiation from sun and the sky, which reaches the earth surface	($W.m^{-2}$)
R_{long}	= effective long wave radiation emitted by the earth, at air temperature: $57.2\ 10^{-9}\ (T_a)^4\ (0.56-0.078\sqrt{e_{act}})(0.10+0.90(n/N))$	($W.m^{-2}$)
T_a	= absolute temperature of the air	(^oK)
e_{act}	= actual vapour pressure of the air at 2 m	(mb)
E_a	= empirical aerodynamic term to account for water evaporation provided that air and water are at equal temperature = $0.26\ (K + 0.54\ U_2)\ (e_{sat} - e_{act})$	($mm.day^{-1}$)
K	= roughness coefficient of evaporating water surface: 0.5	
U_2	= wind velocity at 2 m	($m.sec^{-1}$)
e_{sat}	= saturated vapour pressure of the air at temperature T_a	(mb)
γ	= psychometric constant = 0.65 mb. $^oC^{-1}$	($mb.^oC^{-1}$)

A2.1.1 Energy supply

The required data is:

- Short wave incoming radiation at the top of the atmosphere (R_o)
- Effective long wave radiation emitted by the earth (R_{long})
- Sunshine duration as percentage of the length of the day (n/N)

The incoming radiation R_o as obtained from the literature (de Jong 1969) for Nyala at latitude 12 °N is presented in Table A.6.

Table A.6
Short Wave Incoming Radiation at the Top of the Atmosphere (R_o) for Latitude 12°N

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	
756	822	890	924	926	913	916	919	899	849	777	734	860	cal/cm^2/day
367	400	433	449	450	444	445	447	437	413	378	357	418	W/m^2

To estimate the short wave radiation reaching the earth surface (R_{sk}), the following equation has been used:

$$R_{sk}/R_o = (0.28 + 0.50\ n/N)$$

At Nyala no measurements are available of sunshine duration, so the factor n/N should be estimated. This is done by averaging data from the stations Ghazala Gawazat and El Fasher (see table A.4). To estimate the effective outgoing long wave radiation, R_{long} or the net long wave radiation, use has been made of an empirical expression given by Penman (see table A.5).
The net energy available for evaporation from radiation is the difference between the incoming shortwave radiation and the outgoing long wave radiation. The estimate of this difference for Nyala is included in table A.4.

A2.1.2 Temperature

The observations in Nyala include daily maximum and minimum temperatures. Measurements with a thermograph, giving a continous record

of temperature are not available. The mean daily temperature (table A.4) provided by the Sudan Meteorological Department is the average of the daily maximum and minimum. Although this is usually slightly above the true mean daily temperature, it was used for the Penman calculations.
The annual mean temperature for Nyala is 27.3°c. The hottest month is May with a mean of 30.9 °C and the coldest is January with 23.3°C.
Mean daily maximum is highest in May with 38.4°C, while the maximum temperature ever observed was in April at 43.8°C. Mean daily minimum is lowest in January at 15.5°C with the absolute minimum observed also in January at 5.0°C. All temperature data apply to the period 1951 - 1980.

A2.1.3 Humidity

Relative humidity of air depends upon vapour content and temperature.
It decreases rapidly in the course of the morning and attains its minimum at or shortly past noon, after which it increases until sunrise. In the dry climate of the Nyala area, saturation is only reached during rainstorms. The vapour pressure in this climate does not change much during the day. The most complete record at Nyala is relative humidity data measured at 0600 and 1200 hrs, from the period 1941 - 1970. The average of these values has been used as estimate of the mean daily relative humidity (see table A.4).

In the dry season from November until April, vapour pressures are very low. The arrival of humid air masses precedes the rain season and therefore in May vapour pressures rise, although rainfall still is negligible. During July and August vapour pressures reach a maximum, when rainfall is also at its maximum. The moisture still present in soils and vegetation during September causes continuing high values in this month also, but the recession of the humid air masses to the south soon brings the return of the dry season with its low vapour pressures.

A2.1.4 Wind velocity

In Nyala no observations are made with a wind run meter. The wind force is estimated by visual observation of the movement of palm trees. Such data are of course inaccurate, but had to be used, because more accurate data from nearby stations were not available. To obtain an estimate of the wind velocity at 2 meter above the ground surface, a correction factor of 0.6 was applied.

A2.2 Measuring Evaporation

The direct measurement of the evaporation is most accurately done with evaporation pans. The pan results multiplied with a factor (for class A pans usually 0.6-0.8) correspond with the open water evaporation calculated with the Penman formula. The Nyala meteorological station does not possess an evaporation pan. The nearest stations with comparable climatic conditions where a pan is found are Ghazala Gawazat and Zalingie. Evaporation in the Nyala meteorological station is measured with a Piche evaporimeter. This instrument consists of a small tube filled with water, which is closed by a porous piece of paper. The change in water level in the tube, recorded every day, indicates the water loss by evaporation. The correlation between the data from this instrument and the Penman evaporation varies, with time because the evaporimeter gives a measure of the drying power of the air (the aero-dynamic term in the Penman equation) and not of the total energy balance like Penman.
In Adam (1973) the Penman evaporation estimate was correlated with data from the Piche evaporimeter at 19 stations in Sudan for the period 1963-1971. The ratio between the Penman and Piche evaporation was determined at each station for each month. The ratio suggested for Nyala was applied (see table A.7.). However the results did not appear very accurate.

The WAPS-2 project installed evaporation pans at the WAPS-2 office and at the veterinary laboratory in August 1984.
The conditions at both sites are distinctly different. At the WAPS-2 office on the border of the town, no vegetation is present and conditions are comparable to those at the meteostation.

Table A.7

Average Open Water Evaporation from Pan and Piche Measurements (mm/day)

Month	Pan		Piche		Piche
	Ghazala Gawazat 485m.	Zalingie 900m.	Ghazala Gawazat 485m.	Zalingie 900m.	Nyala met.stat. 655m.
Jan	7.1	4.7	6.2	3.8	6.7
Feb	8.5	5.9	7.3	4.5	7.6
Mar	9.5	6.6	8.2	5.3	8.3
Apr	9.5	7.3	7.9	5.6	8.0
May	8.9	8.1	6.6	5.2	6.9
June	6.7	5.7	6.5	5.3	7.4
Jul	4.1	3.3	5.0	3.5	5.6
Aug	3.3	2.7	4.8	3.5	6.4
Sep	3.6	3.1	5.1	4.5	8.2
Oct	5.4	4.7	4.9	5.3	10.1
Nov	7.1	4.7	5.9	3.7	6.7
Dec	6.7	4.4	6.0	3.6	4.2
Mean	6.7	5.1	6.2	4.5	7.2

Note: 1. Ghazala Gawazat, data 1951-1980
- pan coefficient 0.65
2. Zalingie, data 1967-1976
- pan coefficient 0.65
3. Nyala, data 1951-1980
4. Piche coefficient according Adam (1973)

At the veterinary laboratory conditions are expected to be similar to those prevailing in the area of the gardens along the wadi.
The objective of the measurements was to study the difference in the evaporation between both locations (table A.8).
The evaporation at the veterinary laboratory is lower, mainly due to the higher humidity and the lesser exposure of the site. The data indicate that the evaporation is between 50-70% of the evaporation at the site of the WAPS-2 office (see table A.8.).
The absolute values have a poor relation with the calculated Penman evaporation rate. An explanation for this phenomena is not clear but it probably is related to a poor estimate of the net radiation in the Penman calculation. Temperature measurements of the water in the pan indicate that the water is cooler than the air, which conflicts with Penman's assumption of equal temperatures.

The evaporation pans are covered by a wire mesh for protection. The applied pan coefficient should take into account the effect of this cover on the evaporation. However it was not possible to determine an accurate estimate of the pan coeffecent during the WAPS-2 project period. The pan coefficients were preliminarly determined at 0.75.

A2.3 The Evaporation at Nyala

The calculated Penman evaporation at Nyala is based on the data from the meteorological station, which is situated in an area without vegetation. The evaporation near the wadi is expected to be different because of the presence of green vegetation and irrigation practises. To obtain the potential evaporation estimate for the garden area a correction was applied to the Penman estimate based on the pan measurements carried out by WAPS-2 at the veterinary laboratory (see table A.9).

Table A.8 Evaporation Data at Nyala 1983-1985

Year	Month	Meteorological Station: Mean Temp. (°C)	Mean humid. (%)	Piche (1)	Piche (2)	Penman (mm/day)	WAPS-2 off. Pan (3)	Vet.Lab. Pan (3)
1983	Jan	19.0	16	17.3	6.9	4.3		
	Feb	24.8	13	21.2	8.5	5.6	Remark:	
	Mar	26.3	9	20.9	8.4	6.2	Pans installed	
	Apr	30.5	8	-	-	6.3	August 1984	
	May	32.4	20	18.6	7.4	7.4		
	Jun	31.2	41	13.9	8.3	7.0		
	Jul	28.6	27	8.9	7.1	6.2	-	-
	Aug	28.5	59	7.4	5.9	6.2	-	-
	Sep	29.0	-	9.6	5.8	6.6	-	-
	Oct	data not available					-	-
	Nov	data not available					-	-
	Dec	data not available					-	-
1984	Jan						-	-
	Feb	26.4	9	19.7	7.9	5.7	-	-
	Mar	30.0	9	21.3	8.5	6.1	-	-
	Apr	31.5	7	23.2	9.3	6.4	-	
	May	32.2	24	18.5	7.4	6.8	-	
	Jun	30.9	36	13.7	8.2	6.7		
	Jul	27.7	50	8.4	6.7	6.0	-	
	Aug	28.8	52	9.7	7.8	6.2	7.2	4.7
	Sep	28.8	48	10.5	6.3	6.4	6.6	3.8
	Oct	30.2	23	17.5	7.0	6.4	11.0	5.9
	Nov	-	-	-	-	-	9.6	5.7
	Dec	-	-	-	-	-	9.0	4.2
1985	Jan	26.6	14	17.9	7.2	5.0	-	6.5
	Feb	22.6	10	19.2	7.7	5.3	-	6.3
	Mar	29.8	13	20.3	8.1	6.3	11.2	7.4
	Apr	31.2	16	-	-	7.0	11.8	8.0
	May	31.6	27	11.5	4.6	7.3	8.8	7.1
	Jun	30.6	38	13.2	7.9	6.8	10.0	5.8
	Jul	27.0	62	8.0	6.4	5.9	5.7	-
	Aug	27.2	64	7.2	5.8	6.0	4.7	3.2
	Sep	27.7	55	8.0	4.8	6.2	5.5	3.2

(1) Measurement from evaporimeter.
(2) Corrected measurement (free after Adam (1973):
ratios: Oct-May 0.4, June 0.6 Jul-Aug 0.8, Sep 0.6
(3) Pan Coefficient 0.75

Table A.9 Determination of Potential Evaporation (in mm/day) in the Garden Area of Nyala.

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Met. Station.	4.8	5.5	6.2	6.7	6.8	6.6	5.9	5.8	6.2	6.3	5.6	4.9	5.9
Correction (%)	110	120	120	110	100	90	80	70	70	90	100	100	97
Garden Area	5.3	6.6	7.4	7.4	6.8	5.9	4.7	4.1	4.3	5.7	5.6	4.9	5.7
Season	dry						wet			dry			

The correction enhances the difference in evaporation between the wet and dry season. The annual evaporation is reduced to 2090 mm, or 5.7 mm/day. The accuracy of the correction however is limited, because at present only one year of pan-measurements are available. It is therefore important that the pans are continued to be used in the coming years, to achieve a better estimate of the evaporation in the garden area.

A2.4 Determination of Potential Evapotranspiration at Wadi Nyala

The potential evapotranspiration was determined using an evaporation of 1660 mm for the dry season (September 15-June 15) and 430 mm for the wet season (based on table A.9). A crop coefficient has been applied distinguishing between the following types of vegetation:

- orchards, mainly mango trees, but also citrus and guava.
- vegetables, like tomatoes, peppers, berseem.
- forest planted by man.
- natural forest, less dense, consisting mainly of Dom palms and Acacia.
- natural bushy vegetation and grass, sparsely covering the land.
- no vegetation, wadi sands

Basically the same crop coefficients were applied as these derived for the evapotranspiration calculations in the Kassala Gash Basin project (1982).

Table A.10 Potential Evapotranspiration PE (mm)

Vegetation type	Crop coefficient		Pot. Evapotranspiration	
	Dry season	Wet season	Dry season	Wet season
Orchards	0.8	0.8	1330	345
Vegetables	0.8	0.8	1330	345
Man made Forest	0.8	0.8	1330	345
Natural Forest	0.6	0.6	995	260
Wild bushes	0.3	0.5	500	215
Wadi Sands	0.1	0.3	165	130

A2.5 Determination of Actual Evapotranspiration

The agricultural area was divided considering land use into irrigated and non-irrigated agriculture. For areas which are irrigated it was assumed that evapotranspiration occurs at the potential rate. In areas which are not irrigated, the actual evapotranspiration (AE), depends on the availability of soil moisture and the depth to the groundwatertable. A reduction factor was used for the dry season to take the shortage in soil moisture into account.

For the wet season, the AE was assumed to equal the PE (see table A.12).

The area for which the different land use types were determined falls within the boundaries of the area covered by the aquifer, as shown on Map 3. Aerial photography of 1984 was used for the Town Area and of 1974 for the Downstream Area to identify the land use types.

Table A.11

Area of Land Use Types in Dry and Wet Season (in km^2)

Land Use	Town Area		Downstream Area		Total Area	
	Dry	Wet	Dry	Wet	Dry	Wet
Orchards:irrigated	0.70	0.30	0.4	0.2	1.1	0.5
not irrigated	0.34	0.74	0.3	0.5	0.6	1.2
Vegetables: irrigated	0.10	0.10	0.3	0.2	0.4	0.3
not irrigated	-	0.15	-	0.6	0.2	0.8
Man-made forest	0.02	0.02	1.2	1.2	1.2	1.2
Natural forest	-	-	8.5	8.5	8.5	8.5
Bare soils with bushes (incl.town area)	0.62	0.47	1.7	1.2	2.3	1.7
Wadi	1.44	1.44	1.8	1.8	3.2	3.2
Total	3.22	3.22	14.2	14.2	17.4	17.4

Table A.12

Actual Evapotranspiration (AE)

Land Use	Reduction Factor		AE (mm)		Evapotranspiration ($10^6 m^3$) Town Area		Downstream Area	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Orchards: irrigated	1.0	1.0	1330	345	0.93	0.10	0.53	0.07
not irrigated	0.7	1.0	930	345	0.32	0.26	0.28	0.17
Vegetables: irrigated	1.0	1.0	1330	345	0.13	0.03	0.40	0.07
not irrigated	0.2	1.0	265	345	-	0.05	-	0.21
Man-made forest	0.7	1.0	930	345	0.02	0.01	1.12	0.41
Natural forest	0.7	1.0	695	260	-	-	5.91	2.21
Bare soils with bushes	0.3	1.0	150	215	0.09	0.10	0.26	0.26
Wadi	0.3	1.0	50	130	0.07	0.19	0.09	0.23
Total					1.56	0.74	8.59	3.63

APPENDIX A3

DISCHARGE MEASUREMENTS WADI NYALA

From the bridge across the wadi at Nyala, which was constructed in 1983, flow velocity measurements were carried out using a propellor with a 10, 25 or 50 kg sinkerweight. The propellor was lowered from the bridge using a winch mounted on a landrover.
Unfortunately, velocity measurements with the propellor were not possible during high flood stages. The wadi is then transformed into a wide, wild flowing river, carrying large quantities of sediment, while also big logs and sometimes trees float down the river. The tremendous flow velocities (up to 5 m/s) and accompanying turbulences made it impossible to carry out discharge measurements.
Under conditions of lower discharge, the maximum flow velocities measured with the propellor, using the 50 kg weight, reached 2.4 m/s. The results of the discharge measurements are summarised in table A.13. In total, 41 measurements were carried out in 1983, 10 in 1984 and 29 in 1985.

The water levels at the bridge, observed from a staff gauge were for each flood correlated with the water levels recorded at the station, located 1.2 km upstream from the bridge. Accordingly, a continuous water level record was obtained at the bridge.

The relation between discharge and water level at the bridge was established and expressed in a rating curve. Using this curve, hourly discharges at the bridge were determined, from which the daily discharge of the wadi was estimated (see tables A.14-A.16)
It turned out to be necessary to construct separate rating curves for almost each flood (see figures A.2-A.4) In total, six rating curves were established for 1983, five for 1984 and 29 for 1985.

The wadi bed, consisting of loose sands is very unstable, due to the flashy nature of the floods. The wadi is capable of transporting large quantities of sediments and along its course are areas of erosion and sedimentation which shift continously, e.g. after one flood at the bridge, bed levels might be lowered while after the next flood, the deposition of sediment can result in a higher elevation of the bed. The discharge at higher water levels during which no velocity measurements were possible was estimated by extending the rating curves. This extension is allowed, because the cross-section of the wadi is constant between the bridge abutments.

Crest gauges were installed at the runoff station and the bridge to record maximum flood levels. This gauge consists of a two meter long 2" pipe, which contains a graded wooden staff. Chalk applied on the staff, is washed off by the rising flood water, leaving a clear mark of the maximum level, when the flood recedes.

Some of the peak discharges were estimated using data from these crest gauges. However, it must be noted that the slope-area method used is not very reliable for rivers with changing cross-section, like the Wadi Nyala. This is demonstrated with the estimation of the maximum discharge of 1983, which occurred on July 24, 1983. It was estimated with the slope-area method at 315 m^3/s. The extension of the rating curve to the maximum flood level of 1.90 m shows however, a discharge of approximately 500 m^3/s. This latter figure seems more likely, considering the maximum flow velocity at the time of the peak, which was approximately 5 m/s in the centre of the wadi.
Considering also the deepening of the wadi bed during such flows, the estimate from the slope-area method must be conservative. Subsequently, the estimate of 500 m^3/s was applied for the peak flow on July 24, 1983.
Table A.17 gives a summary of the main peak flows, observed at Nyala during 1983, 1984 and 1985.

Table A.13
Discharge Measurement Summary   Location: Mekkah Bridge, Wadi Nyala
1983

Meas. No	Date	Time (hrs)	Staff Height(m)	Width (m)	Area (m^2)	Velocity (m/s)	Discharge (m^3/s)
	1983						
1	27-06	8.30	0.84	98.00	45.47	1.046	47.546
2	27-06	10.00	0.745	84.50	30.68	0.856	26.270
3	17-07	8.30	0.71	90.00	70.63	0.736	51.952
4	17-07	12.00	0.48	80.50	40.46	0.399	16.12
5	17-07	13.00	0.42	78.25	39.44	0.310	12.242
6	24-07	17.30	0.70	130.25	85.26	1.17	99.891
7	24-07	18.00	0.64	130.00	86.41	0.874	68.703
8	25-07	8.00	0.24	62.75	19.30	0.735	14.188
9	25-07	9.00	0.22	62.50	19.5	0.712	13.891
10	26-07	7.40	0.64	81.75	36.53	1.101	40.21
11	26-07	8.30	0.615	80.50	34.53	1.089	37.63
12	26-07	11.00	0.585	79.75	31.129	0.863	26.859
13	26-07	12.00	0.585	78.75	25.891	0.951	24.625
14	26-07	16.30	0.44	69.75	21.59	0.575	12.419
15	26-07	17.00	0.425	69.75	21.01	0.602	12.641
16	27-07	8.50	0.26	34.75	6.79	0.561	3.797
17	27-07	9.09	0.25	36.00	8.16	0.548	4.48
18	29-07	2.00	0.605	94.50	27.466	0.752	20.66
19	30-07	1.10	0.64	96.00	30.2	0.810	24.468
20	31-07	7.35	0.37	41.50	7.5	0.487	3.65
21	01-08	8.15	0.66	72.25	28.226	0.745	21.026
22	01-08	9.00	0.65	83.85	28.032	0.665	18.63
23	01-08	16.45	0.58	81.00	23.48	0.595	13.964
24	02-08	7.35	0.54	76.00	21.075	0.526	11.077
25	02-08	7.50	0.64	83.00	26.014	0.627	16.317
26	06-08	12.50	0.40	61.75	10.476	-----	------
27	14-08	8.25	0.61	88.00	22.26	0.616	13.714
28	14-08	9.00	0.60	88.00	21.441	0.603	12.933
29	14-08	13.00	0.53	80.00	14.404	0.454	6.533
30	15-08	8.00	0.66	92.00	24.753	0.545	13.48
31	15-08	8.50	0.64	79.75	23.322	0.638	14.877
32	24-08	8.10	0.60	86.00	19.57	0.514	10.064
33	24-08	8.50	0.60	86.00	18.554	0.452	8.385
34	28-08	8.20	1.11	101.00	58.522	1.609	94.146
35	28-08	9.30	0.89	105.00	43.204	1.486	64.221
36	28-08	13.00	0.77	75.25	36.306	0.936	33.978
37	28-08	13.55	0.74	97.00	33.579	0.900	30.222
38	13-09	8.05	0.57	75.00	14.628	0.465	6.798
39	15-09	8.45	0.54	75.00	10.203	0.370	3.777
40	15-09	11.55	0.67	78.00	23.407	0.620	14.505
41	15-09	12.25	0.62	78.00	20.291	0.530	10.758

Table A.13 (cont.)

Discharge Measurement Summary   Location: Mekkah Bridge, Wadi Nyala

1984 - 1985

Meas. No.	Date	Time (hrs)	Staff Height(m)	Width (m)	Area (m^2)	Velocity (m/s)	Discharge (m^3/s)
	1984						
1	05-07	16.00	1.27	142.50	106.44	1.946	207.092
2	05-07	17.00	1.05	138.75	68.46	1.463	100.178
3	04-08	13.00	0.30	58.75	9.26	0.566	5.243
4	04-08	14.00	0.26	60.00	7.73	0.553	4.274
5	12-08	9.00	0.35	60.50	13.90	0.457	6.346
6	14-08	8.45	0.58	Instrument failure			-
7	27-08	8.30	0.44	23.00	4.36	0.436	1.899
8	27-08	9.00	0.425	23.20	3.75	0.378	1.419
9	04-09	12.30	0.505	87.50	17.82	0.301	5.366
10	04-09	13.00	0.495	87.50	16.70	0.281	4.688
11	24-09	9.30	0.46	66.50	12.33	0.39	4.82
	1985						
1	30-06	8.00	0.645	52.50	20.66	0.491	10.140
2	30-06	14.30	0.59	73.25	21.55	0.688	14.828
3	30-06	15.00	0.58	73.25	21.80	0.685	14.941
4	06-07	11.00	1.00	87.50	99.0	1.46	144.7 ?
5	06-07	16.30	0.595	63.75	26.70	1.170	30.747
6	06-07	17.30	0.565	56.25	23.62	1.139	26.911
7	11-07	17.00	0.925	92.00	53.0	1.707	90.50
8	11-07	18.30	0.80	92.00	52.90	1.227	64.923
9	12-07	9.00	0.49	57.25	18.19	0.875	15.924
10	12-07	9.30	0.475	56.25	19.50	0.720	14.045
11	15-07	15.00	0.695	90.00	48.05	0.802	38.552
12	15-07	16.00	0.645	90.00	50.61	0.638	32.310
13	27-07	12.30	1.025	102.50	46.92	1.832	85.960
14	27-07	13.30	0.875	101.25	44.06	1.470	64.789
15	30-07	15.00	0.69	85.75	89.37	1.081	96.620
16	30-07	16.00	0.675	86.25	83.85	1.021	85.637
17	02-08	12.00	0.79	100.75	69.96	0.966	67.571
18	02-08	12.30	0.77	101.75	71.15	0.839	59.673
19	15-08	13.30	1.30	Not complete, instrument failure!			
20	11-09	9.00	0.575	69.50	76.59	0.956	73.240
21	11-09	9.30	0.54	63.00	68.56	0.981	67.242
22	11-09	9.00	0.515	64.00	63.09	0.92	58.1
23	11-09	13.30	0.45	64.75	44.57	0.785	34.981
24	11-09	14.00	0.435	64.75	49.63	0.637	31.638
25	12-09	9.00	0.115	63.75	13.01	0.441	5.740
26	12-09	9.30	0.105	63.75	11.70	0.401	4.697
27	23-09	10.00	1.125	78.50	90.81	1.954	177.453
28	23-09	14.30	0.675	53.50	32.11	1.004	32.228
29	23-09	15.30	0.625	52.50	28.98	0.917	26.594

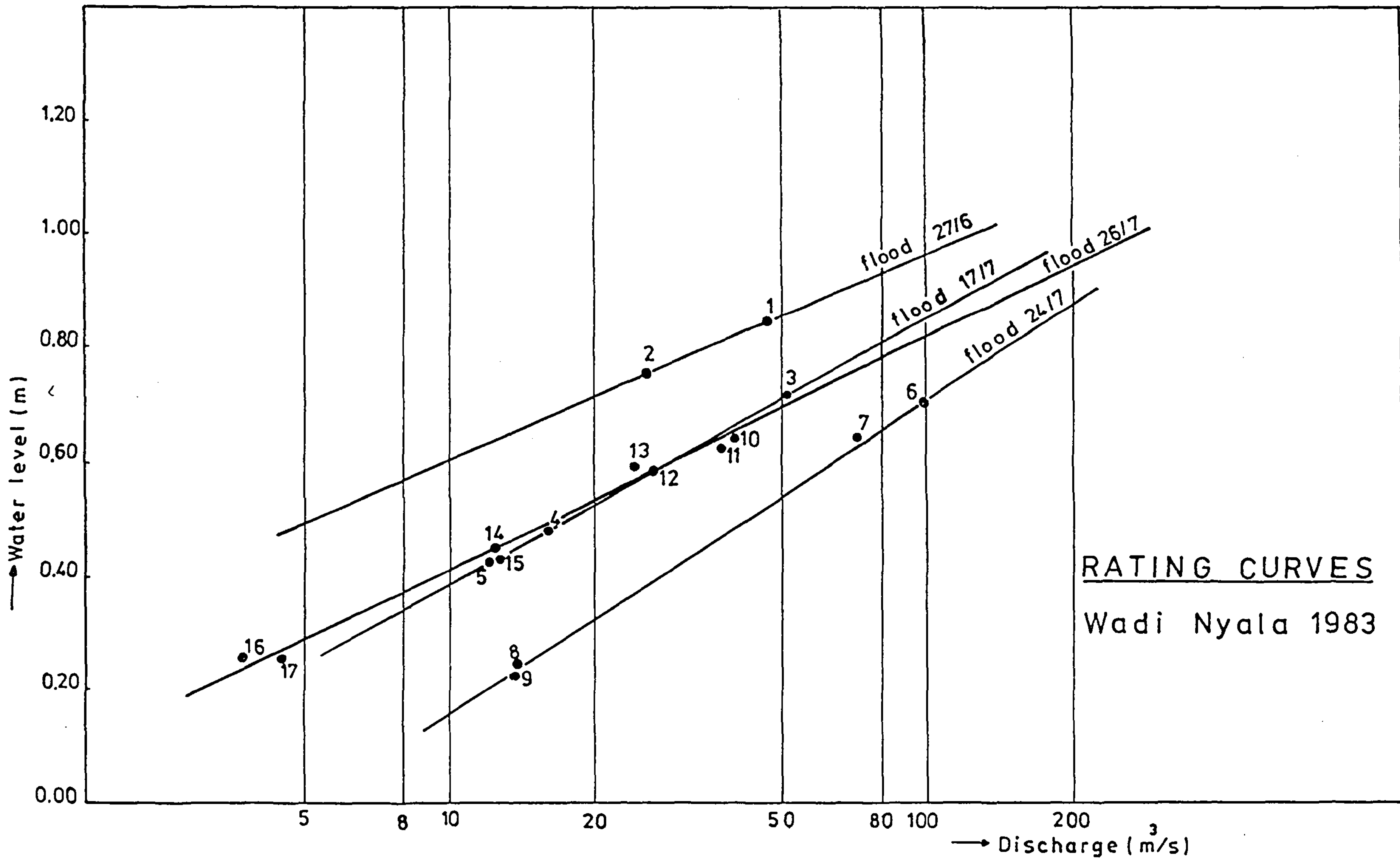

RATING CURVES
Wadi Nyala 1983
flood 27/6
flood 17/7
flood 26/7
flood 24/7
Water level (m)
Discharge (m3/s)
0.00
0.20
0.40
0.60
0.80
1.00
1.20
5
8
10
20
50
80
100
200

Figure A.2

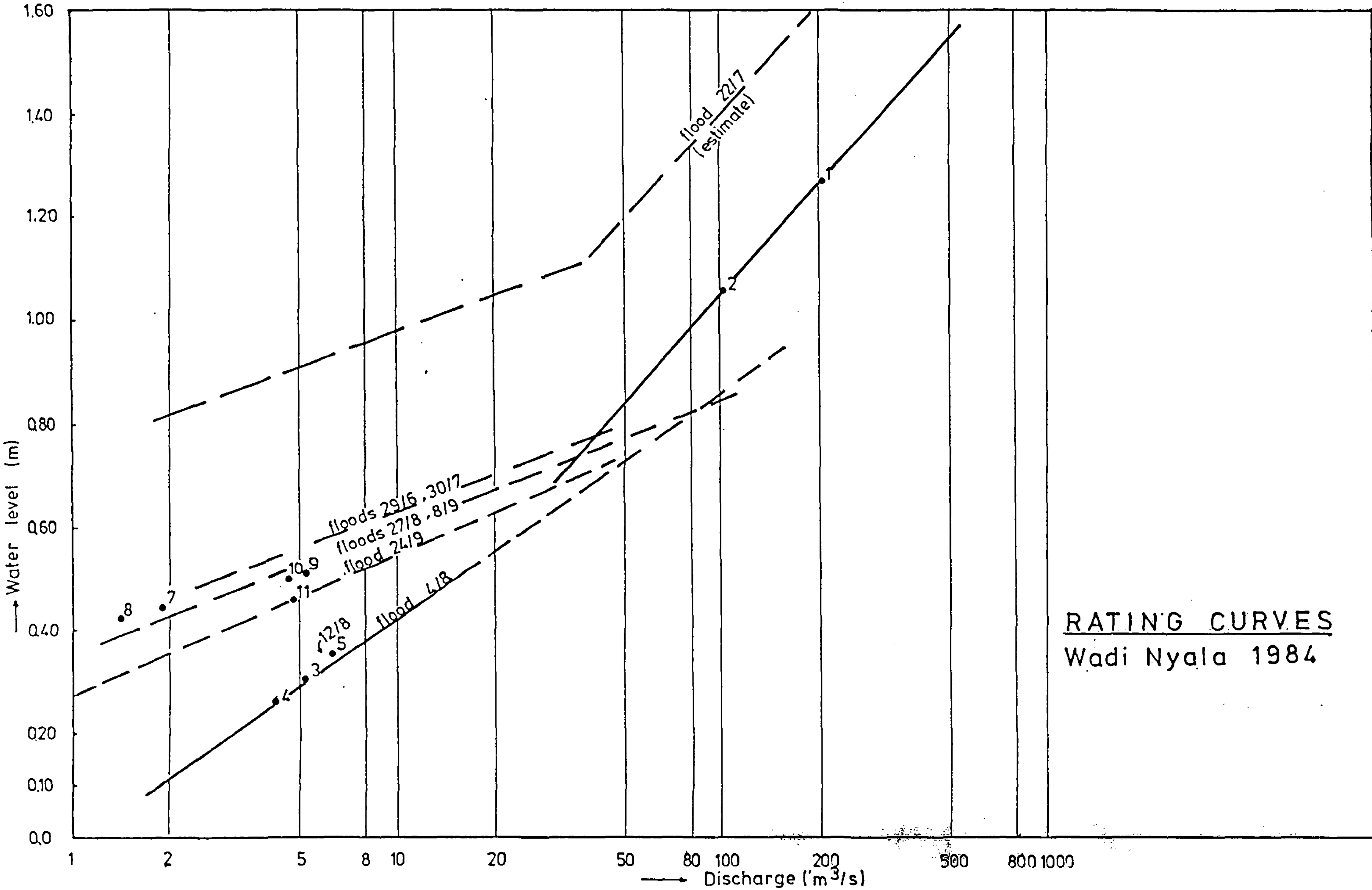
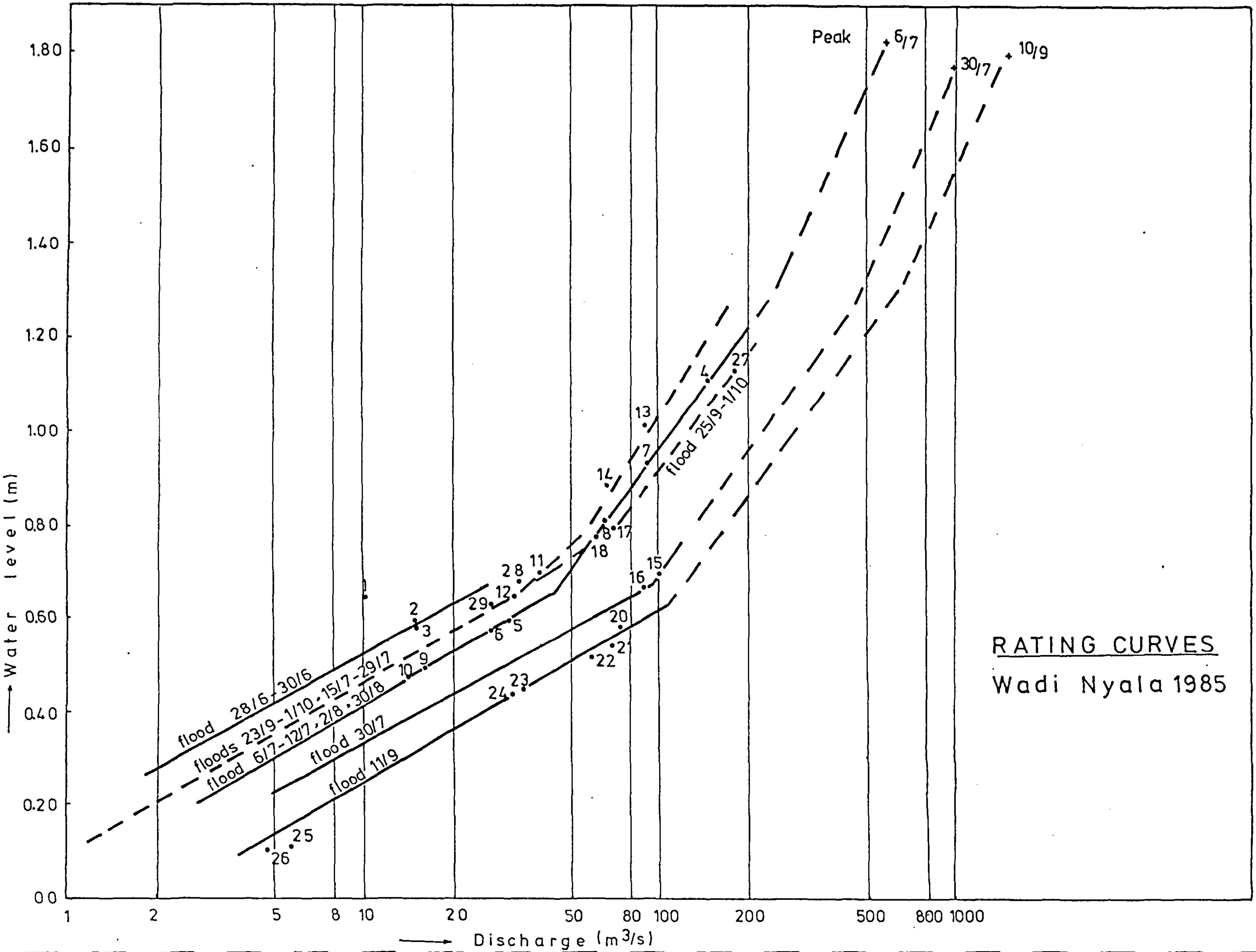

RATING CURVES
Wadi Nyala 1984
Water level (m)
Discharge (m3/s)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.10
0.0
1
2
5
8
10
20
50
80
100
200
500
800
1000
flood 22/7 (estimate)
floods 29/6, 30/7
floods 27/8, 8/9
flood 24/9
flood 4/8
12/8
1
2
3
4
5
7
8
9
10
11

Figure A.3



RATING CURVES
Wadi Nyala 1985
Water level (m)
Discharge (m3/s)
Peak 6/7
30/7
10/9
flood 28/6 - 30/6
floods 23/9 - 1/10 - 15/7 - 29/7
flood 6/7 - 12/7 - 2/8 - 30/8
flood 30/7
flood 11/9
flood 25/9 - 1/10

Figure A.4

DAILY RECORD OF HYDRO-METEOROLOGICAL DATA

Table A.14

STATION NAME: Wadi Nyala
LAT : 12° 03′ LONG : 24° 52′
ALTITUDE : 658 m

DATA : Daily Runoff
UNIT : 10^6 m^3/day
YEAR : 1983

DAT.	JAN.	FEB.	MAR.	APR.	MAY.	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
1								1.9				
2								1.6				
3								1.1				
4								0.2				
5								0.1				
6						0.1		0.6				
7						0.1		2.1				
8								1.0				
9								0.4				
10							2.4	0.7				
11							1.6	0.1				
12							0.2	2.9	0.4			
13						0.3		0.6	2.1			
14								1.2	0.5			
15								1.0	1.2			
16					0.1			0.1	0.4			
17							4.9		0.4			
18							0.1					
19												
20												
21												
22												
23								0.3				
24							12.0	0.6				
25							3.6					
26							2.9					
27						2.6	0.3	0.5				
28							1.6	0.4				
29							1.0	0.2				
30							0.8	0.4				
31							0.3	0.6				
TOT.					0.1	3.1	31.7	21.6	6.5			

ANNUAL TOTAL : 63.0×10^6

DAILY RECORD OF HYDRO-METEOROLOGICAL DATA

Table A.15

STATION NAME : Wadi Kyala

LAT : 12° 03′ LONG : 24° 52′

ALTITUDE : 658 m

DATA : Daily Runoff

UNIT : $10^6 m^3$/day

YEAR : 1984

DAT.	JAN.	FEB.	MAR.	APR.	MAY.	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
1							0.7	-	-			
2							0.7	-	-			
3								0.1	-			
4								0.2	0.2			
5							0.7	-	0.1			
6							2.2	-	0.1			
7							0.2	-	0.1			
8								-	0.1			
9								-	-			
10								-	-			
11								0.1	-			
12								0.4	-			
13								0.1	-			
14								1.0	-			
15								0.1	-			
16								0.1	-			
17								0.1	-			
18								0.1	-			
19								0.1	-			
20								0.1	-			
21								0.1	-			
22							0.2	0.1	-			
23							0.1	0.1	1.6			
24								0.1	0.4			
25								-	0.1			
26								0.5	0.7			
27								0.5	0.2			
28							0.5	0.1	0.2			
29						0.3	0.5	0.1	-			
30						0.1	0.1	-	-			
31						-	-	-	-			
TOT.						0.4	5.9	4.1	3.8			

ANNUAL TOTAL : 14.2 x $10^6 m^3$

DAILY RECORD OF HYDRO-METEOROLOGICAL DATA

Table A.16

STATION NAME: Wadi Nyala
LAT: 12° 03′ LONG: 24° 52′
ALTITUDE: 658 m

DATA: Daily Runoff
UNIT: $10^6 m^3$/day
YEAR: 1985

DAT.	JAN.	FEB.	MAR.	APR.	MAY.	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
1						-	0.3	0.1	0.1	0.0		
2						-	0.1	5.5	0.1	0.0		
3						-	-	0.7	1.3	0.0		
4						-	-	0.2	0.5	0.0		
5						-	-	0.1	0.1	0.0		
6						-	7.6	0.1	0.1	-		
7						-	0.3	0.1	0.1	-		
8						-	0.1	0.1	0.0	-		
9						-	0.4	0.4	0.0	-		
10						-	0.1	0.1	14.4	-		
11						-	8.8	0.8	16.8			
12						-	1.2	2.4	0.4			
13						-	0.3	1.3	0.1			
14						-	0.2	0.4	0.1			
15						-	4.4	6.0	0.1			
16						-	0.3	0.5	0.1			
17						0.3	0.1	0.2	0.0			
18						0.2	0.1	0.1	0.0			
19						-	0.1	0.1	0.0			
20						0.1	0.9	0.1	0.0			
21					-	-	1.2	0.1	0.0			
22					-	-	0.2	0.1	0.0			
23					-	0.4	0.1	0.0	3.5			
24					-	0.2	0.1	0.0	0.2			
25					0.1	-	0.1	0.0	0.1			
26					-	-	0.1	0.0	0.1			
27					-	-	2.4	0.0	0.0			
28					-	1.1	0.7	0.2	0.0			
29					-	0.5	0.2	0.1	0.0			
30					-	1.2	13.3	5.0	0.0			
31					-		0.4	0.4				
TOT.					0.1	4.0	44.1	2[illegible].0	3[illegible].2	0.0		

ANNUAL TOTAL 112.4

Remarks: 0.0 indicates small flow
- indicates no flow

Table A.17
The Main Flood Peaks in Wadi Nyala during 1983-1985

Date	Time of peak (hrs)	Maximum waterlevel at bridge (m)	Duration of flood (hrs)	Maximum discharge (m^3/s)	Total Flood discharge ($\times 10^6$ m^3)
1983					
27-06	0500	1.11	45	150	2.6
11-07	1000	0.98	38	110	1.7
17-07	0500	1.70	94	425	5.0
24-07	1200	1.90	38	500	13.0
25-08	2300	1.13	59	300	5.7
07-08	1000	1.20	30	180	2.1
12-08	1800	1.36	33	180	4.1
28-08	0500	1.40	42	135	3.6
13-09	2100	1.14	36	150	1.8
1984					
01-07	2300	1.07	14	102	1.4
05-07	1500	1.40	31	100	0.7
06-07	2200	2.54	40	600	2.4
26-08	2300	0.90	74	100	1.2
23-09	1400	1.00	61	85	2.1
1985					
28-06	1900	1.13	24	155	1.3
06-07	0800	1.83	65	600	8.0
11-07	1100	1.48	continuous flow	330	10.5
15-07	0800	1.55		260	4.7
30-07	1100	1.86		1000	13.7
02-08	0500	1.20		185	6.4
11-08	2300	1.30		120	3.2
15-08	0900	1.65		300	7.5
30-08	1100	1.40		400	5.4
03-09	2000	1.00		110	1.8
10-09	2400	1.85		1500	31.6
23-09	1000	1.15		190	3.9

Note: Peak discharges were estimated with the slope-area method using Mannings equation:

$$Q = \frac{A\, R^{2/3}\, s^{1/2}}{n}$$

with A= area
R= hydraulic radius
s= slope of watertable
n= roughness coefficient
= 0.035

APPENDIX B

ELECTROMAGNETIC SURVEY

During the WAPS-2 project an electromagnetic method of investigation is applied for the first time in the Sudan for a groundwater study. Hence a more detailed description of the principles of the method will be given here.

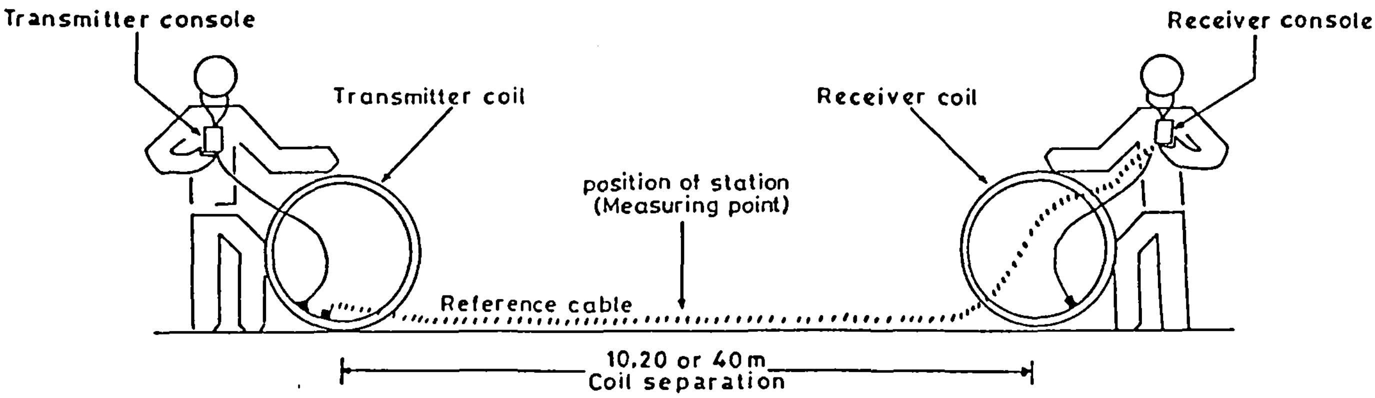
B.1 Principles

The electromagnetic (EM) method is based on the measurement of magnetic fields associated with alternating currents induced in the earth by a primary, time varying magnetic field (H_p). This primary magnetic field can be produced by an artificial source by means of passing an AC current through a transmitter coil (or primary loop). The frequency usually applied, is between a few hundred and several thousand hertz, depending on the EM system used. The induced, very small currents in the subsurface depend on the conductivity of the sediments and rocks through which they flow, creating a secondary magnetic field (H_s).

Usually the primary and secondary fields have different directions and phases. The combined result of the primary magnetic field due to the transmitter and the secondary magnetic field can be detected at some distance from the primary coil, using a second coil. The second, receiver coil is connected with a device which indicates the ground conductivity, making use of the ratio of the amplitude and phase of the secondary and primary magnetic field. A clear and extensive description of the theory and applications of the EM method is given in Telford et al (1976). There are many EM systems using different sources (natural or artificial), different configuration, and measuring different parts of the total resulting magnetic field. For this project use have been made of a moving, artificial source system, the Em 34-3 of Geonics. For a detailed discussion of the system see McNeill (1980).

Some important incorporations in the design of the EM 34-3 system will be discussed here. Its instrumentation and the field technique are described in the next sections.

Figure B.1:
Vertical Coplanar Loop Mode (VL Mode) of Operation EM34-3 System



Both a vertical loop (VL) configuration, with the coils in a vertical co-planar position (see figure B.1) and a horizontal loop (HL) configuration, with the coils in a horizontal alignment, have been applied. The HL configuration (or mode) is also known as the Slingram method.

The possible penetration depths at various intercoil spacings, for both modes of operation are listed in table B.1.

Table B.1: Possible Exploration Depths for the EM34-3 System at Various Intercoil Spacings.

Intercoil spacing s(m)	Frequency f(Hz)	Exploration depth (m) VL	HL
10	6400	7.5	15
20	1600	15	30
40	400	30	60

As the subsurface is inhomogeneous, the measured conductivity value is the total effect of the electrical conductivity properties of all the ground material within the penetration depth of a certain coil configuration and spacing. The quantity so obtained is defined as the 'apparent conductivity', and has the dimension of milliSiemens per meter (mS/m). This dimension is equal to millimho per meter (mmho/m) which was previously in use.

The apparent conductivity is inversely proportional to the apparent resistivity. To convert the readings of the EM survey into apparent resistivity values, use is made of the relation:

$$\text{apparent resistivity } (\Omega m) = \frac{1000}{\text{apparent conductivity (mS/m)}}$$

e.g. 40 mS/m is equivalent to 25 Ωm.

The expected ranges of electrical resistivities and conductivities of the unconsolidated sediments and the rocks of the survey area are listed in table B.2.

Table B.2: Range of Electrical Resistivities and Conductivities of Sediments and Rocks.

Type of sediments/rocks	Resistivity range (Ωm)	Conductivity range (mS/m)
Sand; dry	1 000 - 10 000	0.1 - 1.0
Sand; saturated with fresh water	50 - 500	2 - 20
Sandy clay	20 - 50	20 - 50
Clay	2 - 40	25 - 500
Schist, granite;weathered	100 - 1 000	1 - 10
Schist; fresh	300 - 3 000	0.3 - 3.3
Quartzite; fresh	1 000 - 10 000	0.1 - 1.0
Granite, gneiss; fresh	1 000 - 10 000	0.1 - 1.0

Under certain conditions, technically defined as operation at low values of induction number B, the apparent conductivity of the subsoil is a very simple function of the intercoil spacing s, the operating frequency f, and the secondary magnetic field H_s. These conditions are incorporated in the design of the instrument; the indicated apparent conductivity σ_a is defined by:

$$\sigma_a = \frac{2}{\pi f \mu_o s^2} \left(\frac{H_s}{H_p} \right)_{\text{quadrature component}}$$

where

σ_a = apparent conductivity of the ground (mS/m)

f = operating frequency (Hz)

μ_o = magnetic permeability of free space (H/m)= $4\pi x10^{-7}$ H/m

s = intercoil spacing (m)

H_s = secondary magnetic field at the receiver coil (A/m)

H_p = primary magnetic field at the receiver coil (A/m)

quadrature component = 90° out of phase component of the magnetic field ratios picked by the receiver

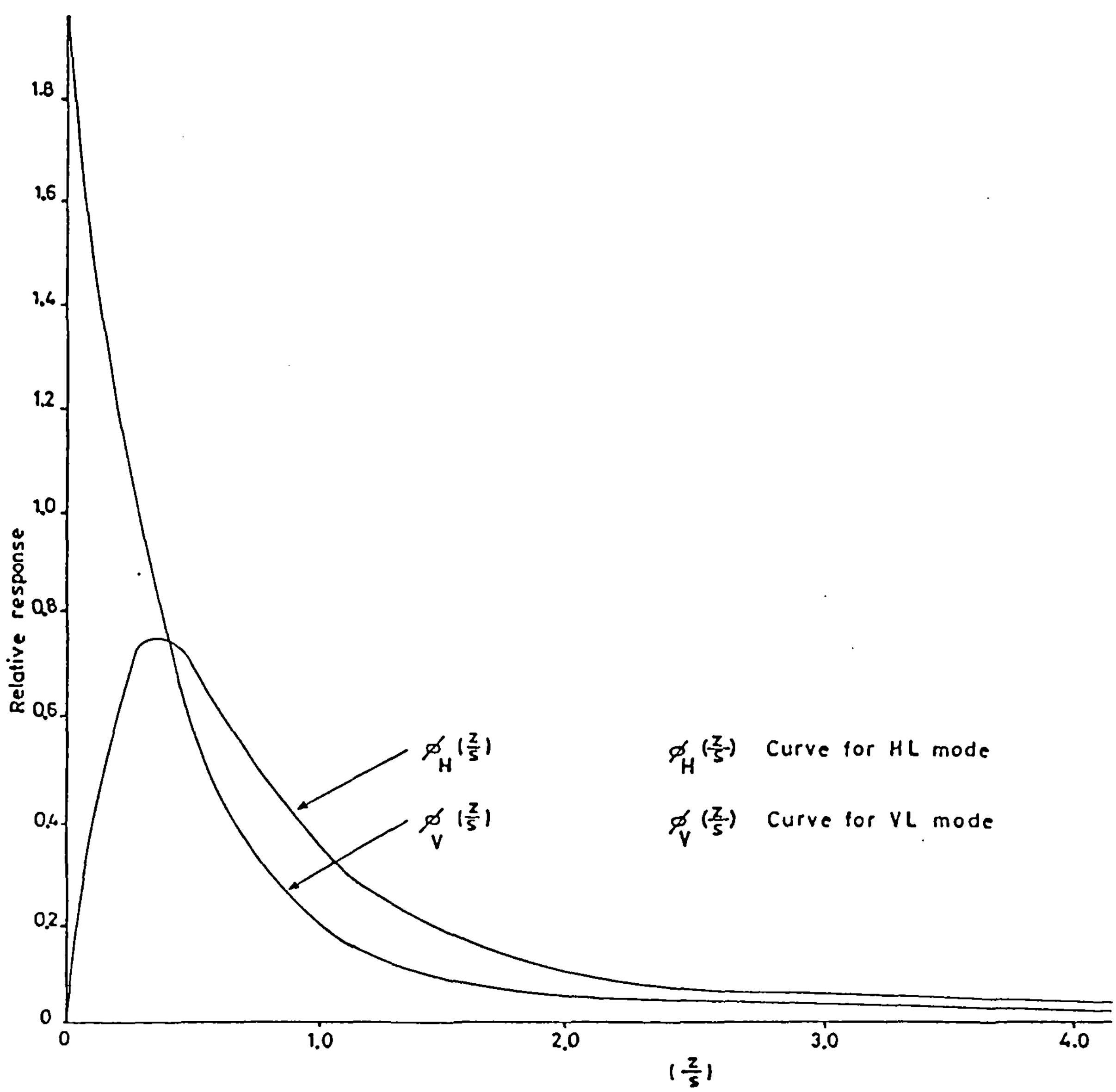
The in-phase component is considered to be zero.
The definition holds for both the VL and HL configuration.
Operating at low values of B means, that the ratio of the intercoil spacing (s) and the electrical skin depth (δ) is much less than unity. Electrical skin depth

$$\delta = \sqrt{\frac{1}{\pi \mu_o \sigma f}}$$

It can be shown that this is equivalent to stating that: over either uniform halfspaces or a horizontally stratified earth no magnetic coupling between current loops occurs.
Furthermore it can be shown, that for any value of B and for any orientation of the coils over either a uniform halfspace or a horizontally stratified earth, all current flow is horizontal. This is of great importance in simplifying the interpretation. Varying the conductivity of any layer will proportionately vary only the magnitude of the current in that layer. To calculate the resultant magnetic field H_s at the surface of a horizontally layered earth it is simply necessary to calculate the independent contribution from each layer, which is a function of its depth and conductivity, and

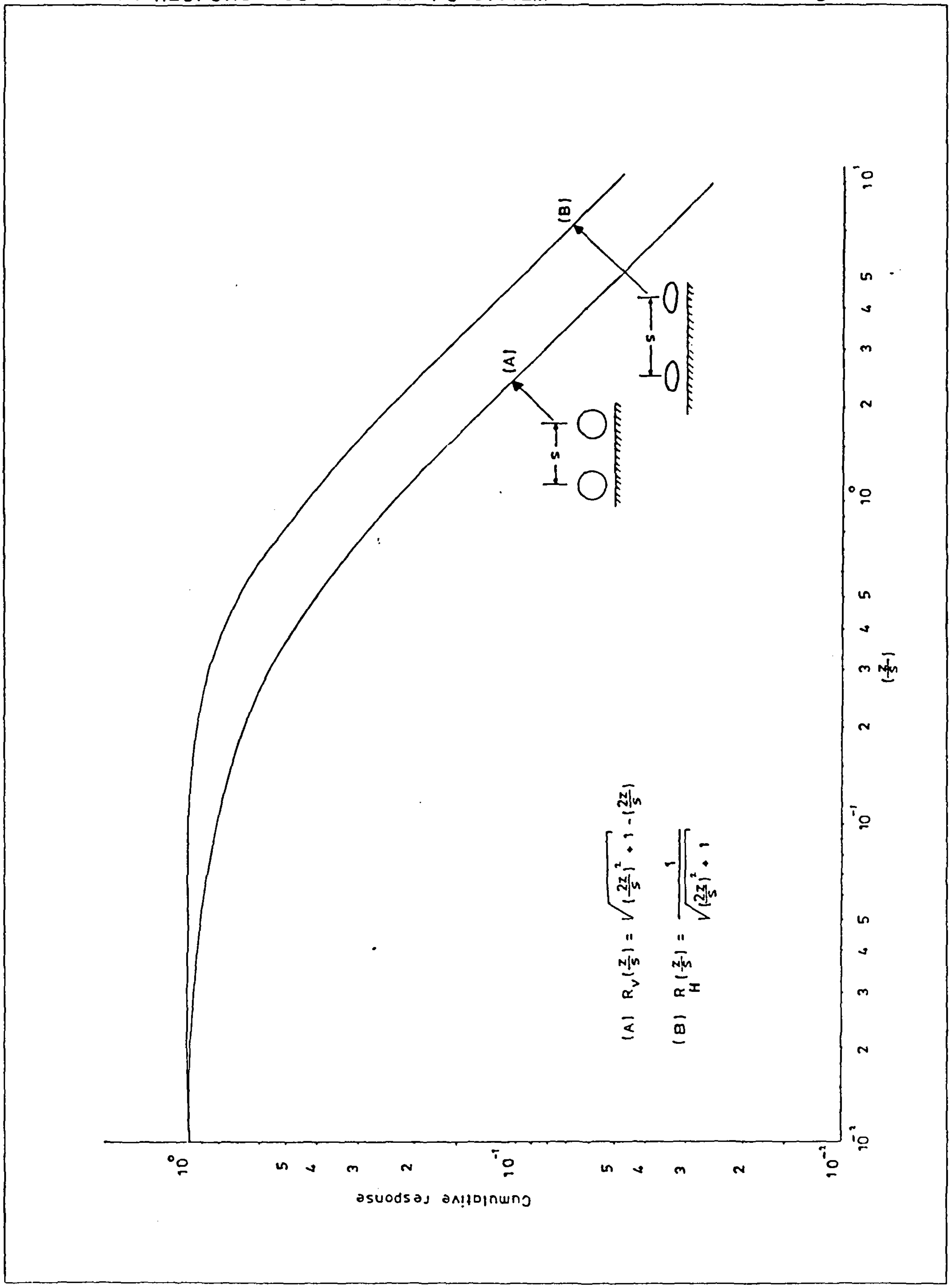
to sum all the contributions. This capability of the EM34-3 system makes it possible to calculate the EM responses of horizontal layer models as applied in electrical resistivity sounding (VES) interpretation technique. See section C.5.
The instrumental response functions for either coil operating configuration are shown in figure B.2 for the relative response and in figure B.3 for the cumulative responses. These functions define the relative influence of current flow as a function of depth.

Figure B.2:
Relative Response Curves EM34-3 System



CUMULATIVE RESPONSE CURVES EM34-3 SYSTEM

Figure B.3



The relative response curves ϕ_V (z/s) and ϕ_H (z/s) describe the relative contribution to the secondary magnetic field (H_s) arising from a thin layer at any depth z/s, i.e. the ratio between the real depth (z) of the layer and the intercoil spacing (s). It is seen from the figure that for the VL mode, the relative contribution from near-surface material to the secondary magnetic field is large and the response falls off monotonically with depth. For the HL mode, maximum response is given by materials located at a depth of 0.4s while materials at a depth of 1.5s still contribute significantly in this configuration. For the HL, near-surface materials make a very small contribution to the secondary magnetic field and therefore this coil configuration is insensitive to changes in near surface conductivity.

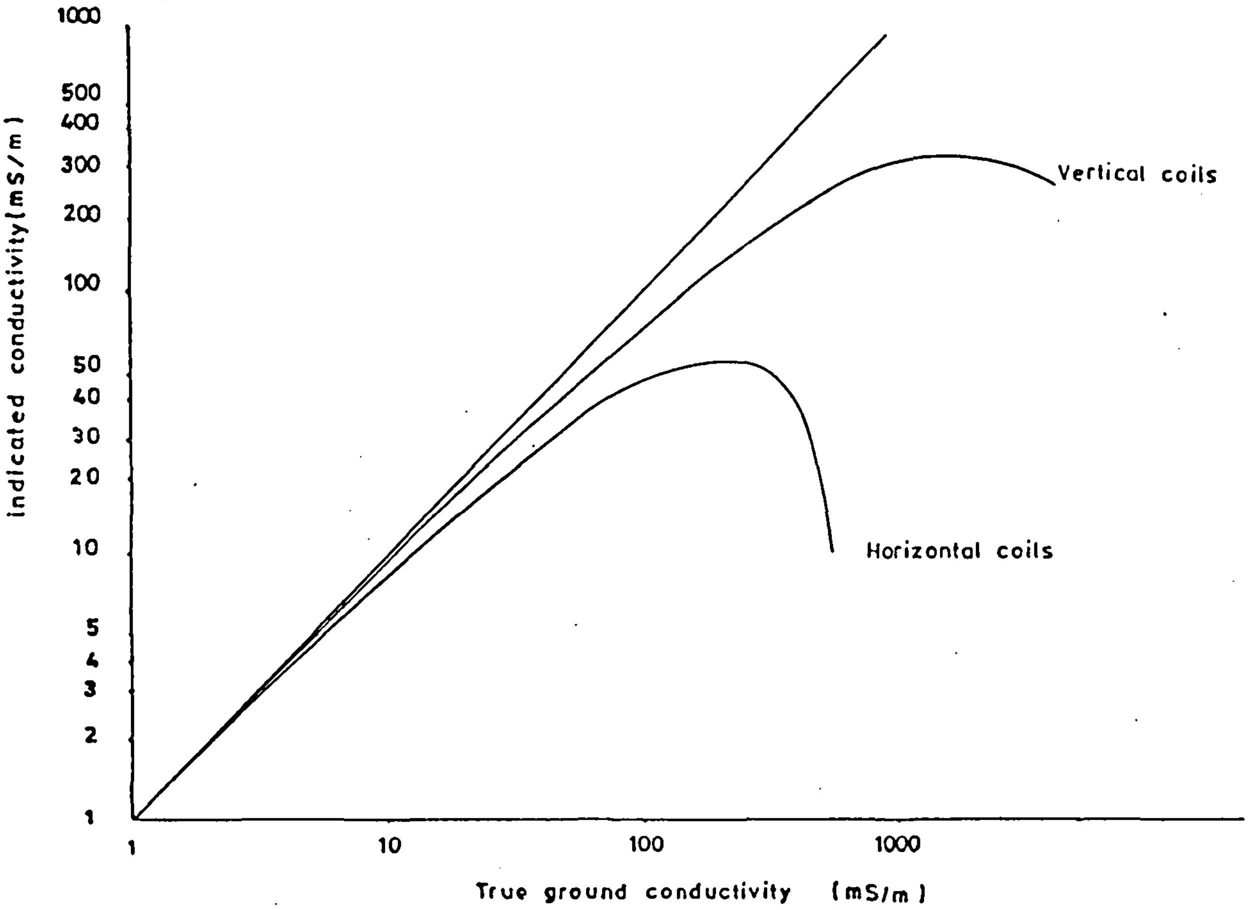
The cumulative response curves R_V (z/s) and R_H (z/s) of figure B.3 show for the VL and HL configurations the relative contribution to the secondary magnetic field from all material below a depth z/s. The cumulative response functions $R_{\frac{V}{H}}$ (z/s) are derived from the relative response functions using the equation:

$$R_{\frac{V}{H}}(z/s) = \int_z^{\infty} \phi_{\frac{V}{H}}(z/s)dz$$

The figure shows, for example, that for the HL configuration all material below a depth of two intercoil spacings (2s) yields a relative contribution of approximately 25% to the secondary magnetic field at the receiver coil.
At high values (>50 mS/m) the indicated conductivity is no longer linearly proportional to the actual conductivity. Figure B.4 shows a plot of the measured ground conductivity versus true conductivity for both modes of operation.
This effect is stronger for the HL mode as a result of its greater depth of penetration. The deviation can be corrected using the graph of figure B.4. However, when the true ground conductivity rises above 200 mS/m, the HL mode cannot be used properly.

Figure B.4:

Graph of Indicated vs. True Conductivity EM34-3 System



The EM34-3 system as applied for this study has several advantages over other geophysical methods, especially compared with electrical resistivity methods:

a. no direct injection of current is applied. This avoids the problems with high contact resistances caused e.g. by dry sandy top layers, as experienced with the resistivity method;

b. the masking effect of high resistivity top layers (e.g. dry sand) is less than with the resistivity method. The measured conductivity values are only slightly affected by high resistivity near-surface layers, especially in the HL mode;

c. it is a particulary well suited method for systematic investigations in areas with shallow survey targets, as is the case of Wadi Nyala aquifer.

d. the method has proved to be very well suited for the delineation of faults, fractured zones or fissures of high permeability at shallow depths;

e. it is a rapid and easy to handle method. Only simple equipment is necessary with a minimum of accessories. The speed of operation depends mainly on the physical condition of the operators. More than 150 measurements a day can easily be made;

f. only two men are needed to carry out the survey. Combined with e. this means a substantial reduction in man-hours.

The limitations of the EM34-3 system for a survey in areas like the Wadi Nyala aquifer are:

a. a quantitative interpretation is not possible. With EM techniques only two layer models can be interpreted which is a too simple approach for the configuration in the alluvial wadi fill;

b. a possible overlap in electrical conductivity ranges of different formations. This also holds for the electrical resistivity method. The ranges of resistivities and conductivities of sediments and rocks found in Nyala area are given in table B.2. E.g. the resistivity values of sands can be in the same range as the values for the weathered Basement Complex, which form the lower boundary of the aquifer.

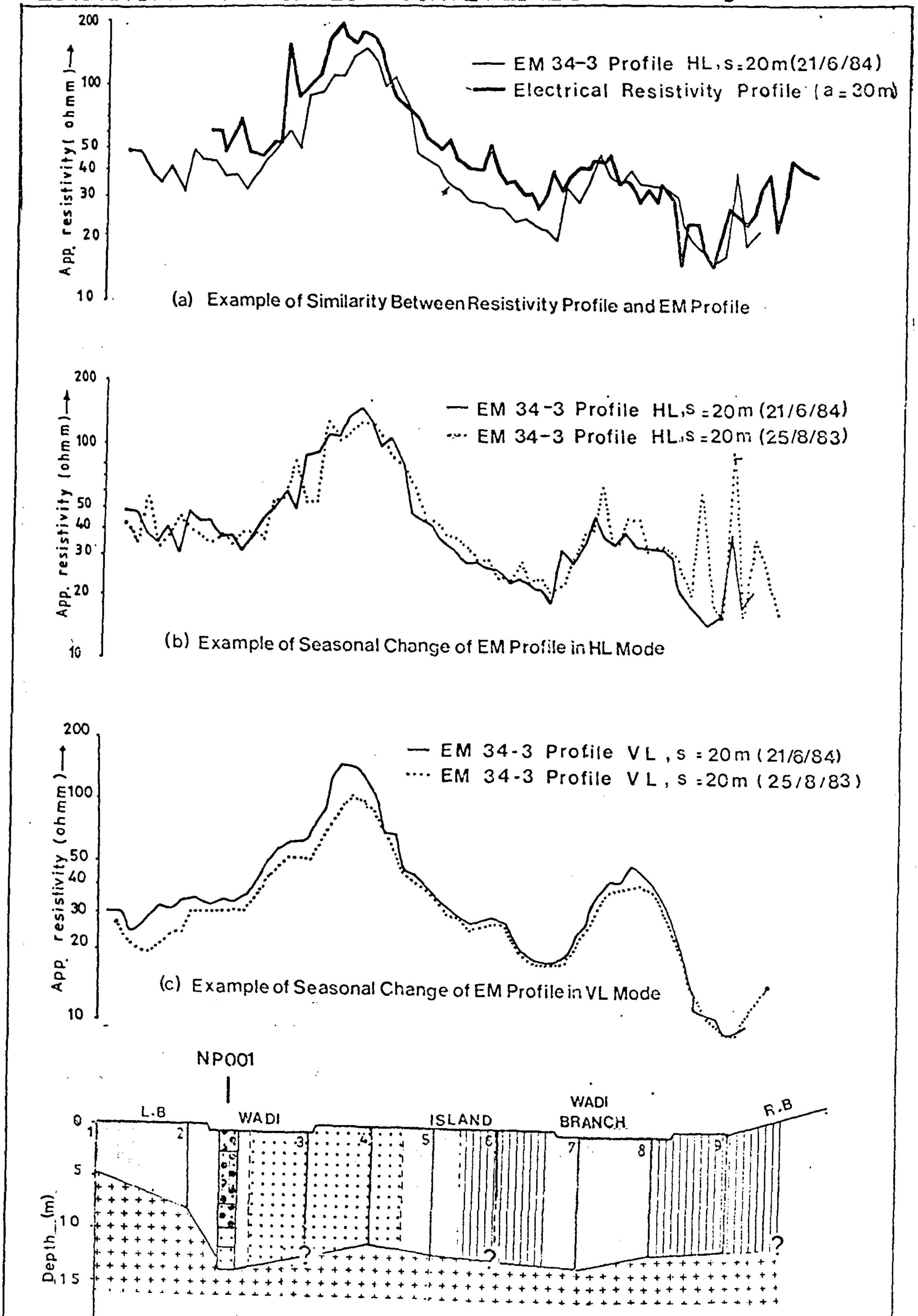
c. when near-surface layers are electrically heterogeneous, considerable random distortion in the conductivity readings occurs. Then the response of underlying target layers may be masked.

In figure B.5 two aspects of the use of the EM34-3 are demonstrated: the similarity between EM profiles and horizontal electrical resistivity profiles, and the difference in EM responses of surveys performed in different seasons. In the figure the EM apparent conductivity field data are converted into apparent resistivity values.

Figure B.5 (a) shows an EM34-3 profile (with s=20 m; HL mode) and a horizontal electrical resistivity profile (with a=30 m; see section C.1) along the same profile-line near Jebel Nyala (surveyed line D4). For location see fig. 6.1. The similarity of the graphs of both methods is striking.

The differences in the EM data measured in the dry, and in the rainy season (after the groundwater level has recovered) are shown for the HL mode and the VL mode in figures B.5 (b) and (c) respectively.

RESISTIVITY PROFILES ALONG SURVEY LINE D4 Figure B.5



Cross-section along D4 (see also figure 6.2(d))

The graphs for the VL mode show consistent and bigger changes in values than the graphs for the HL mode. This can be explained by the different responses of both modes of operation for near-surface material; the seasonal change (about 5 m) of the shallow groundwaterlevel has a more pronounced effect on the VL mode of operation. The higher resistivity values in the VL mode at the end of the dry season (the graph of 21/6/84) are much more pronounced - especially if the logarithmic scale is taken into account - over that part of the alluvium which forms the aquifer.

It is recommended that the seasonal changes in the VL mode graphs are studied in more detail to discover whether this method can be used to trace zones in the wadi alluvium where groudwater is stored.

B.2 Instrumentation

For the EM survey use has been made of a vertical/horizontal loop (VL/HL) induction instrument, the EM34-3 of Geonics. It is a non-contacting, two coil system with a moving, artificial source. The system has a light battery power supply to produce the primary magnetic field. Each coil is connected with a console; one for producing the primary magnetic field (the transmitter), one for detecting the secondary magnetic field (the receiver). See figure B.1.

With the instrument, terrain conductivities are measured. For the instrument specification see table B.2. The equipment is light-weighted and easily portable; two men are needed for operating the instrument.

The frequency of the AC current introduced into the transmitter loop depends on the applied separation distance between the two coils; see table B.1. The intercoil spacing is controlled by a separate indicator on the receiver console; small variations in coil separation, however, will have no effect on the measured value of conductivity.

During instrument operation the vertical coplanar loop mode is relatively insensitive to coil misalignment. The HL mode has a greater sensitivity to misorientation. For this, small waterlevels are adjusted to both transmitter and receiver coil, in order to achieve a proper orientation. In general, the coils are very sensitive for misorientation at low conductivity values.

Table B3: EM34-3 Instrument Specification

Manufactured by	:	Geonics Ltd., Mississauga, Canada
Measured quantity	:	Apparent conductivity of the ground, in milliSiemens per meter (mS/m)
Range of conductivity	:	0-3, 10, 30, 100, 300 mS/m
Instrument noise level	:	0.2 mS/m
Measurement accurracy	:	± 5% at 20 mS/m
Measurement precision	:	± 2% of full scale deflection
Primary field source	:	Self-contained dipole transmitter
Sensor	:	Self-contained dipole receiver
Intercoil spacing	:	Interchangeable 10, 20 or 40 metres
Power supply	:	Transmitter: 8 size D cells Life: 20 hrs continuous duty - "NORMAL" Life: 7 hrs continuous duty - "HIGH" Receiver: 8 size C cells Life: 20 hrs continuous
Referance cable	:	Lightweight 2 wire shielded cable
Dimensions		
Receiver console	:	19.5 x 13.5 x 26 cm
Receiver coil	:	63 cm diameter
Transmitter console	:	15 x 8 x 26 cm
Transmitter coil	:	63 cm diameter
Weights		
Receiver console	:	3.1 kg
Receiver coil	:	3.2 kg
Transmitter console	:	3.0 kg
Transmitter coil	:	7.0 kg
Shipping weight	:	41.0 kg

B.3 Field Technique

To carry out an EM survey the coils are separated by a fixed distance and traversed in-line along a profile line. The coil separation depends on the exploration depth of interest. At a measuring point on a profile line (such a point will be called a station) a reading of the terrain conductivity is taken, usually in both coil configurations (VL and HL). The field lay-out for the VL mode is shown in figure B.1.

To take a reading in a next station the transmitter and receiver coil shift along the profile-line over a certain distance, called station interval (or station spacing). The length of a station interval depends on the required detail of the survey. The readings are plotted at the midpoint of the system, i.e. the stations are located midway between the coils.
If possible, the coils must be kept at the same height to ensure that there is no variation in the primary magnetic fields due to difference in elevation.

An EM profile-line, should be planned at a safe distance from cultural noises, i.e. power lines, reinforced concrete, water pipes, and from industrial noise. This type of noise will affect the 40 m intercoil spacing most and will be largest on the most sensitive (= low conductivity) range. Atmospheric noise (i.e. caused by thunderstorms, magnetic storms) will be most severe in the VL mode of operation.

The time needed to obtain a HL reading is on average twice the time needed for a VL measurement, because in the HL mode more care has to be taken to get a correct orientation of the two coils. The time to obtain a VL and a HL reading at one station is only 1 to 2 minutes. The total time for successive readings on a profile line of both VL and HL modes depends on the station interval.

Due to the high speed operation of EM surveying, if needed, a previously studied EM profileline can be repeated easily for good siting, wich is one of the advantages of this method.

B.4 Data Acquisition and Processing

The EM data acquisition took place in two phases.

Phase I: from September to December 1983
The survey began with a reconnaissance study along a profile line (no. 201 A-K) inside the wadi bed, starting upstream of Nyala Town,

2.4 km west of Mekkah Bridge, and ending in the downstream area near Bileil. The total length of this profile is 20.3 km. Other reconnaissance profilelines were measured along tracks (i.e. Majouck-Bileil), and inside some wadi branches. After this, the survey was concentrated on the wadi alluvium near Nyala Town, between the runoff station and Kondua Forest. Several EM profiles perpendicular to the wadi bed were made, mainly along or near surveyed profile lines. For the location of the EM lines use was made of the 1:20 000 map which was compiled from aerial photographs and the surveyed profile lines. All the measurements were performed with s=20, both in VL and HL mode of operations. The station interval was 10 m along the profiles, near Nyala Town, and 20m along the reconnaissance lines, and along the profiles in the Downstream Area. The EM profiles of phase I are numbered from 001 to 058.

Phase II: June 1984, and February-March 1985
During this phase, the survey was concentrated in the Downstream Area, from Kondua Forest to Bileil area. The EM profiles were made along surveyed profile lines perpendicular to the wadi channel, and are numbered according to these lines: D6 - D19. For a proper correlation of the information from the perpendicular profiles, an EM profile was measured inside the wadi bed (no. 202), from the crossing with surveyed line D6 to the crossing of profile line D19. This profile partly overlaps EM reconnaissance profiles 022 and 201. All profiles were measured with s = 20 m, both in the VL and HL modes of operation, and with a station interval of 20 m.

Furthermore, several detailed EM studies were made, most of them near boreholes, or on VES locations. For the detailed studies, all three coil separations, and several station intervals have been applied, in both modes of operation.

The EM profilelines are shown on the map of figure 6.1. Because of the reconnaissance character of some lines the locations of the stations are not indicated in detail. The locations of the detailed EM studies are also indicated on the map. The EM measurements along VES spreads are indicated on the VES location map of figure C.5.

All EM profiles and detailed EM studies are listed in table B.4. The table also contains information about the lengths of the profiles, the applied coils distances, the station interval and the number of stations.

A total number of 11 reconnaissance lines (total length 45.9 km), and 28 EM profiles along or near surveyed lines (total length 66.5 km) were made. The number of detailed studies near boreholes and VES location is 34.

Sources of error during the data acquisition are:

a. mistakes in the exact location of a profile line and/or station number on the map. The deviation from the indicated locations is estimated to be less than 50 m.

b. differences in height between the transmitter coil and the receiver coil; see section B.3. This affects mainly the HL mode, and is estimated to be less than 5% of the measured apparent conductivity per meter of height difference. As the survey area in general is flat, this source of error only will be appreciable in exceptional cases;

c. readings taken at stations which are not at a safe distance from cultural noises (see section B.3). Mostly they show up clearly by pronounced differences and fluctuations in conductivity values in consecutive stations along a profile line;

d. misreadings caused by wrong range readings on the receiver console. This source of error is considered to be exceptional, because it can easily be avoided by comparing consecutive readings along a profile line in the field, and by checking the conductivity values at crossings of two EM profiles.

In the field, the measured conductivity values are recorded on sheets. Later, the field data are stored on data cartridges (tapes) using a HP 85 desk-top computer. The data is plotted as profile graphs, using a semi-log scale with the EM values on the vertical, logarithmic scale and the locations of the stations on the horizontal scale. The values are represented as resistivities rather than the measured conductivity values because they show more pronounced variations in the range of values which are of interest for the alluvial aquifer study.

Table B.4: List of EM Profiles and Detailed EM Studies

EM profile no.	Type of study*	Station interval (m)	Coil separation s (m)	Total number of stations	Profile length (m)	Graph fig no.	Notes
001	D	10,20,40	10,20,40	15	140	-	near borehole NP003
002	D	10,20	10,20	38	370	-	near borehole NP008
003	R	20	20	55	1080	B.6a	near Majock village
004	P	20	20	62	1220	6.3d,B.6b	near surveyed profile line D4
005	R	20	20	48	940	B.6c	near Majock village
006	R	20	20	70	1380	B.6d	near Majock village
007	R	20	20	58	1140	B.6e	near surveyed profile line D1
008	R	20	20	70	1380	B.6f	east of Majock village
009	R	20	20	169	3360	B.6g	along road Kundua-Mousay; measured in two sections (A-B)
010	D	15	10,20,40	16	240	-	near Majock village
011	R	20	20	51	1000	B.6h	near borehole NP005
012	R	20	20	538	10740	B.6i	along road Majock-Bieleil; measured in five sections (A-E)
013	D	20	10,20,40	21	400	-	east of majock village
014	D	10	10,20,40	39	380	-	near borehole NP009
016 A	D	10	20	14	130	-	near borehole NP008
016 B	D	10	20	18	170	-	200 m east of NP008
019	R	20	20	39	760	B.6j	inside wadi branch
020	D	10	20	16	150	-	near borehole NP009
021	D	10,20,40	10,20,40	68	670	-	near borehole NP005
022	P	20	20	126	2500	B.6k	inside wadi channel
023	P	20	20	116	2300	B.6l	inside wadi branch; measured in two sections (A-B)
025	D	10	10,20,40	11	100	-	near borehole NP010
027	D	10	10,20,40	16	150	-	near borehole NP011
028	D	10	10,20,40	83	1640	6.3c,B.6m	near profile Di
029	R	20	20	104	2060	B.6n	near profile D7
030	P	20	20	100	1980	b.6o	
032	D	10	10,20,40	19	180	-	near borehole NP012
034	D	10	20	28	270	-	near borehole NP012
036	D	10	10,20,40	31	300	6.3b	east of Mekkah Bridge
037	D	10	20	30	290	-	wadi bed, crossing Bridge
038	D	10	10,20,40	51	500	6.3b,B.6p	west of Mekkah Bridge
039	D	5	10,20,40	47	230	6.3a	upstream, near Hai el Gir
042	D	10	10,20,40	19	180	-	near borehole NP014
046	D	10	10,20,40	22	210	-	near borehole NP016
048	D	10	10,20,40	23	220	-	near borehole NP017
049	D	10	10,20,40	11	100	-	near borehole NP013
050	D	10	10,20,40	11	100	-	near borehole NP015
051	P	10	20	38	370	B.6q	east Kouria Road
052	P	10	20	92	910	B.6r	near surveyed profile line D3
053	P	10	20	72	710	B.6s	near surveyed profile line D2
054	P	10	20	53	520	B.6t	near surveyed profile line U2
055	P	10	20	51	500	B.6u	near surveyed profile line U2
056	P	10	20	61	600	B.6v	near souque
057	P	20	20	35	680	B.6w	inside wadi bed
058	P	20	20	62	1280	B.6x	inside wadi bed near NP018
094	V	10	20	30	290	-	along spread VES 094
095	V	10	20	30	290	-	along spread VES 095
096	V	10	20	18	170	-	along spread VES 096
097	V	10	20	36	350	-	along spread VES 097
098	V	20	20	7	120	-	along spread VES 098
099	V	20	20	13	240	-	along spread VES 099
100	V	20	20	15	280	-	along spread VES 100
101	V	20	20	6	100	-	along spread VES 101
102	V	20	20	7	120	-	along spread VES 102
103	V	20	20	10	180	-	along spread VES 103
105	V	20	20	13	240	-	along spread VES 105
106	V	20	20	13	240	-	along spread VES 106
107	V	20	20	17	320	-	along spread VES 107
108	V	20	20	13	240	-	along spread VES 108
110	V	20	20**	21	400	-	along spread VES 110

Table B.4 (cont.)

EM profile no.	Type of study*	Station interval (m)	Coil separation s (m)	Total number of stations	Profile length (m)	Graph fig no.	Notes
111	V	20	20**	16	300	-	along spread VES 111
112	V	20	20**	14	260	-	along spread VES 112
114	V	20	20**	22	420	-	along spread VES 114
115	V	20	20**	12	220	-	along spread VES 115
116	V	20	20**	20	380	-	along spread VES 116
117	V	20	20**	26	500	-	along spread VES 117
118	V	20	20**	12	220	-	along spread VES 118
119	V	20	20**	18	340	-	along spread VES 119
120	V	20	20**	16	300	-	along spread VES 120
121	V	20	20**	16	300	-	along spread VES 121
122	V	20	20**	10	180	-	along spread VES 122
123	V	20	20**	10	180	-	along spread VES 123
126	V	20	20**	12	220	-	along spread VES 126
127	V	20	20**	13	240	-	along spread VES 127
128	V	20	20**	13	240	-	along spread VES 128
129	V	20	20**	14	260	-	along spread VES 129
130	V	20	20**	13	240	-	along spread VES 130
131	V	20	20	13	240	-	along spread VES 131
132	V	20	20**	13	240	-	along spread VES 132
133	V	20	20**	13	240	-	along spread VES 133
134	V	20	20**	13	240	-	along spread VES 134
201A-K	R	20	20	1103	22040	B.6y	inside wadi bed (Sept.-Oct.1983) measured in eleven sections (A-K)
202	P	20	20	638	12740	B.6z	inside wadi bed (March 1985) overlaps partly EM profiles no. 022 and 201
D6	P	20	20	91	1800	B.6aa	along surveyed profile line D6
D7	P	20	20	91	1800	B.6bb	along surveyed profile line D7
D8	P	20	20	112	2220	B.6cc	along surveyed profile line D8
D9*	P	20	20	143	2840	B.6dd	west of surveyed profile line D9
D9	P	20	20	145	2880	B.6ee	along surveyed profile line D9
D10	P	20	20	135	2680	B.6ff	along surveyed profile line D10
D11	P	20	20	146	2900	B.6gg	along surveyed profile line D11
D12	P	20	20	140	2780	B.6hh	along surveyed profile line D12
D13	P	20	20	140	2780	B.6ii	along surveyed profile line D13
D14	P	20	20	133	2640	B.6jj	along surveyed profile line D14
D15	P	20	20	138	2740	B.6kk	along surveyed profile line D15
D16	P	20	20	152	3020	B.6ll	along surveyed profile line D16
D17	P	20	20	152	3020	B.6mm	along surveyed profile line D17
D18	P	20	20	152	3020	B.6nn	along surveyed profile line D18
D19	P	20	20	152	3020	B.6oo	along surveyed profile line D19

* D : detailed study
P : profile over or near surveyed line
R : reconnaissance study
V : short EM profile along VES spread

** Additional measurement in centre of spread with s=10 and 40 m

B.5 Interpretation

The results of the EM-survey are presented as follows:

1. computer plots of the graphs of EM profiles on a horizontal scale of 1:10 000 or 1:20 000, depending on the station-interval. See figures B.6a - 6oo. The locations of the profiles together with the station numbers are indicated on the map of figure 6.1.

2. an iso-resistivity contour map of the HL mode values for s = 20 m. See figure B.7.

The interpretation of the EM data has been accomplished by the qualitative analyses. Quantitative EM interpretation techniques generally are limited to two-layer earth models, which approach is too simple for the area under study.

The interpretation of the EM survey is mainly based on the HL mode values. The VL mode data have been used:

a. to get information about the character of the top-layers;
b. to compare EM field data with calculated EM34-3 responses of VES layer models at the same station. Together with the HL mode field data it limits the equivalency problems of VES layer model interpretation (see appendix C).

On some EM profiles the graph shows an interruption; this happens mainly in the HL mode graphs. At these stations, the EM field data have a negative conductivity reading.

For the interpretation of the profiles and the iso-resistivity contour map, use has been made of:

a. information concerning the lithology of the alluvial deposits and the underlying Basement Complex rocks from boreholes and wells;
b. information about depths to the Basement Complex rocks from boreholes and wells, and from the general knowledge about the geology of the area;
c. hydrogeological data, such as groundwater levels, EC values, the distribution of the wells, yields of boreholes and wells;
d. calculated EM34-3 system responses of electrical resistivity layer models representing several hydrogeological conditions in the wadi aquifer.

Because of the constraints in the resolving power of the EM method, no vertical division of the different alluvial deposits can be made.

In some cases a shallow depth to the Basement Complex rocks can be inferred from the EM data, but in general no depth interpretations can be made.

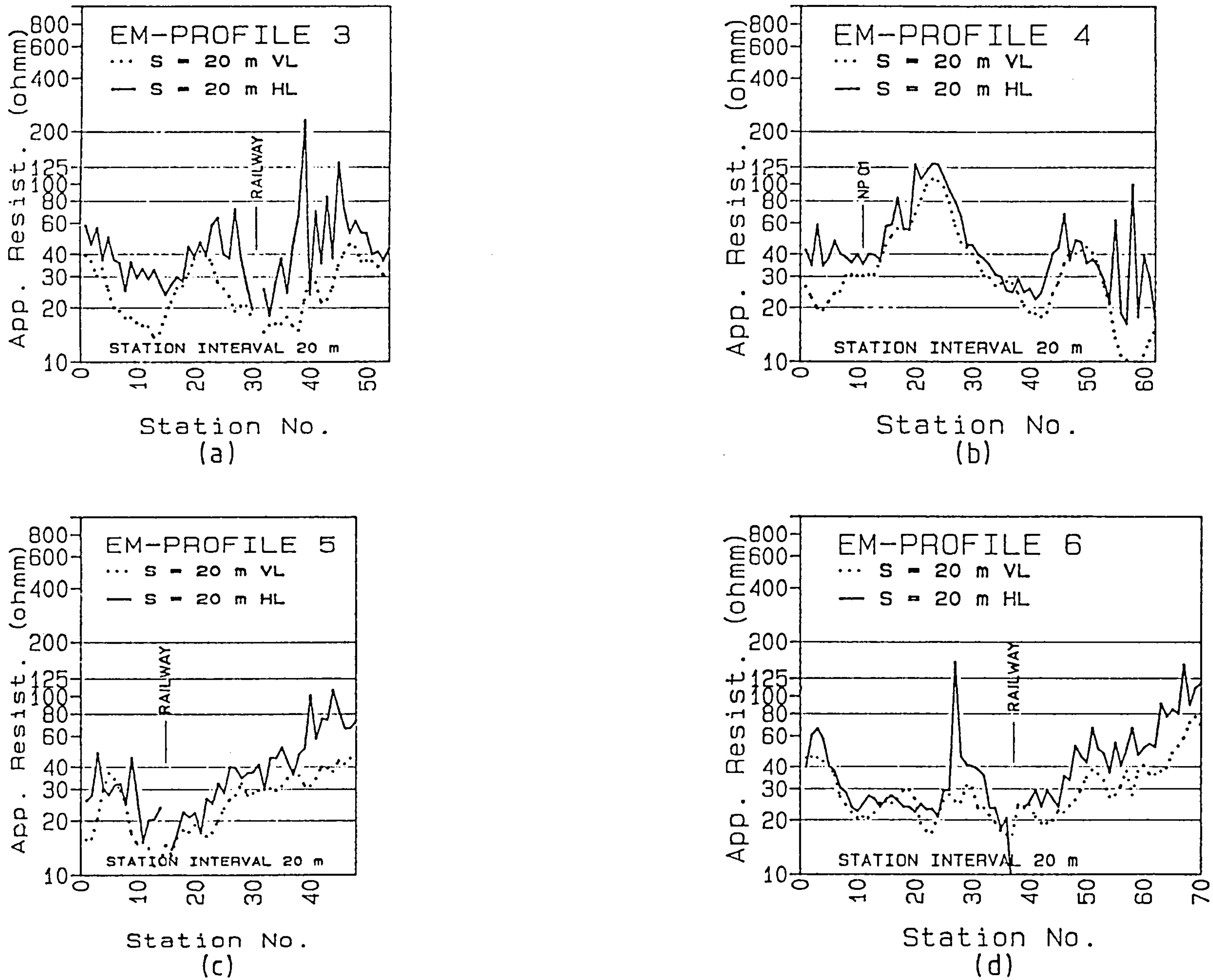
On the iso-resistivity map of the HL mode values, areas with apparent resistivities lower than 30 Ωm correspond with alluvial deposits of a mainly clayey composition.

Areas with apparent resistivities between 30 and 125 Ωm correspond either with a mainly sandy or with a clayey/sandy part of the wadi alluvium. If the HL values show some fluctuations on the profile curve, the alluvium in general is a mixture of clay and sand; where the HL values show a more or less smooth curve, the alluvium is mainly sandy.

Areas with apparent resistivities higher than 125 Ωm correspond in general with a shallow depth to the bedrock (<10m). However, in areas with dry alluvial sands, apparent resistivities higher than 125 Ωm can also be found where the depth to the bedrock is greater than 10m. To be on the safe side concerning the dimension of the aquifer for the establishment of a groundwater balance, the shallow depth interpretation is maintained if no other information (e.g. from boreholes, electrical resistivity soudings) was available.
On most graphs of the EM profiles several local anomalies appear, especially in the HL mode. The following geological situations can give the same type of response:

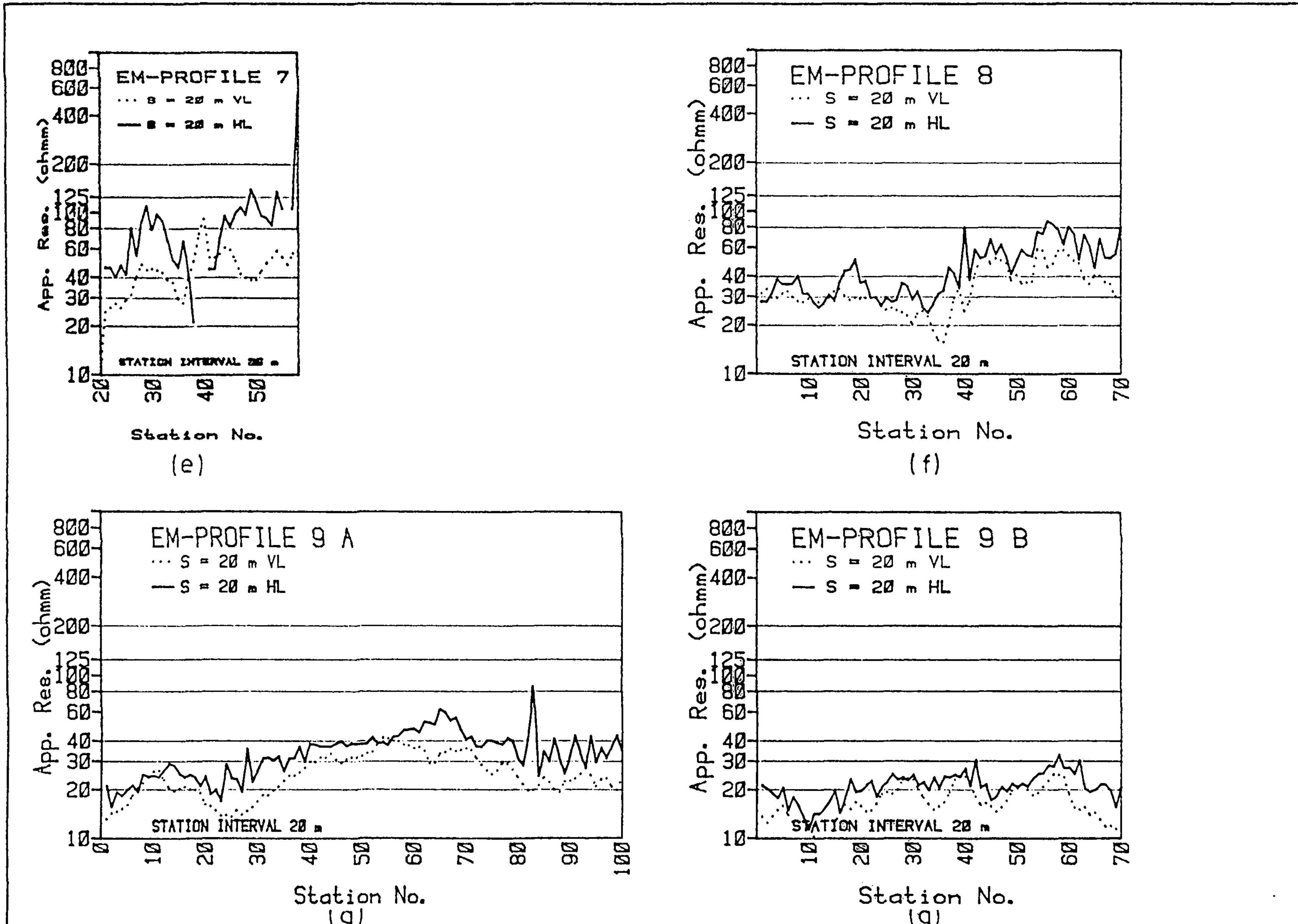
a. a ridge in the Basement Complex;
b. a local increase in thickness of the alluvium; goz sands, etc.;
c. two nearby conductors (e.g. two nearby faults);
d. a wide conductor (e.g. a fractured zone);
e. a local change in conductivity in the superficial deposits (alluvium, goz sands, etc.).

Therefore, it is difficult to interprete these local anomalies from EM data alone. On aerial photographs several lineaments are visible. Some of them coincide with alignments of anomalies on graphs of successive parallel EM profiles. They are indicated on the geological map, Map 2. The most plausible explanation is that they are faults and/or fractured zones. However, this has not been sufficiently proved by information from boreholes.



COMPUTER PLOT OF EM GRAPHS

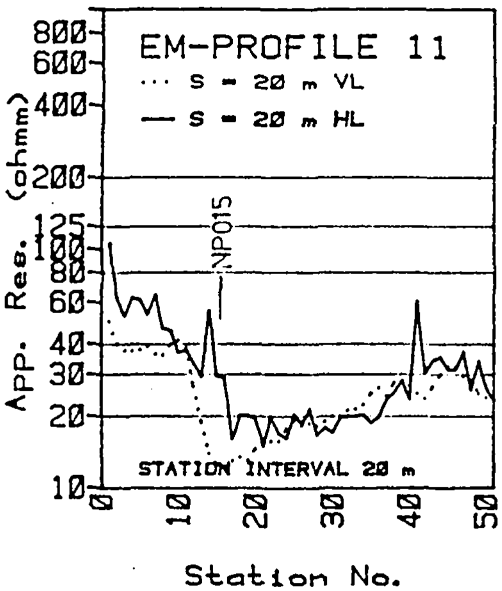
Figure B.6.a,b,c,d



COMPUTER PLOT OF EM GRAPHS

Figure B6efg

COMPUTER PLOT OF EM GRAPHS



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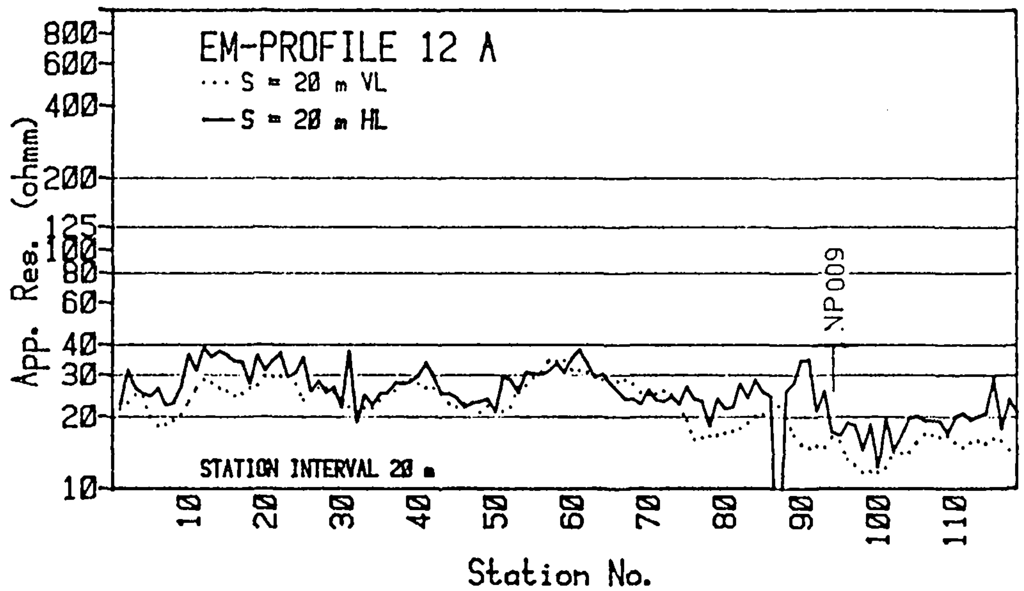
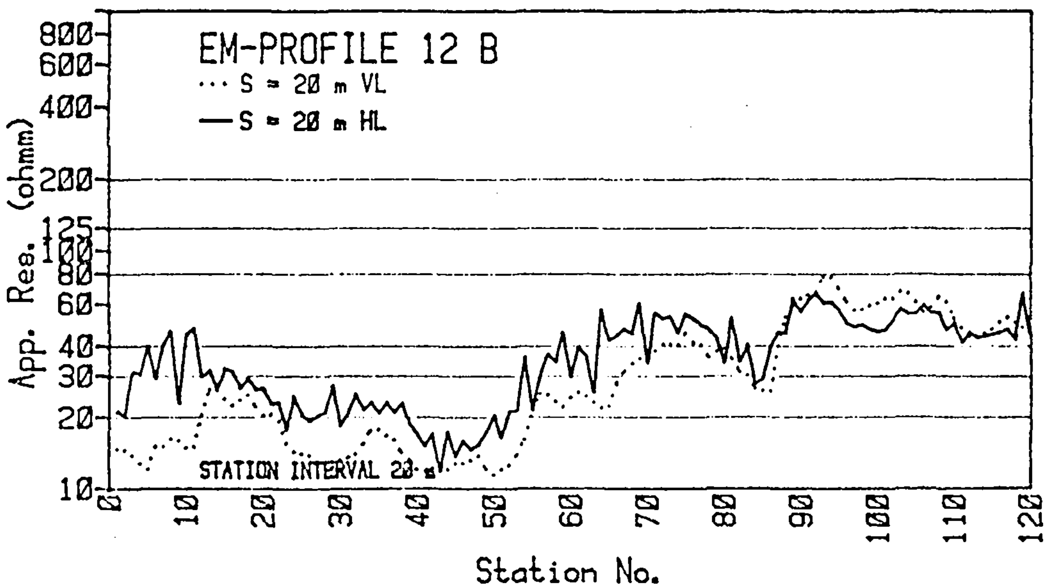
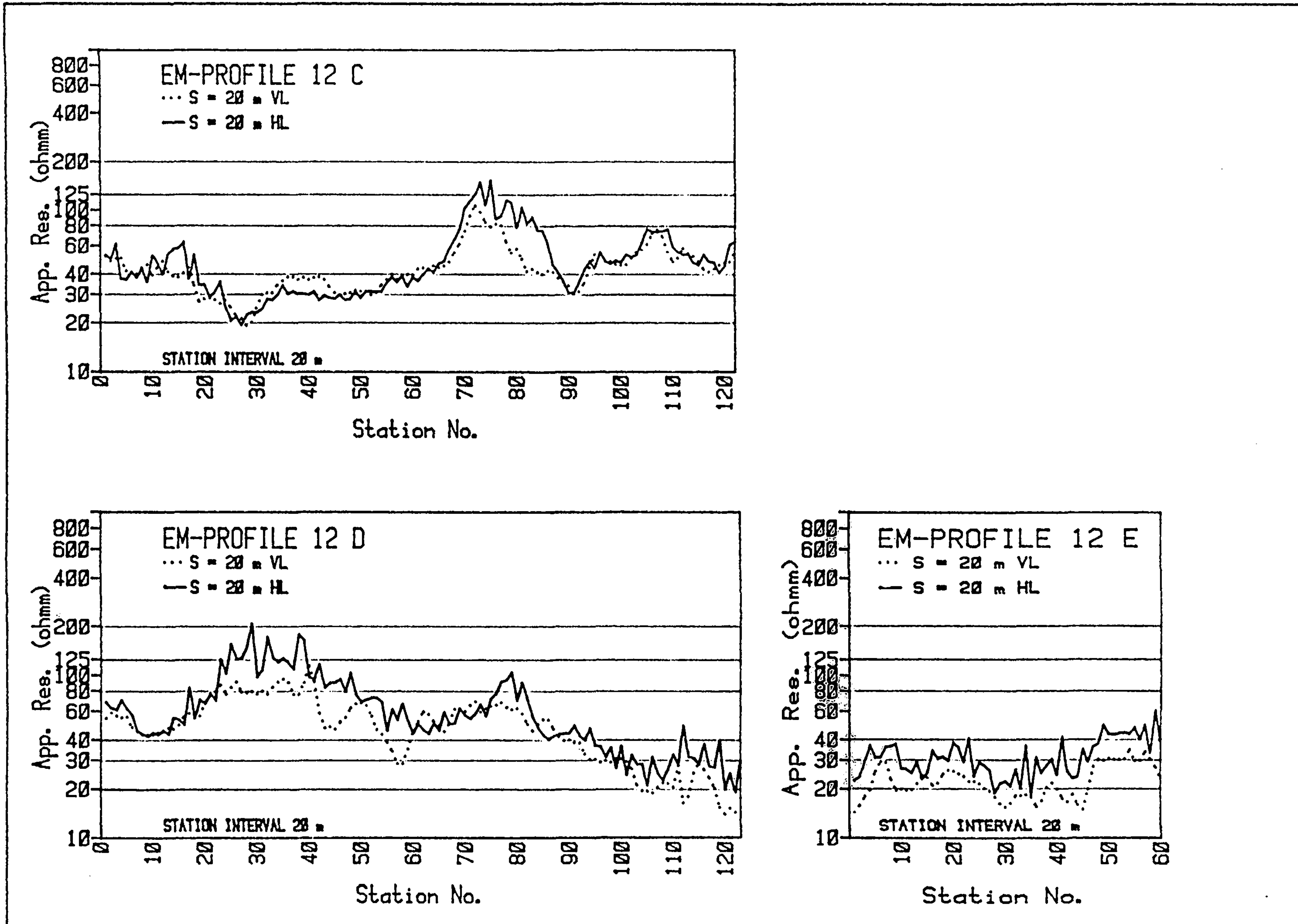


(i)



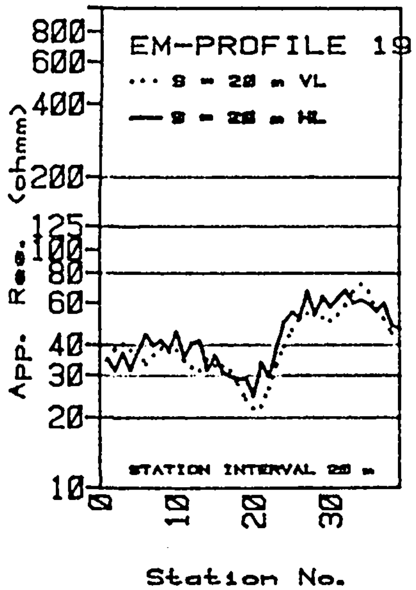
(i)

Figure B.6hi



COMPUTER PLOT OF EM GRAPHS

Figure B.6 i(cont)



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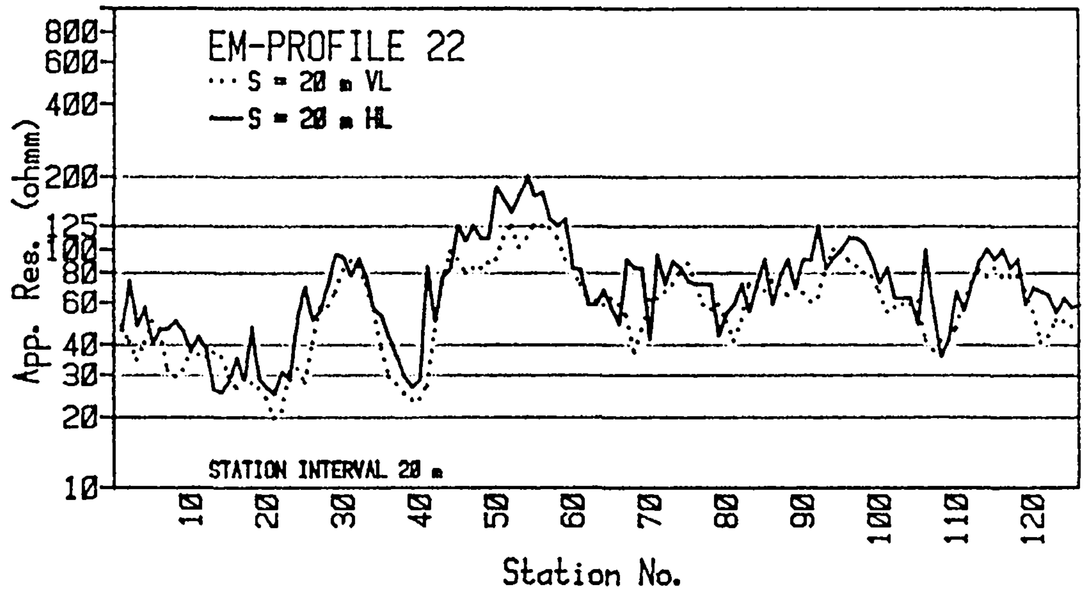

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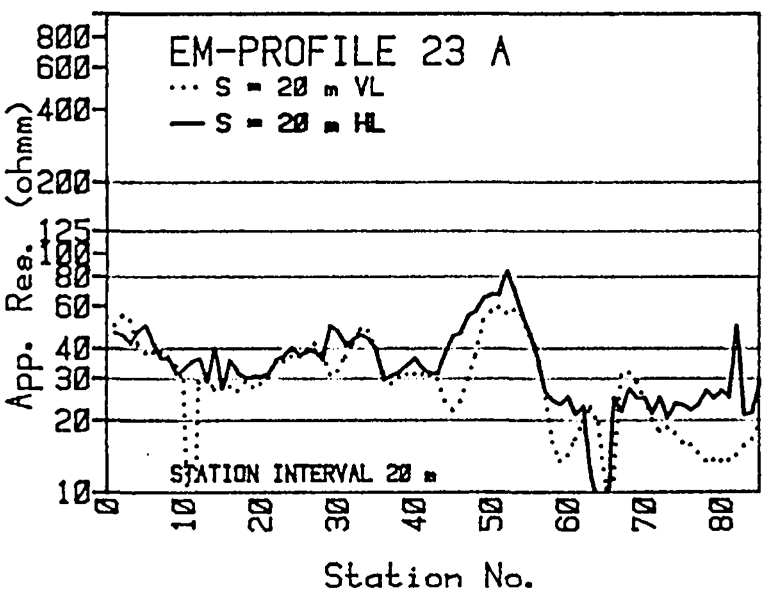

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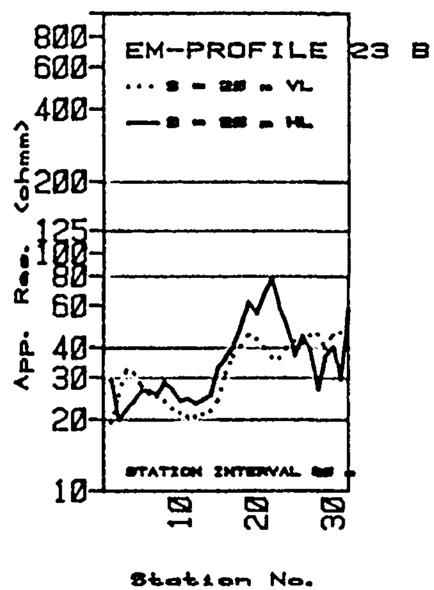
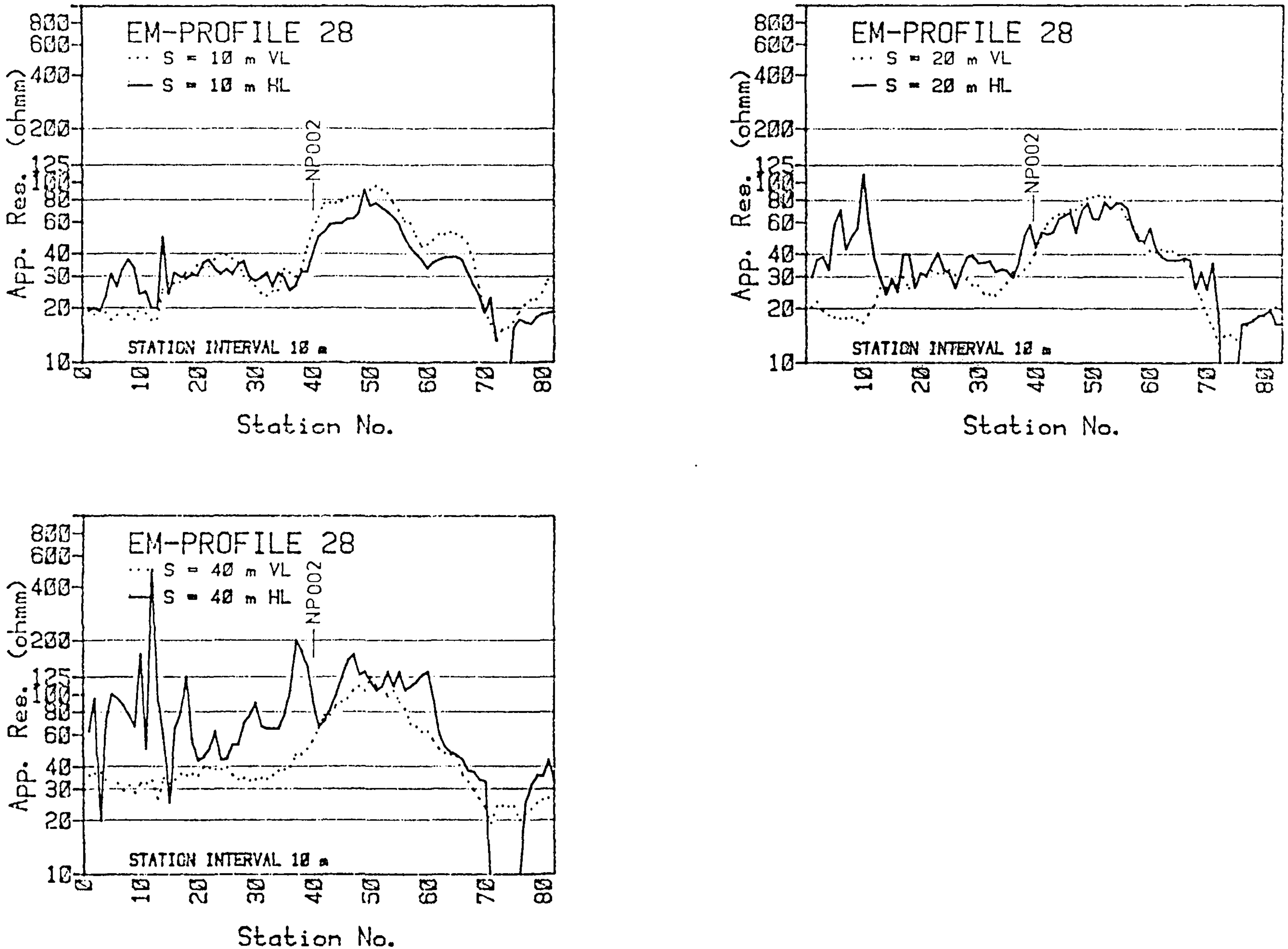


(l)

COMPUTER PLOT OF EM GRAPHS

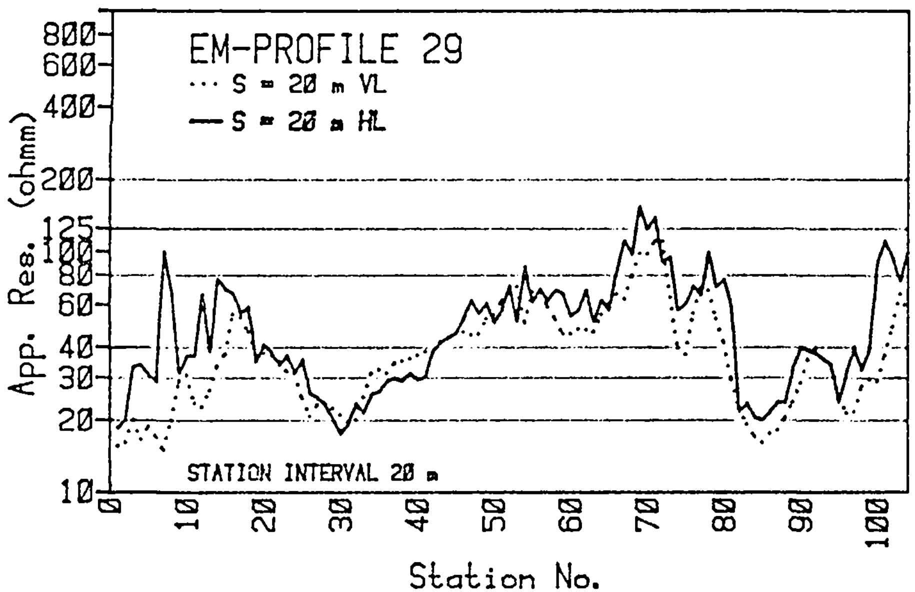
Figure B.6j,k,l



COMPUTER PLOT OF EM GRAPHS

Figure B.6m

COMPUTER PLOT OF EM GRAPHS



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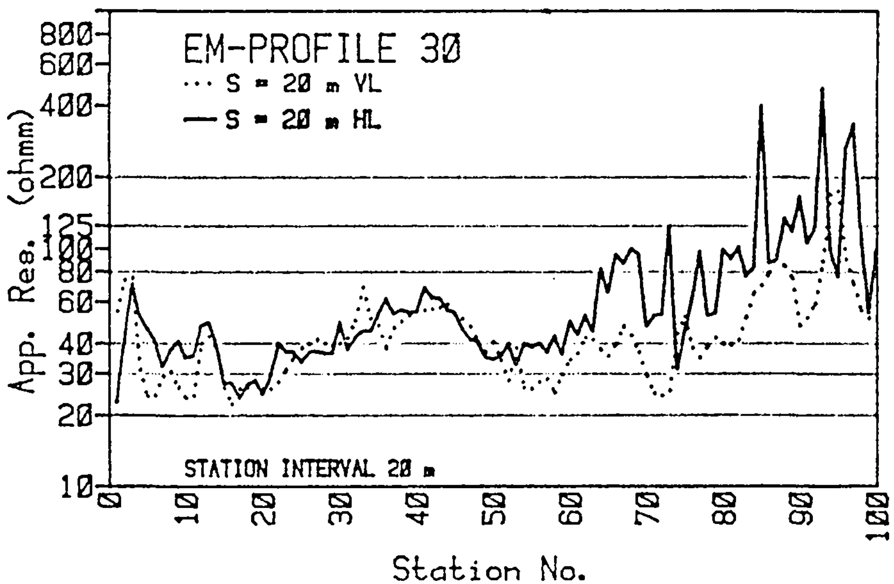
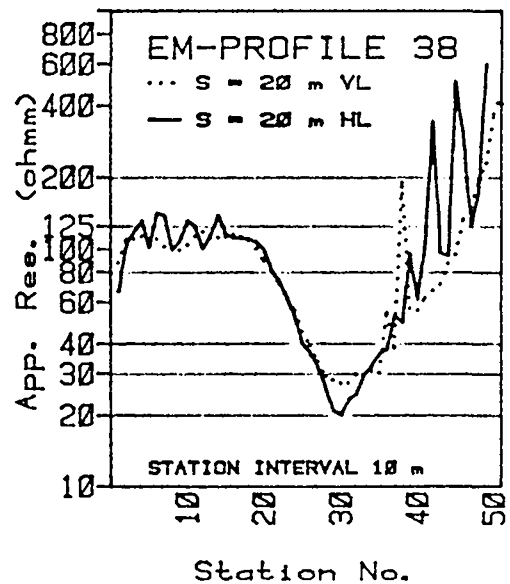
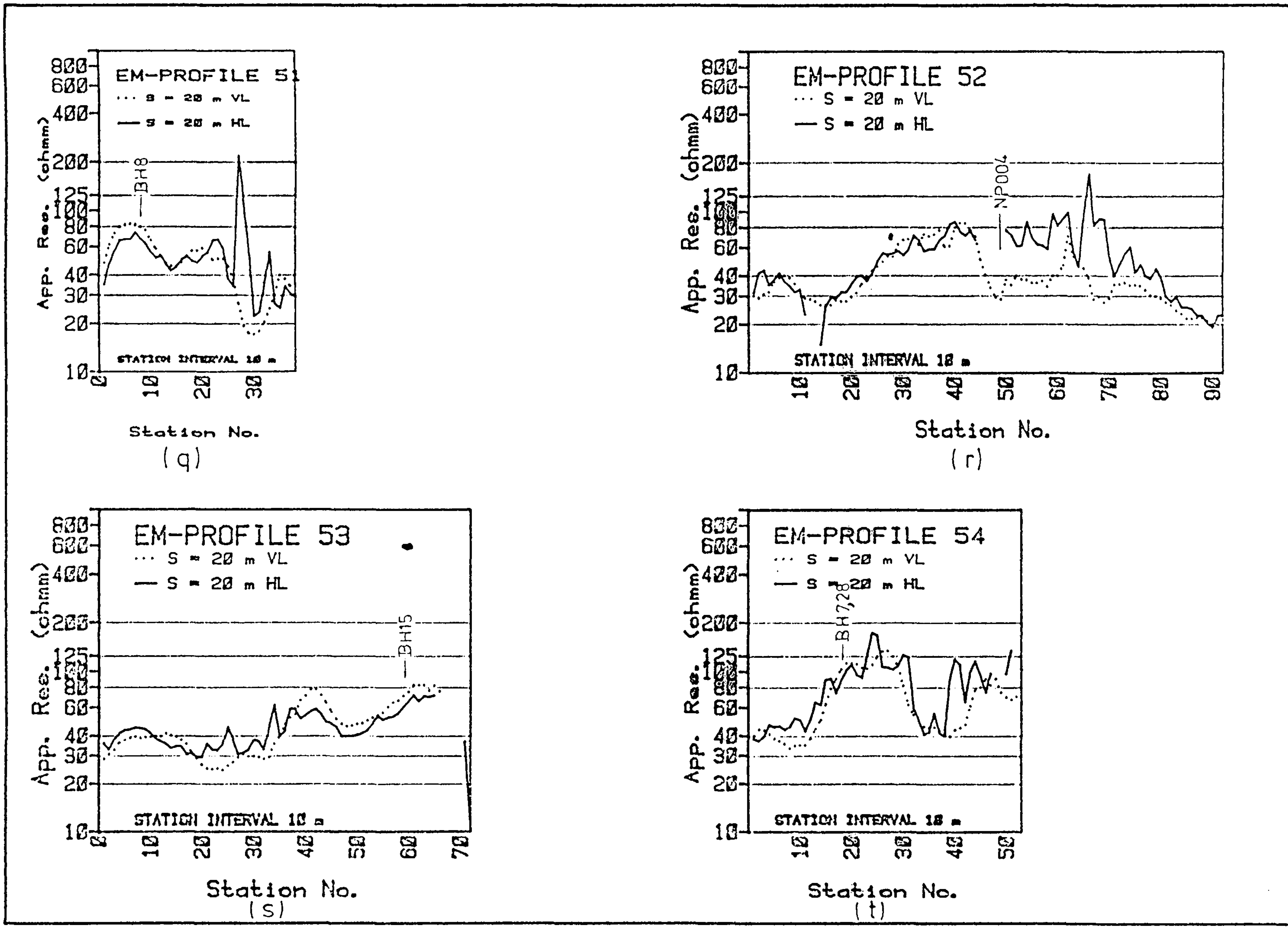


(o)



(p)

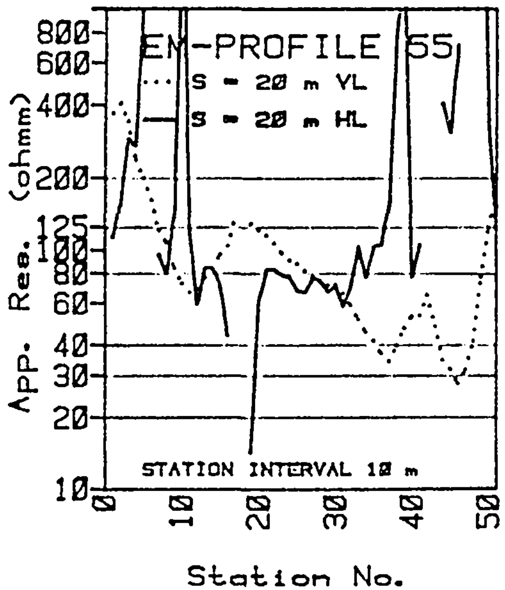
Figure B.6n,o,p



COMPUTER PLOT OF EM GRAPHS

Figure B6 q,r,s,t

COMPUTER PLOT OF EM GRAPHS



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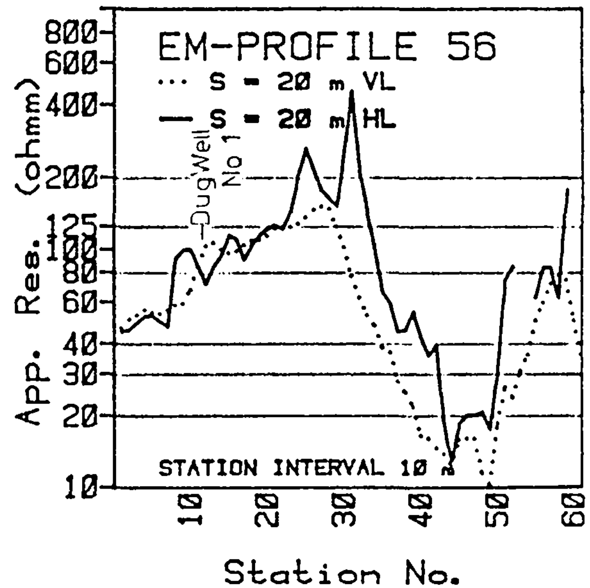

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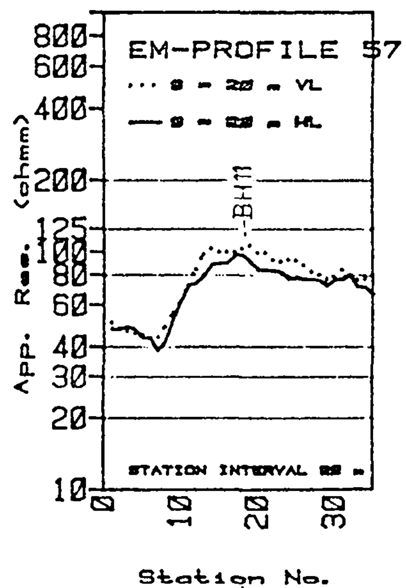

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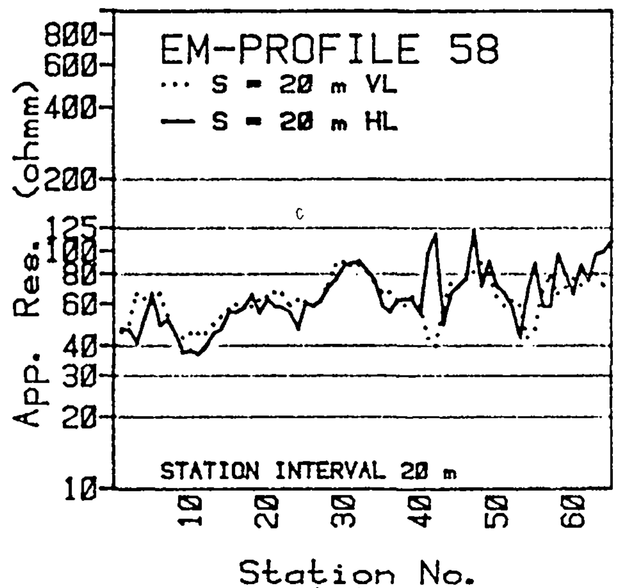

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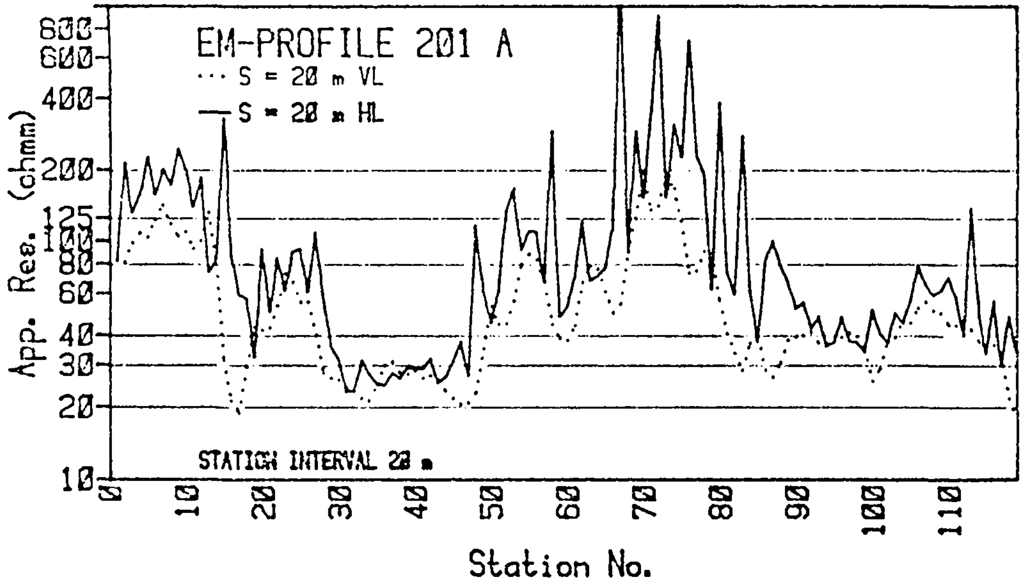
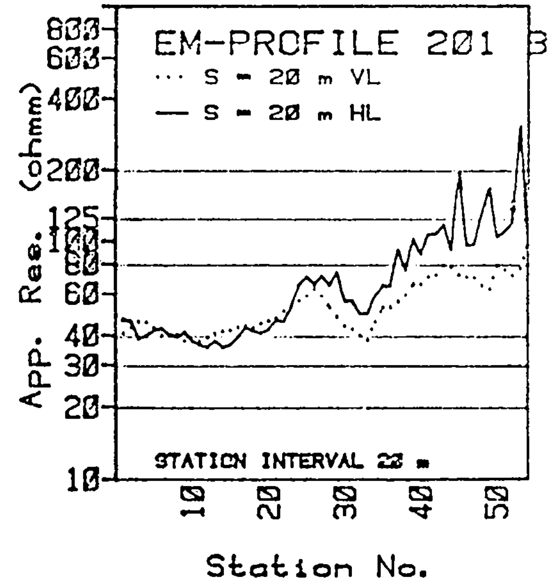
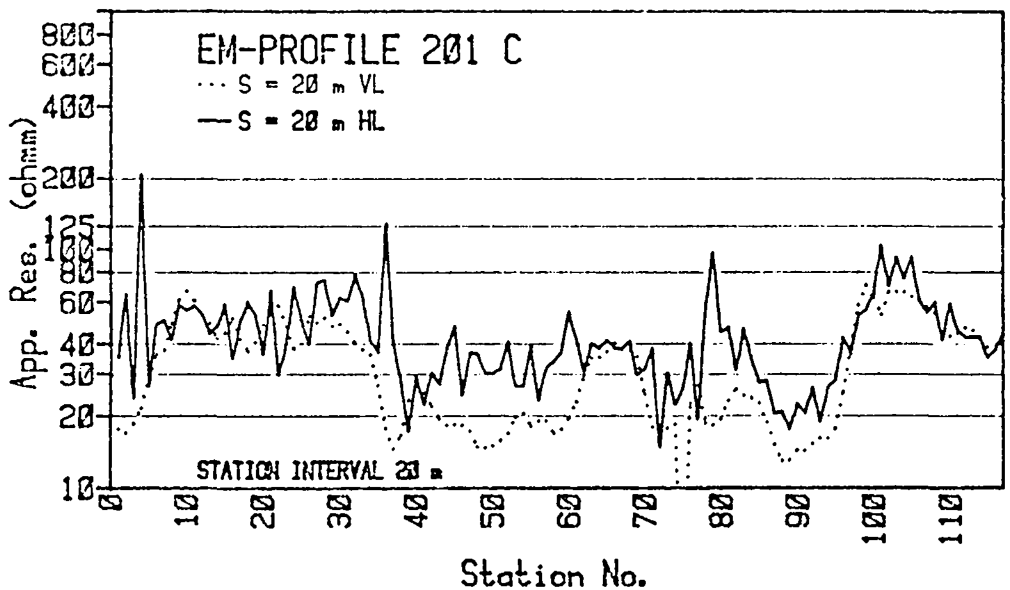
Figure B.6u,v,w,x



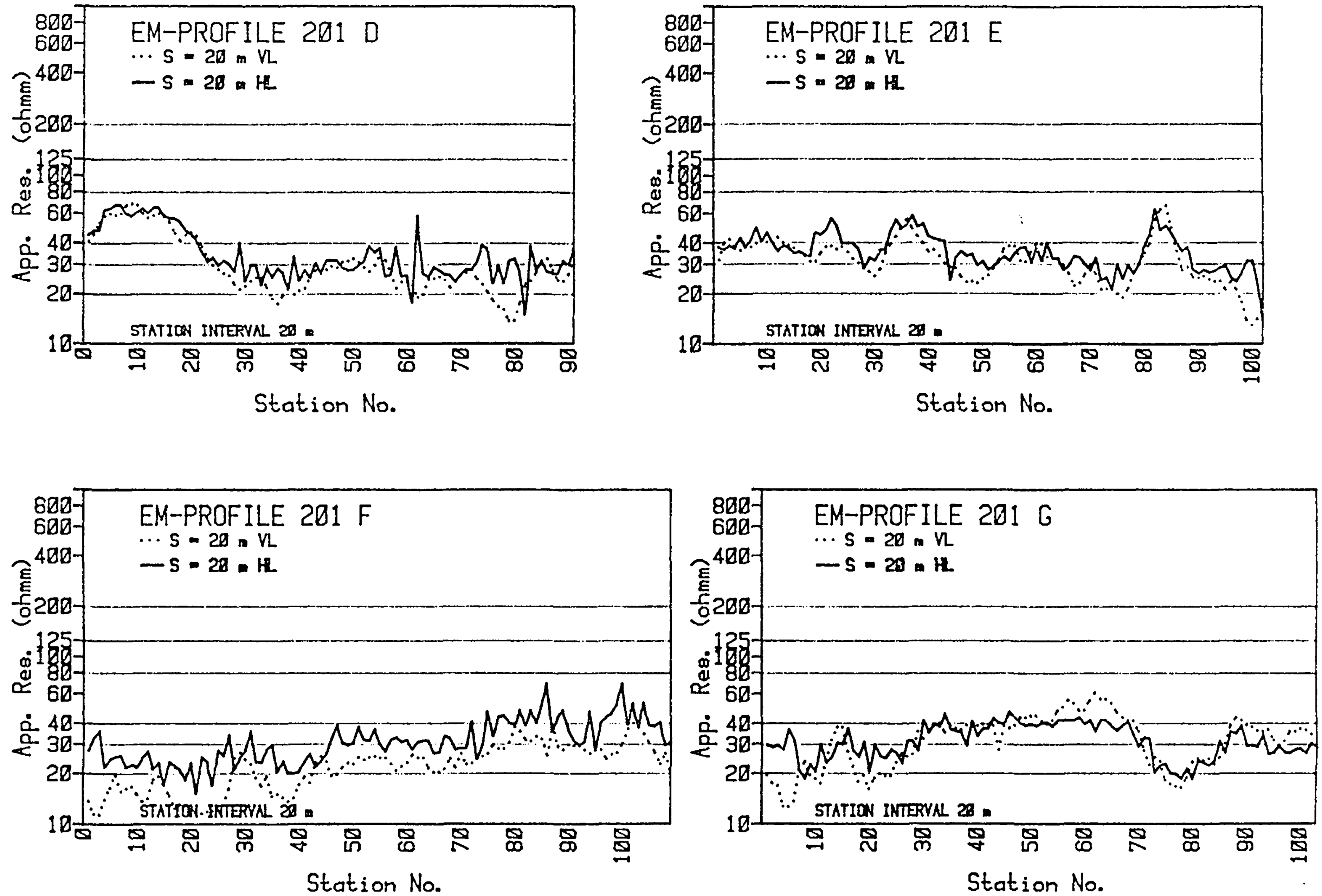




COMPUTER PLOT OF EM GRAPHS

Figure B.6y

COMPUTER PLOT OF EM GRAPHS



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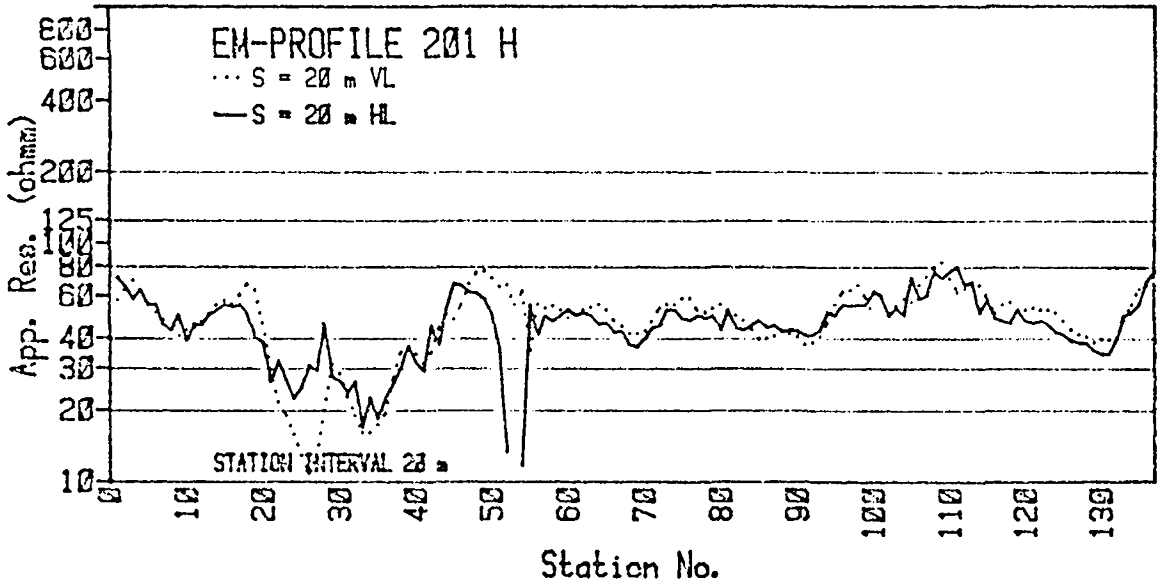

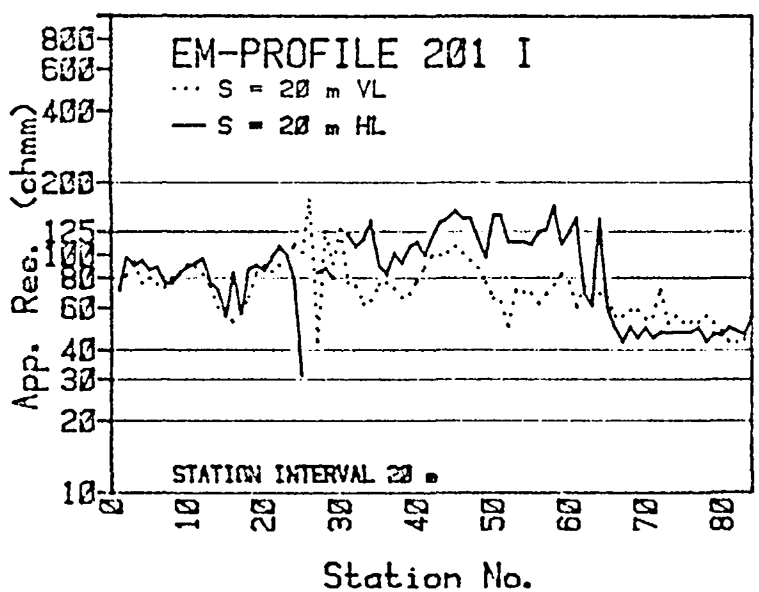

COMPUTER PLOT OF EM GRAPHS

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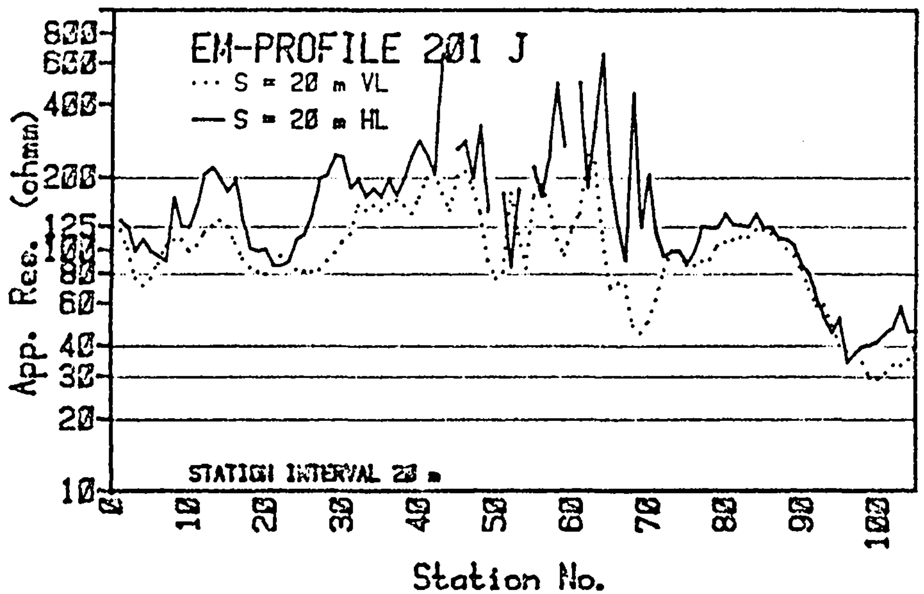
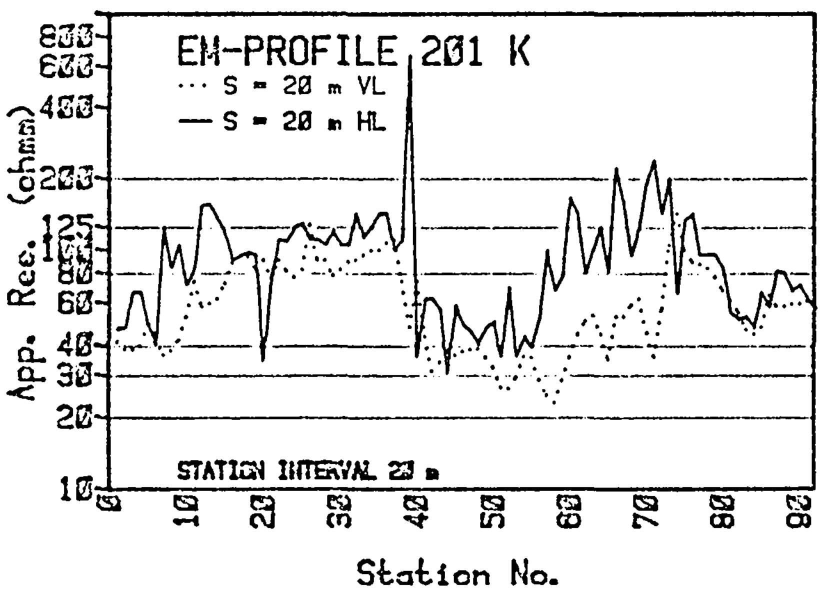
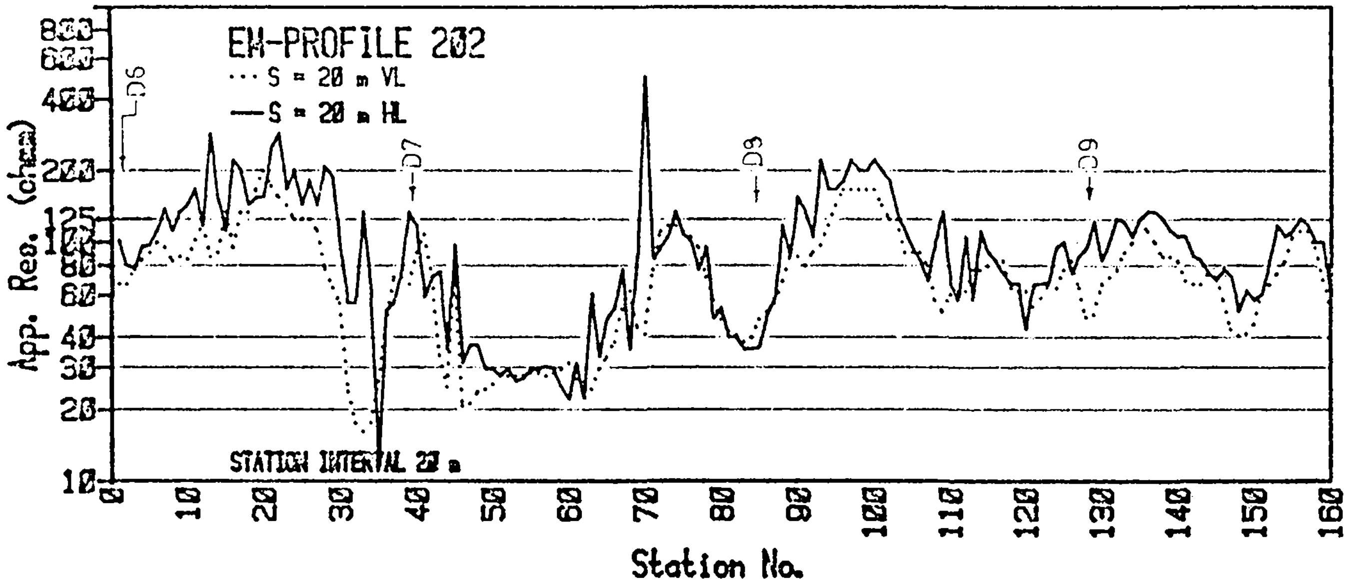
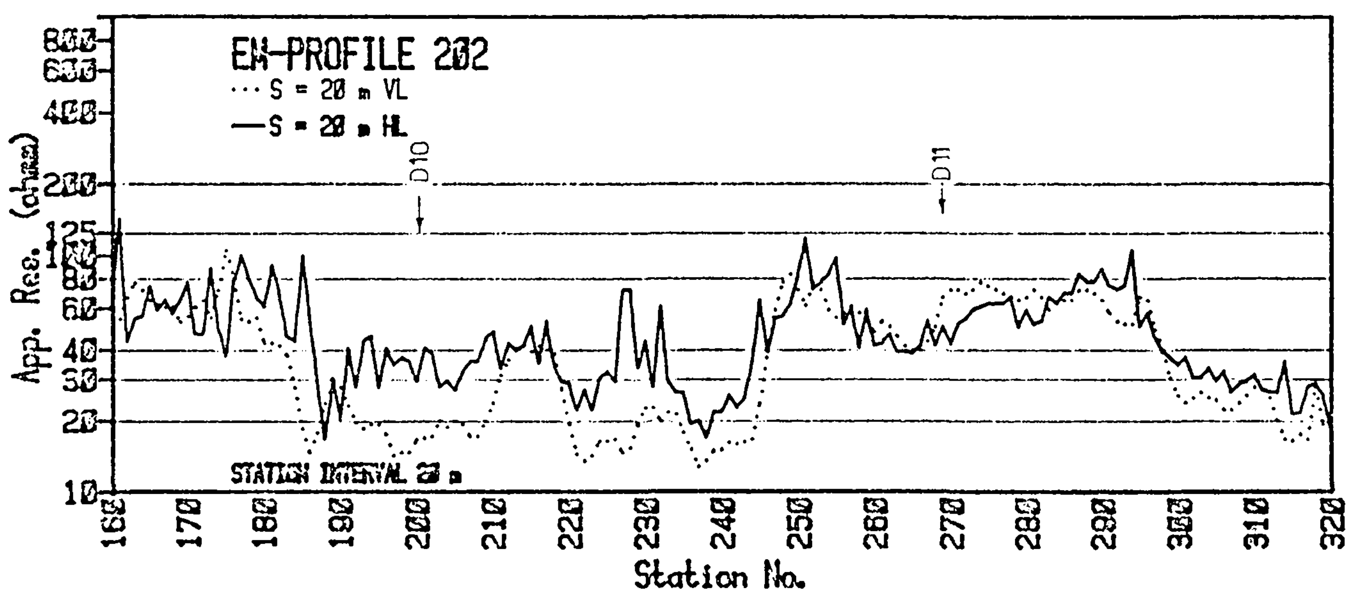




COMPUTER PLOT OF EM GRAPHS

Figure B.6y(cont)

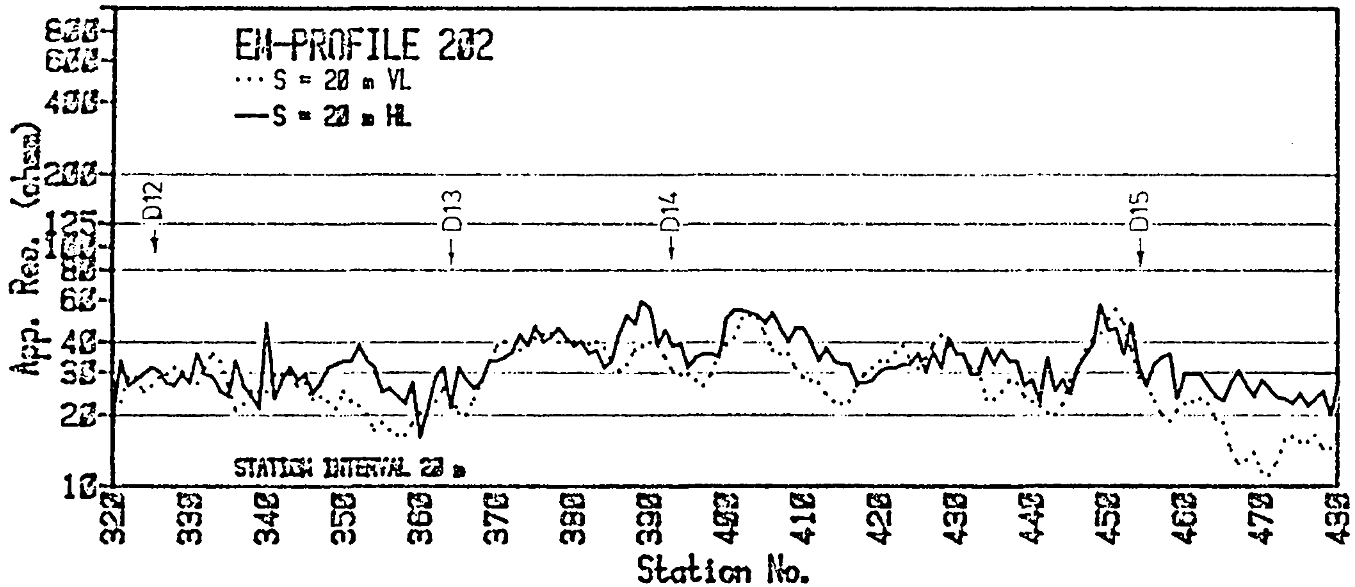




COMPUTER PLOT OF EM GRAPHS

Figure B.6z

COMPUTER PLOT OF EM GRAPHS



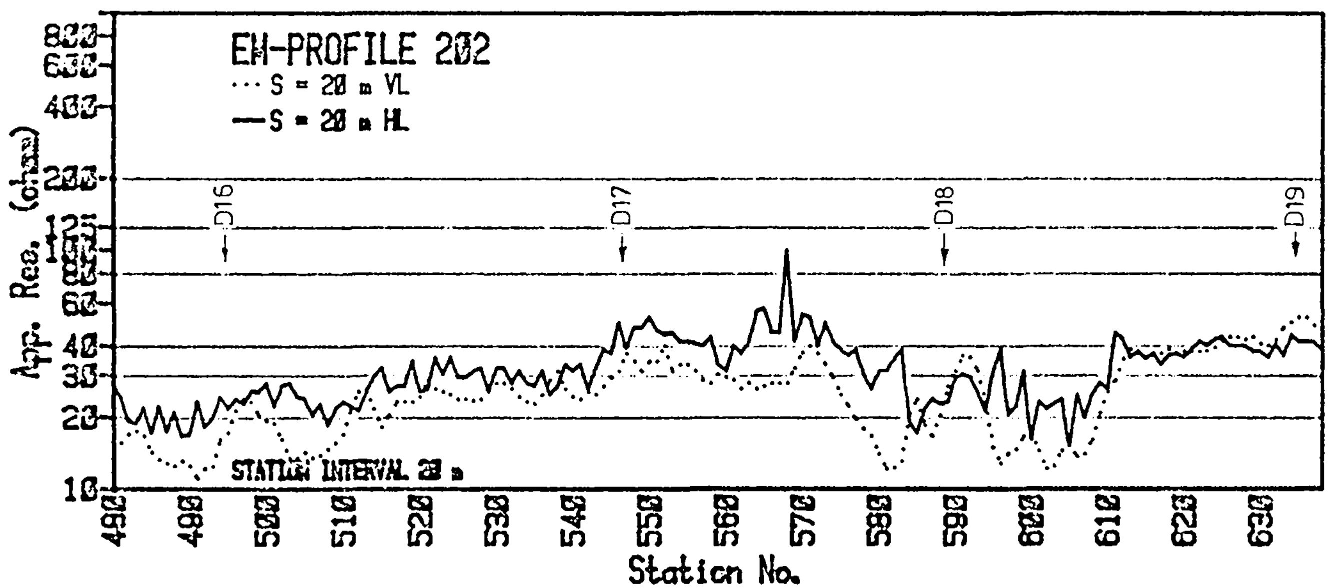


Figure B.6z(cont.)

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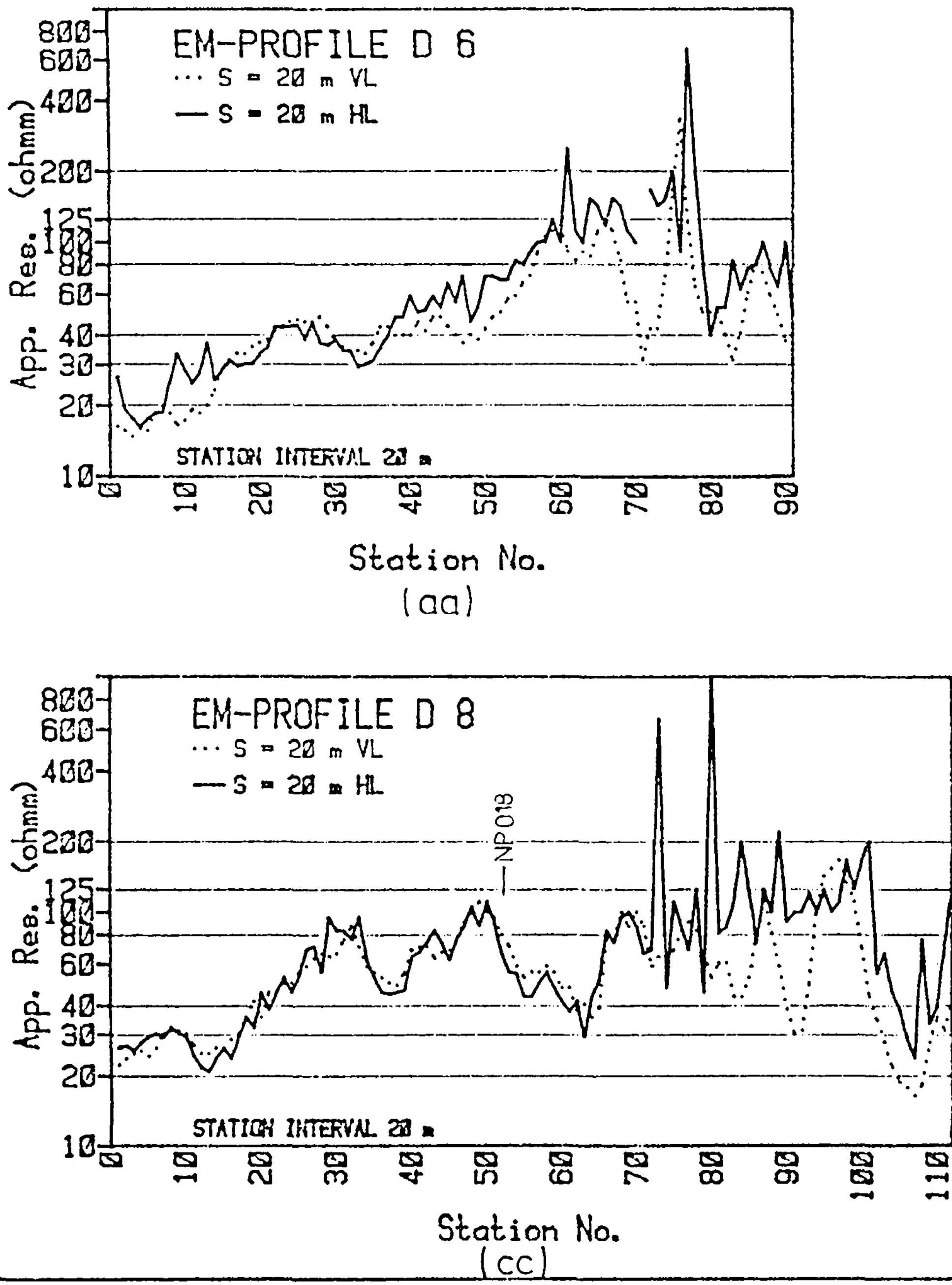
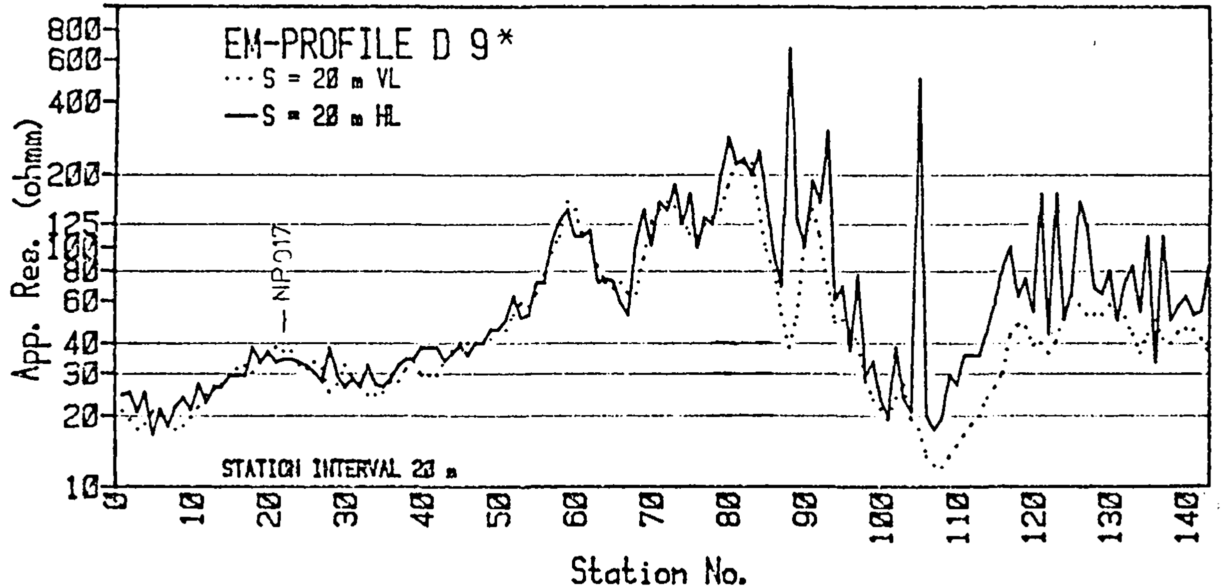


Figure B.6 aa,bb,cc

COMPUTER PLOT OF EM GRAPHS



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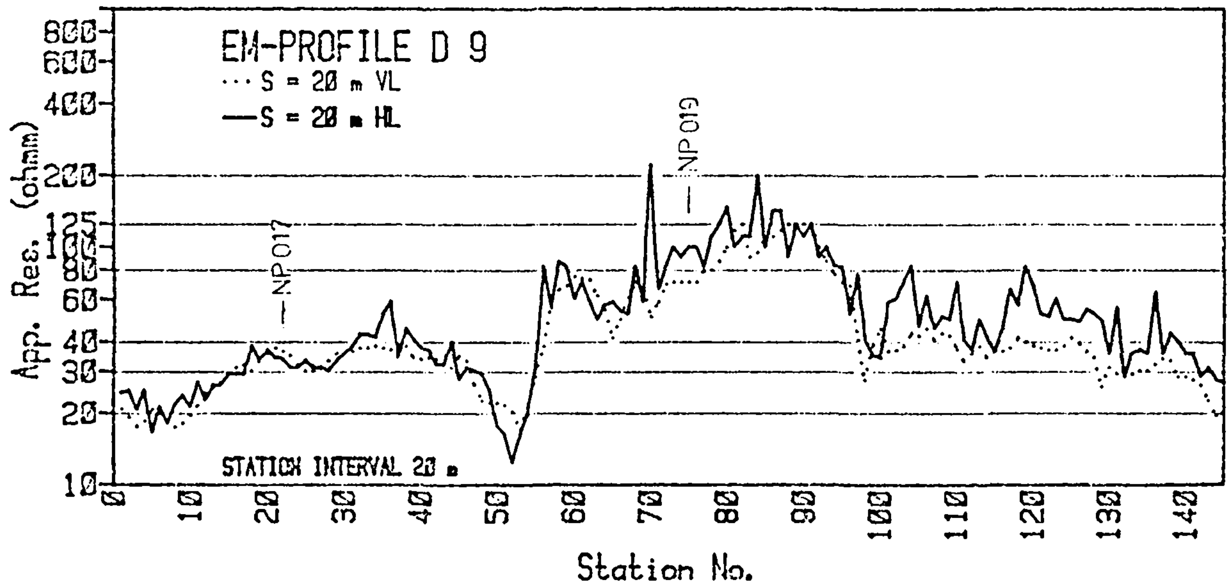
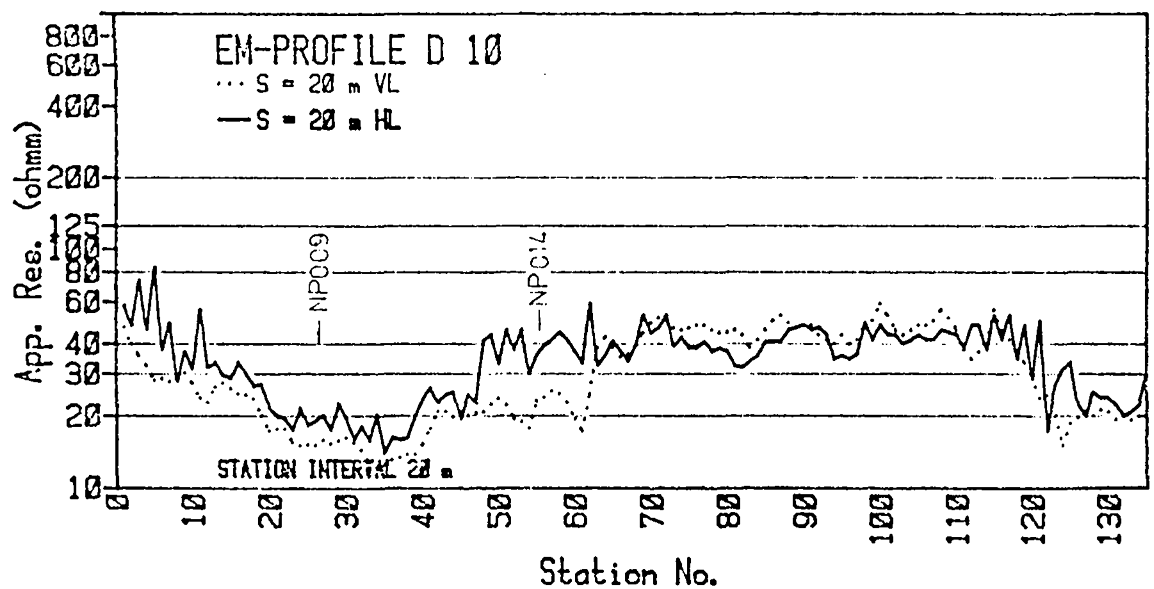


(ee)

Figure B.6 dd,e

COMPUTER PLOT OF EM GRAPHS



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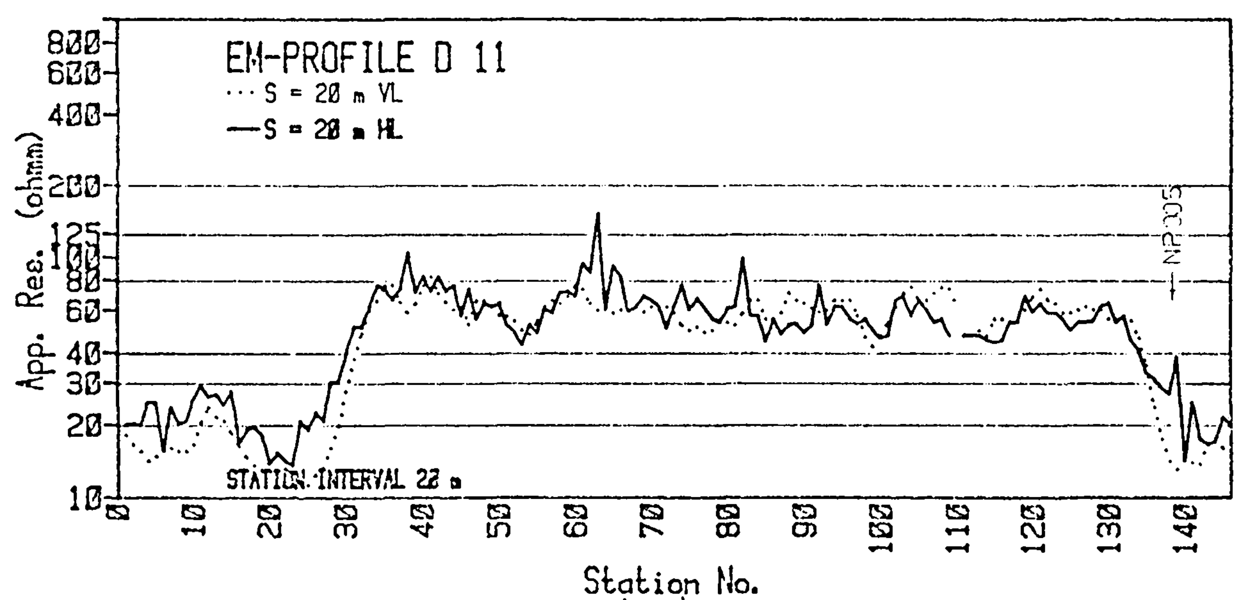
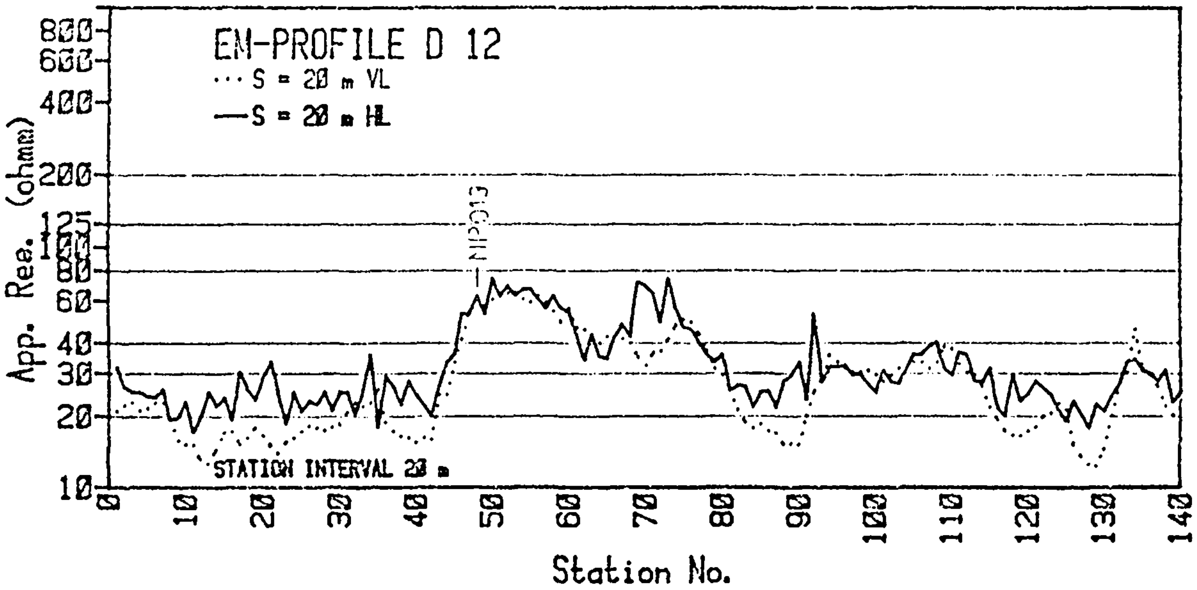


(gg)

Figure B.6 ff,gg

COMPUTER PLOT OF EM GRAPHS



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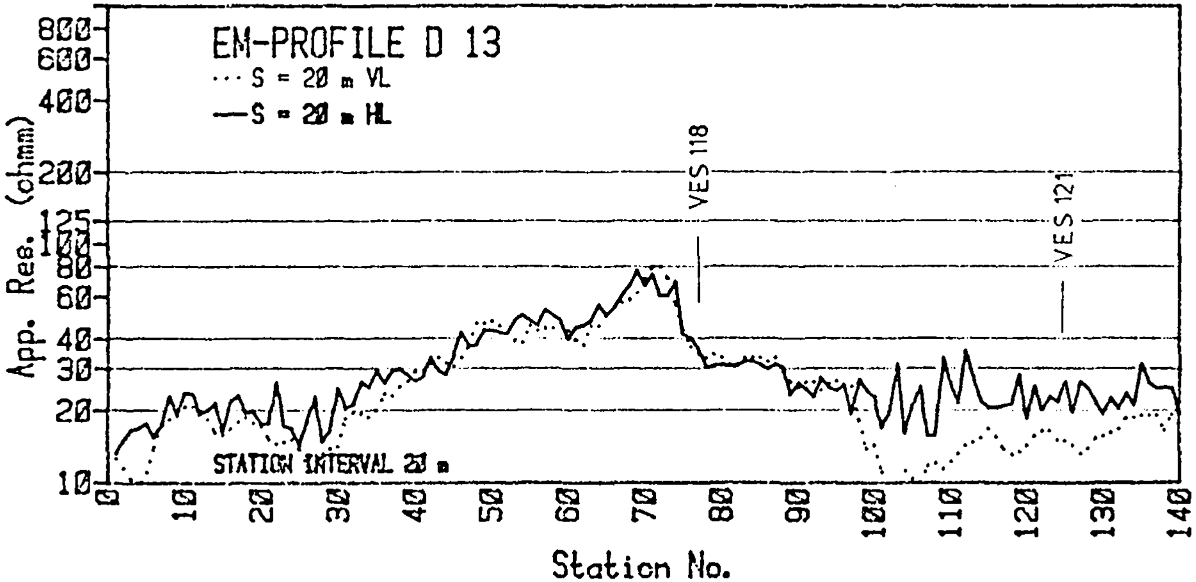
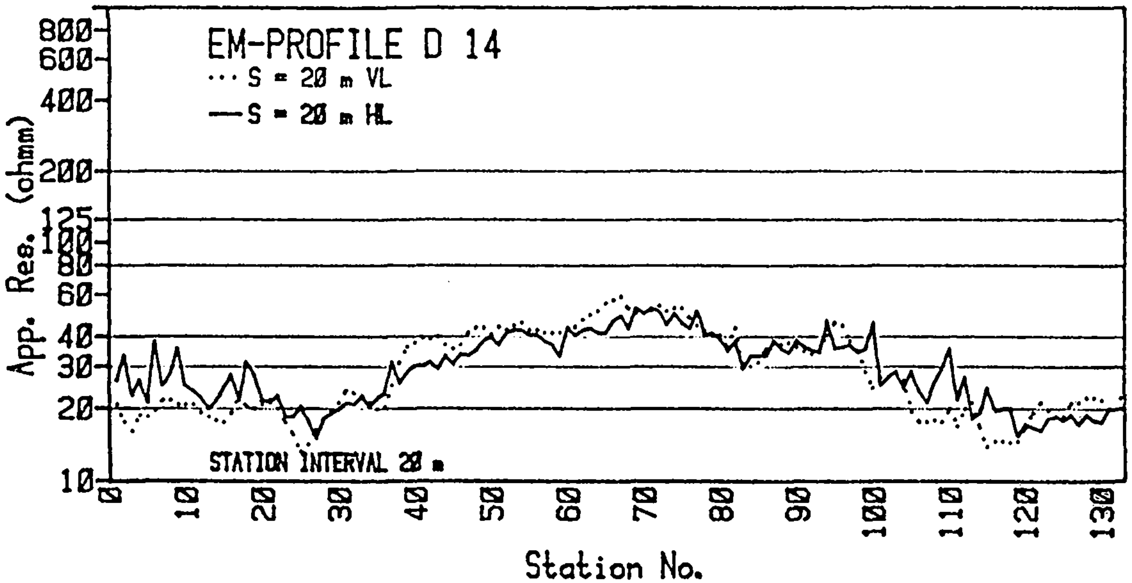


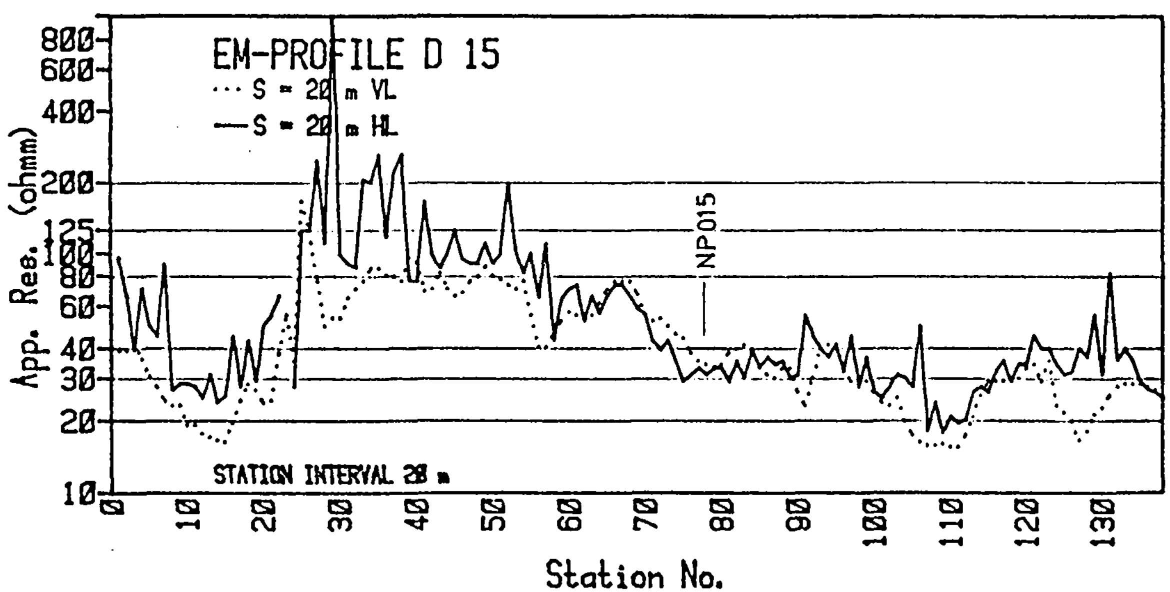
(ii)

Figure B.6 hh, ii

COMPUTER PLOT OF EM GRAPHS



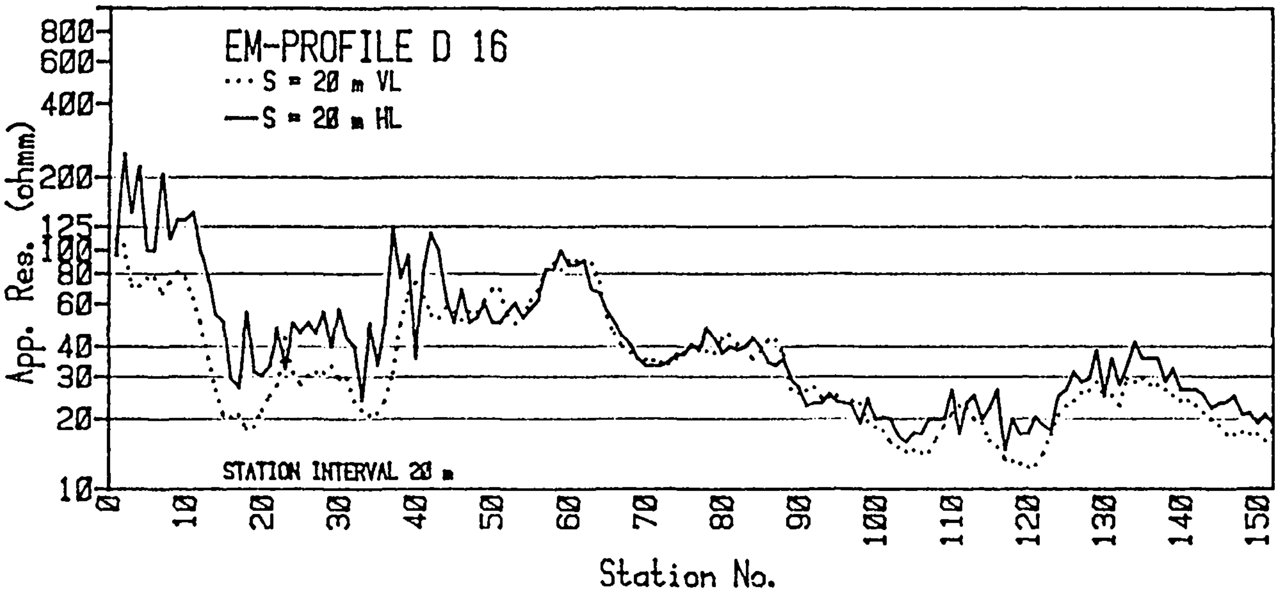
(jj)



(kk)

Figure B.6 jj,kk

COMPUTER PLOT OF EM GRAPHS



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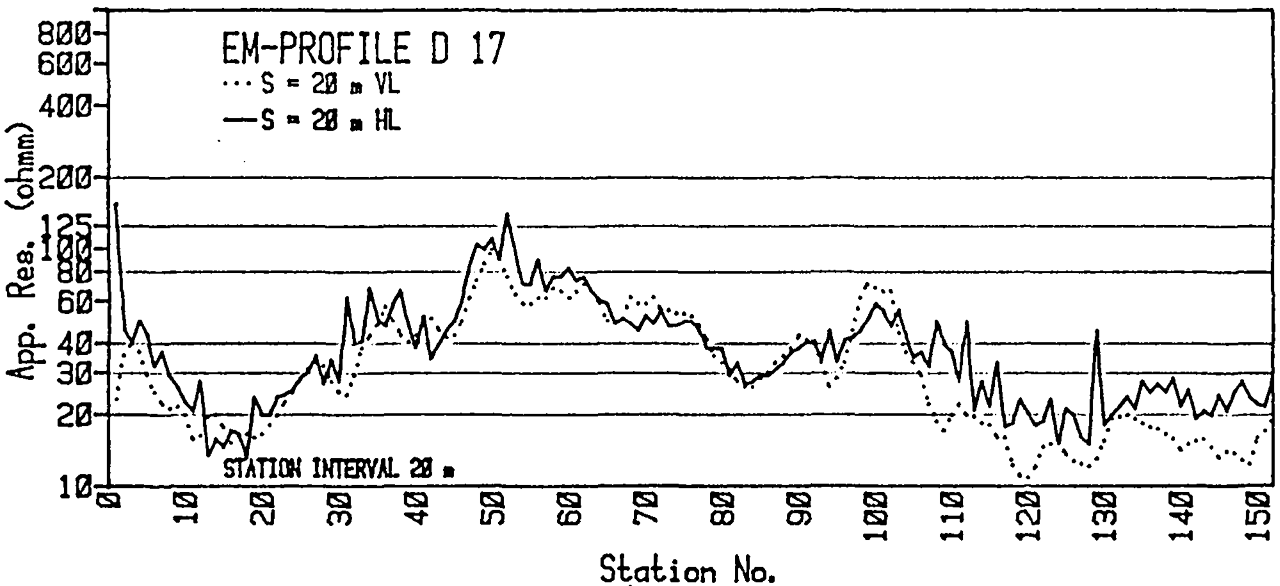
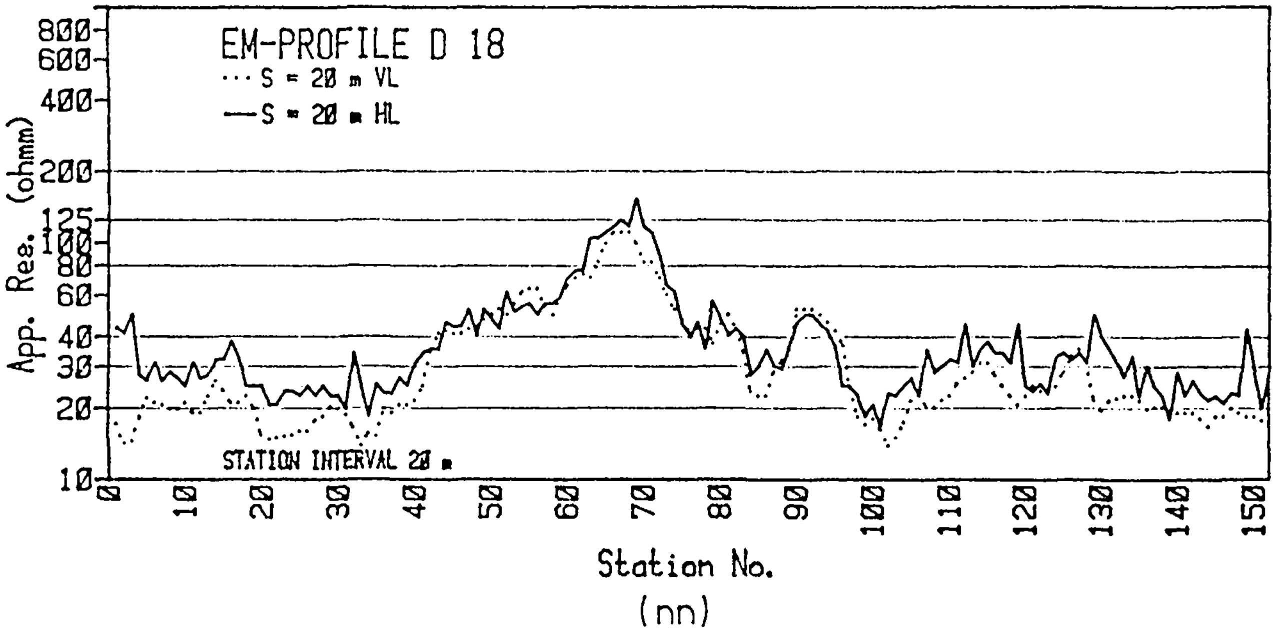


(III)

Figure B.6 II, III

COMPUTER PLOT OF EM GRAPHS



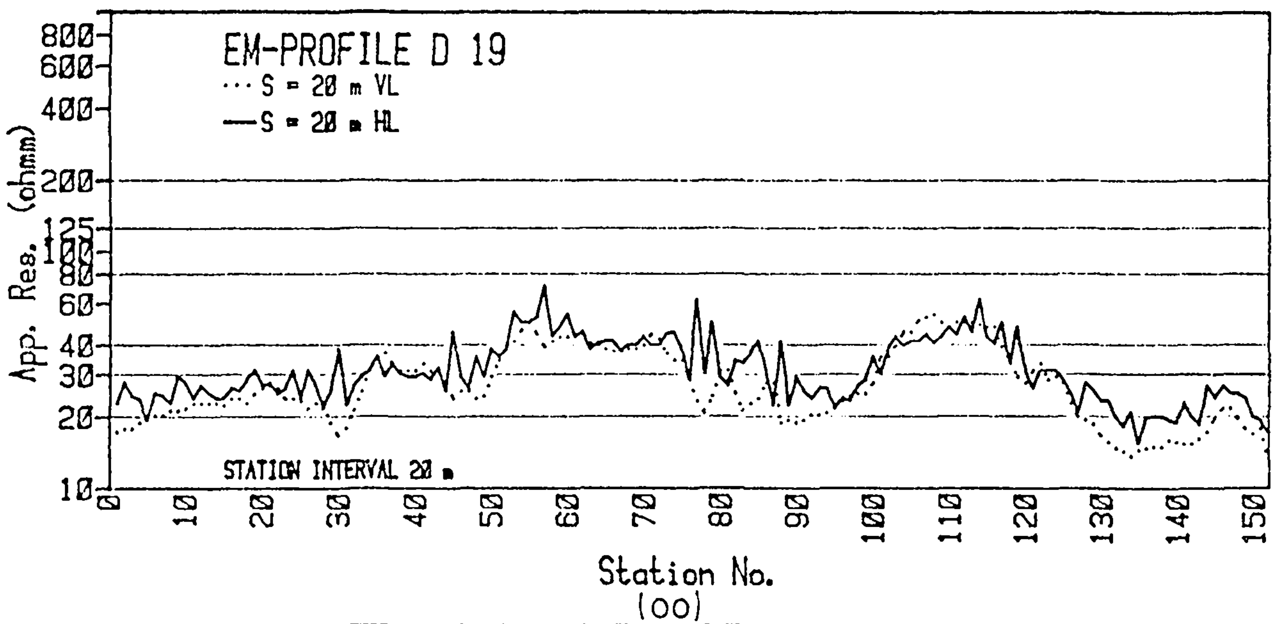
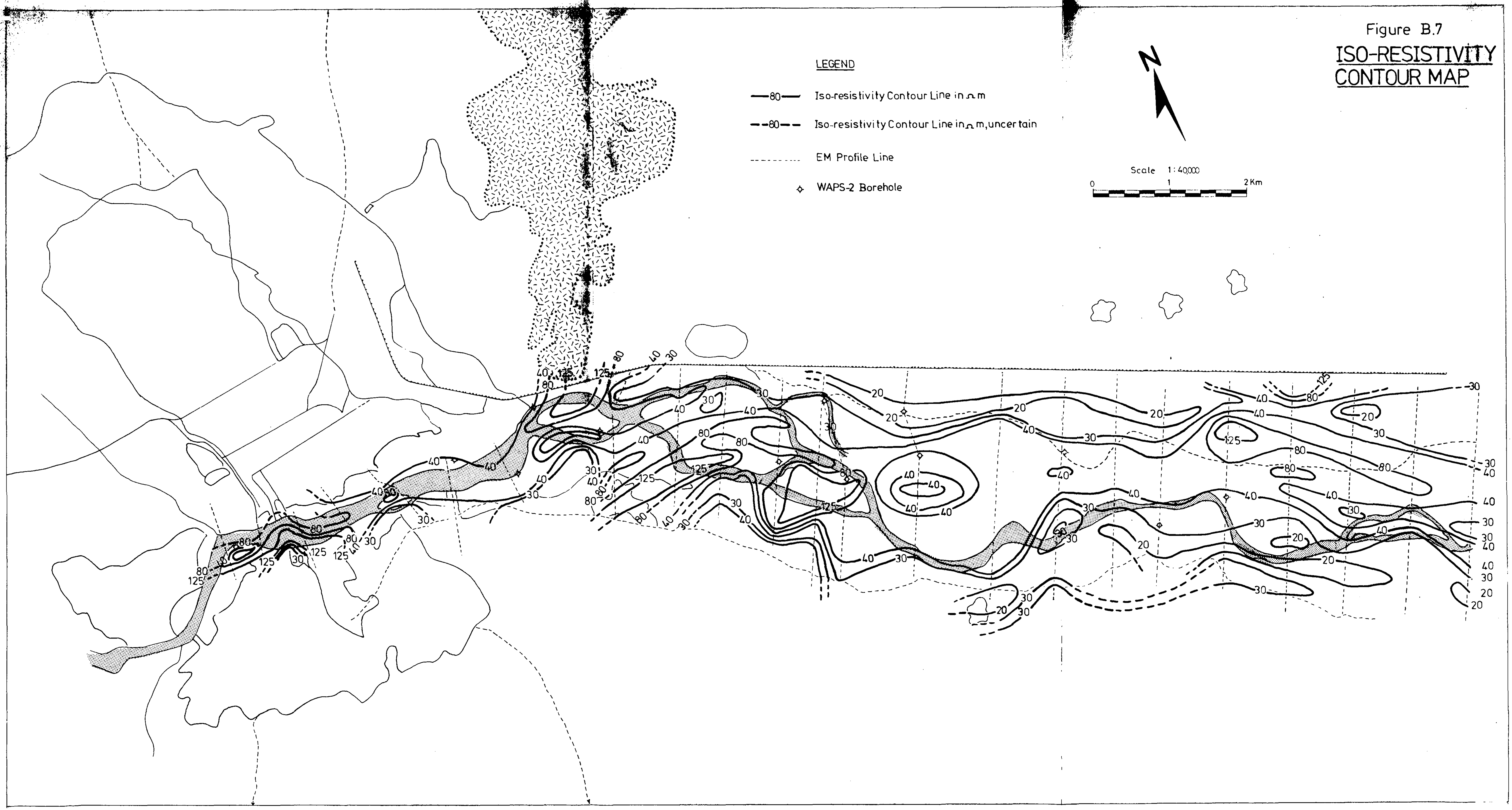


Figure B.6 nn,oo

Figure B.7

ISO-RESISTIVITY CONTOUR MAP



APPENDIX C

ELECTRICAL RESISTIVITY SURVEY

C.1 Principles

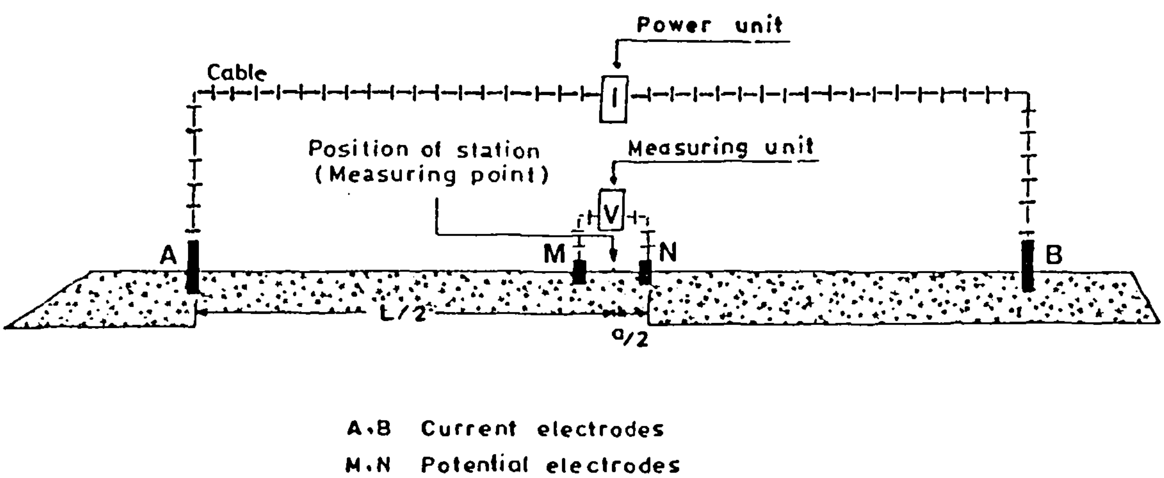
The principles of electrical resistivity methods of investigation are described in detail in many geophysical handbooks (e.g. Telford et al, 1976). Only a short outline will be given here.
The methods used during this project are based upon the measuring of an electrical potential difference by means of measuring-electrodes M and N, generated by a current which is injected into the earth, by means of two current electrodes A and B (see figure C.1). The relation between the current and the potential difference is given by:

$$\Delta V = \frac{\rho I}{C} \qquad \text{(C 1.1)}$$

Where ΔV = measured potential difference (V)
I = measured electrical current (A)
ρ = electrical resistivity (Ωm)
C = geometric constant (m)

The value of C is determined by the configuration of the electrodes. In the Schlumberger and the Wenner array (or configuration) the four electrodes are in one line, the midpoints of the electrode pair A and B coinciding with that of electrode pair M and N.

Figure C.1
Schlumberger Array



For the Schlumberger array, the value of C is given by:

$$C_s = \pi \frac{(AB)^2 - (MN)^2}{4\ MN}, \qquad MN \ll AB \quad (C\ 1.2)$$

where:

AB = distance L between the two outer, current electrodes (m)

MN = distance a between the two inner, potential electrodes (m)

For the Wenner array, the distances AM, MN, and NB are equal.
The value of the constant C is simplified to:

$$C_w = 2\ \pi \qquad (C\ 1.3)$$

where:

a = distance between adjacent electrodes (m)

Formula (C 1.1) can be rewritten as:

$$\rho = C\ \frac{\Delta\ V}{I} \qquad (C\ 1.4)$$

Using this formula, the electrical resistivity of the subsurface can be calculated from the measured values of ΔV and I. In a real case where the subsurface is layered and heterogeneous, the resistivity computed from equation (C 1.4) is defined as the apparent resistivity ρ_a. Only in case of a homogeneous earth, ρ_a is equivalent to the actual resistivity. The expected ranges of electrical resistivities of the rocks and unconsolidated sediments in the Nyala area are listed in table B.2 of Appendix B.

One application of the electrical resistivity method is horizontal electrical profiling (HEP). With this technique, all four electrodes are hold at fixed distance of each other and are shifted along a profile line after each reading of the apparent resistivity. From this, the lateral distribution of the apparent resistivity at a certain depth range (that depends on the fixed distance between the electrodes used and the electrical resistivity distribution of the subsurface) is measured. In many cases, changes in apparent resistivity are related to hydrogeological varations, like lithology and groundwater quality.

Another application of the electrical resistivity method, that is of more importance for groundwater studies, is the vertical, electrical sounding (VES) technique. By measuring the ρ_a for increasing values of AB, the relationship between ρ_a d L/2 is obtained. By plotting ρ_a gainst L/2 on double logarithmic paper, the relationship is represented by a smooth current, which can be interpreted quantitatively. The interpretation is done primarily with the aid of standard curves (master curves) and finally, using a desktop computer with plotter. The form of the VES curve over a horizontally stratified medium is a function of the resistivities and thicknesses of the layers.

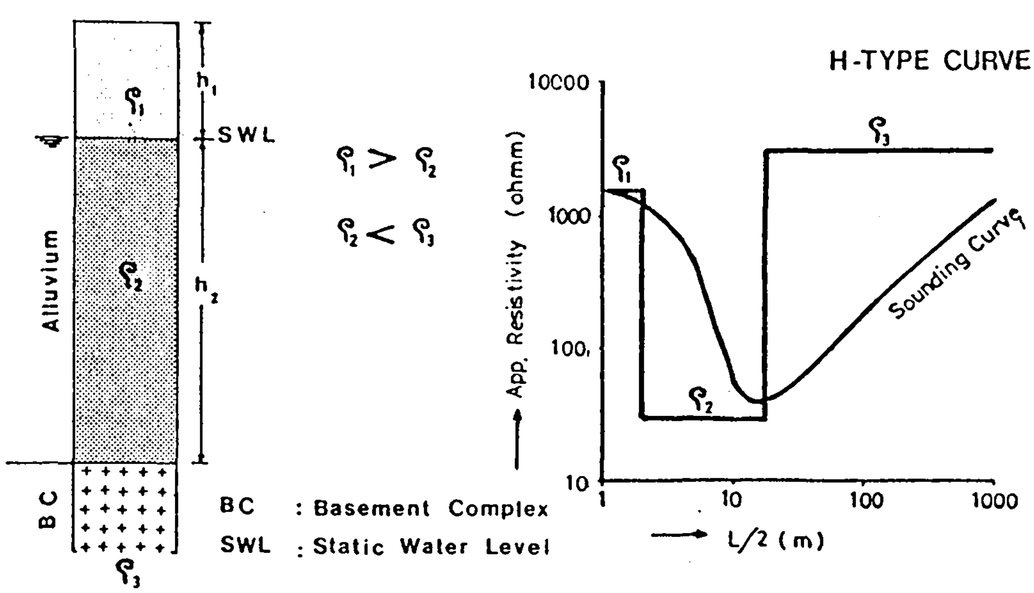
In the survey area, the wadi aquifer can be simplified in many cases as a geo-electrical three-layer model (see figure C.2):

1. a dry alluvial top layer of resistivity ρ_1 and thickness h_1;
2. an intermediate satured alluvial layer of resistivity ρ_2 nd thickness h_2;
3. the Basement Complex of resistivity ρ_3 and infinite thickness.

In most cases, the relation between ρ_1, ρ_2, and ρ_3 is: $\rho_1 > \rho_2$
$\rho_2 < \rho_3$

Figure C.2

Typical Geo-electrical Section of Wadi Alluvium with Corresponding VES Curve



Inside the wadi bed, and on sandy parts of both banks, the values for ρ_1, ρ_2, and ρ_3 e mostly: ρ_1 > 500 Ωm, ρ_2 < 100 Ωm, and ρ_3 > 1500 Ωm. The corresponding sounding curve is discribed as a H-type electrical resistivity sounding curve; see figure C.2. Because of the high electrical resistivity of the Basement Complex rocks, the terminal branch of the measured curve rises at an angle of 45^o.
A geo-electrical parameter which is useful for qualitative interpretations, the S-value (i.e. the total longitudinal unit conductance), can easily be determined for this type of curve.
The S-value is defined as the sum of the ratios of thicknesses and resistivities of all the layers above the lowest, high resistivity, infinite layer. It indicates the total conductivity of the layers for electrical current flow parallel to the layer bedding.

For the above mentioned layer model, the S-value is equal to

$$S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} = \frac{H}{\bar{\rho}_L} \qquad \text{(Siemens)}$$

Where H is the total thickness of the alluvium, and $\bar{\rho}_L$ is the average longitudinal resistivity. The average longtudinal resistivity is defined as

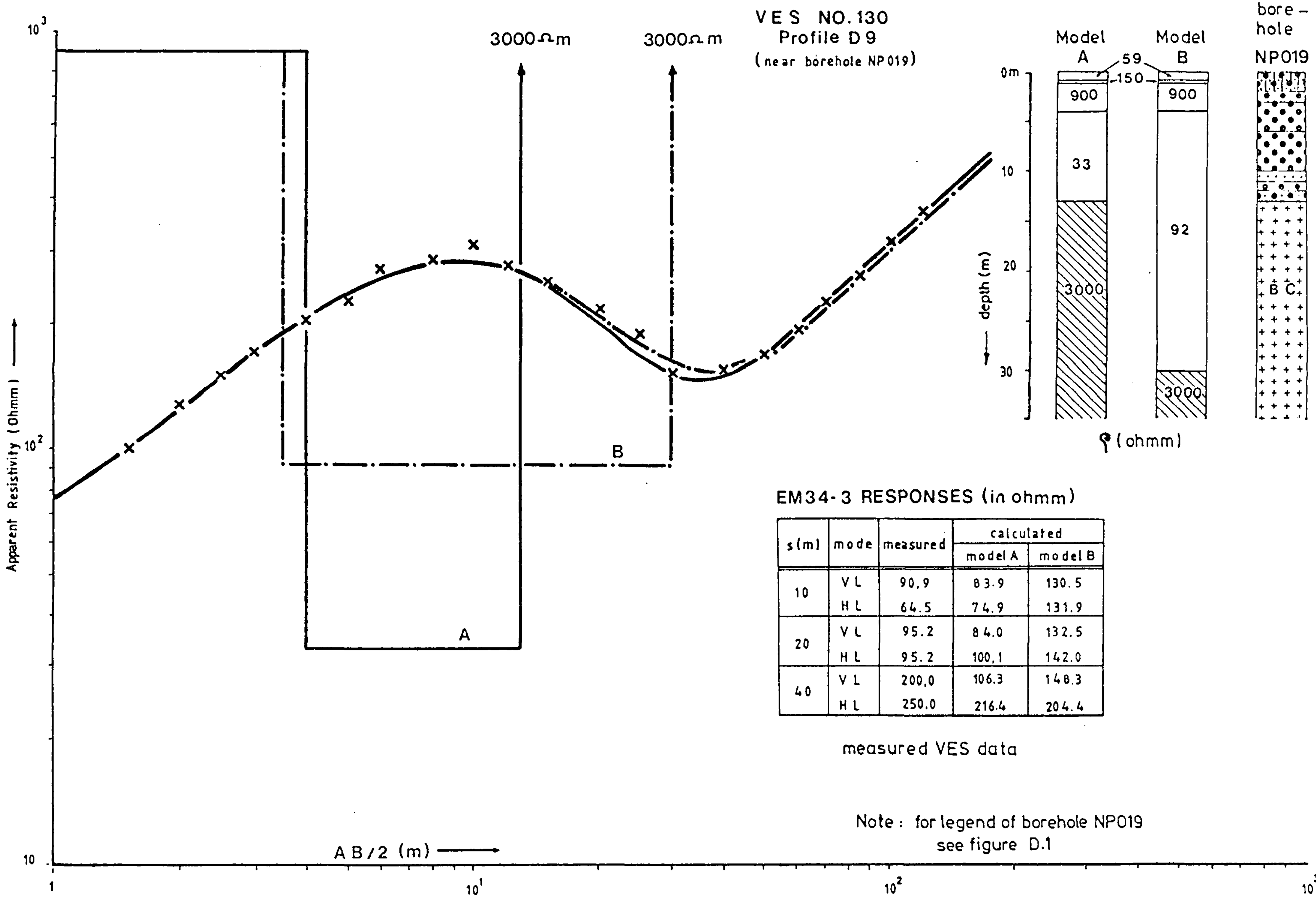
$$\bar{\rho}_L = \frac{H}{S} = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{\rho_i}} \qquad (\Omega m)$$

An increase of S-value from one VES station to another can indicate an increase of the total thickness H of the alluvium, a decrease in the average longitudinal resistivity $\bar{\rho}_L$, or both.

For the H-type curve, the S-value can be approximated graphically by the intercept of the extension from the slope of the terminal 45^o branche with the horizontal line ρ_a = 1 Ωm.

The VES technique has limitations, which particularly holds for a study of a shallow alluvial aquifer. These limitations are:

a. principle of equivalency (or non-uniqueness problem). A VES field curve can be interpreted into several layer models, with different depths to the Basement Complex and with different resistivities for the alluvial deposits.
   The S-values of these models are nearly equal.
   As an example two possible layer model interpretations of VES no. 130 (near borehole NP019) are shown in figure C.3. Within the limits of error, the two model curves fit the same field curve equally well. This means that when applying the VES technique for the alluvial aquifer under study, in many cases it is not possible to distinguish between a thin clayey, sandy alluvium (33 Ωm) and a sandy alluvium (92 Ωm) with a greater depth (30m) to the Basement Complex. Additional EM34-3 measurements on the VES location are a useful tool to narrow the the range of acceptable models. In chapter 6, section 6.2.3 a procedure is given for the combined use of the VES technique and the EM34-3 system. See also van Kuijk (1984).
   In the example of figure C.3 the model which comes nearest to the actual subsurface configuration is layer model A with a depth to basement of 13 m, and with resistivity of 33 Ωm for the main part of the alluvium. The calculated EM34-3 responses of this model correlate best with the EM field data.
b. principle of suppression (a special case of the principle of equivalency). The detection of a layer depends on its relative thickness and the resistivity contrast to other layers. The relative thickness of a layer is defined as the ratio of the bed thickness to its depth of burial; the smaller the value, the less its detectability in a sounding curve. Under favourable conditions (with resistivity contrasts that are large enough), the minimum relative thickness for detection is 0.2.
c. the quantitative interpretation theory for VES curves over layered strata assumes that the layers are laterally homogeneous and horizontal. If they are not, calculated depths and resistivities are in error. It is important therefore, to test for lateral inhomogeneity when carrying out a sounding. A method to do this is to employ EM34-3 measurements along the (expected) length of the sounding spread.



EM34-3 RESPONSES (in ohmm)

s(m)	mode	measured	calculated	
			model A	model B
10	VL	90.9	83.9	130.5
	HL	64.5	74.9	131.9
20	VL	95.2	84.0	132.5
	HL	95.2	100,1	142.0
40	VL	200,0	106.3	148.3
	HL	250.0	216.4	204.4

EXAMPLE OF EQUIVALENCY OF VES CURVES

Figure C.3

C.2 Intrumentation

Two electrical resistivity instruments, the GEA 51 and the GEA 76 and their accessories have been used during the survey. Both instruments are manufactured by TNO-DGV Institute of Applied Geoscience, Delft, The Netherlands.

VES no's. 003, 013-093, 126-139 have been performed with the GEA 51, and no's. 094-125 with the GEA 76. The two instruments have been tested at the same location to check for identical operation. The specifications of both instruments are given in tables C.1 and C.2, respectivally. With the standard equipment, soundings with current electrode spacings L/2 (see figure C.1) of up to 1000 m can be made.

As a power source two heavy duty car batteries of 12V, 100 to 135 Ah have been used.

The GEA 51 consist of two separate casings, a power unit and a measuring unit. The GEA 76 is built into one instrument casing and is mounted on a 19" rack.

Table C.1 GEA 51 Resistivity Instrument Specification

Manufactured by	: TNO-DGV Institute of Applied Geoscience, Delft, The Netherlands
Power Unit	
Power output	: max. 250 W continuously
Output current	: max. 3.15 A DC
Range of output voltage	: 50-100-200-400-1000 V DC
Input voltage	: 24 V
Input current	: max 15 A DC
Measuring Unit	
Voltmeter	: Philips DC-microvoltmeter PM2434
Measuring Range	: 10 µV to 1000 V in 17 ranges
Input impedence	: 1 MΩ in the range to 30 mV 10 MΩ in the range of 100 - 300 mV 100 MΩ in the range of 1 - 1000 V
SP compensation	: from - 300 mV to + 300 mV or in steps of 30 mV continuous regulation from - 40 mV to + 40 mV
Power supply	: 4 dry cell batteries of 1.5 V each

Table C.2 GEA 76 Resistivity Instrument Specification

Manufactured by	: TNO-DGV Institute of Applied Geoscience, Delft, The Netherlands
Power unit	
Power output	: 250 W continuously
Power source	: 24 V DC; 15 A (e.g. 60 Ah car battery min)
Output switch	: hand operated on-off-reverse
Output voltage	: 0-250 V to 1000 V in 3 steps of 250 V; displayed continuously
Input current	: < 1.5 A (output off); < 2 A (output on without load)
Output current	: max. 1.2 A continuously, or 3 A during maximal 5 of every 25 seconds
Measuring part	
Volt meter	
input impedance	: 2 MΩ
scaling	: 0-3 mV to 0-100 V in 10 ranges; 1-3-10 sequence
sensitivity	: 20 μV/mm to 600 mV/mm
supply	: automatic recharged NiCd cells
Current meter	
scaling	: 0-100 mA to 0-3 A in 4 ranges; 1-3-10 sequence
sensitivity	: 650 μA/m to 20 mA/mm
accuracy	: 2.10^{-2} fs + 2.10^{-2} rd
SP compensation	
scaling	: ± 0-3 mV to ± 0-300 mV in 5 ranges; 1-3-10 sequence
sensitivity	: 3 μV/div to 300 μV/div
supply	: 2 x 1.5 V alkaline batteries
Instrument	
Dimension(incl. silent blocks)	: 380 x 450 x 330 (in mm)
Mass	: 32 kg
Conditions	: 0^oC to 45^oC; 80% rel.hum: other conditions optional

C.3 Field Technique

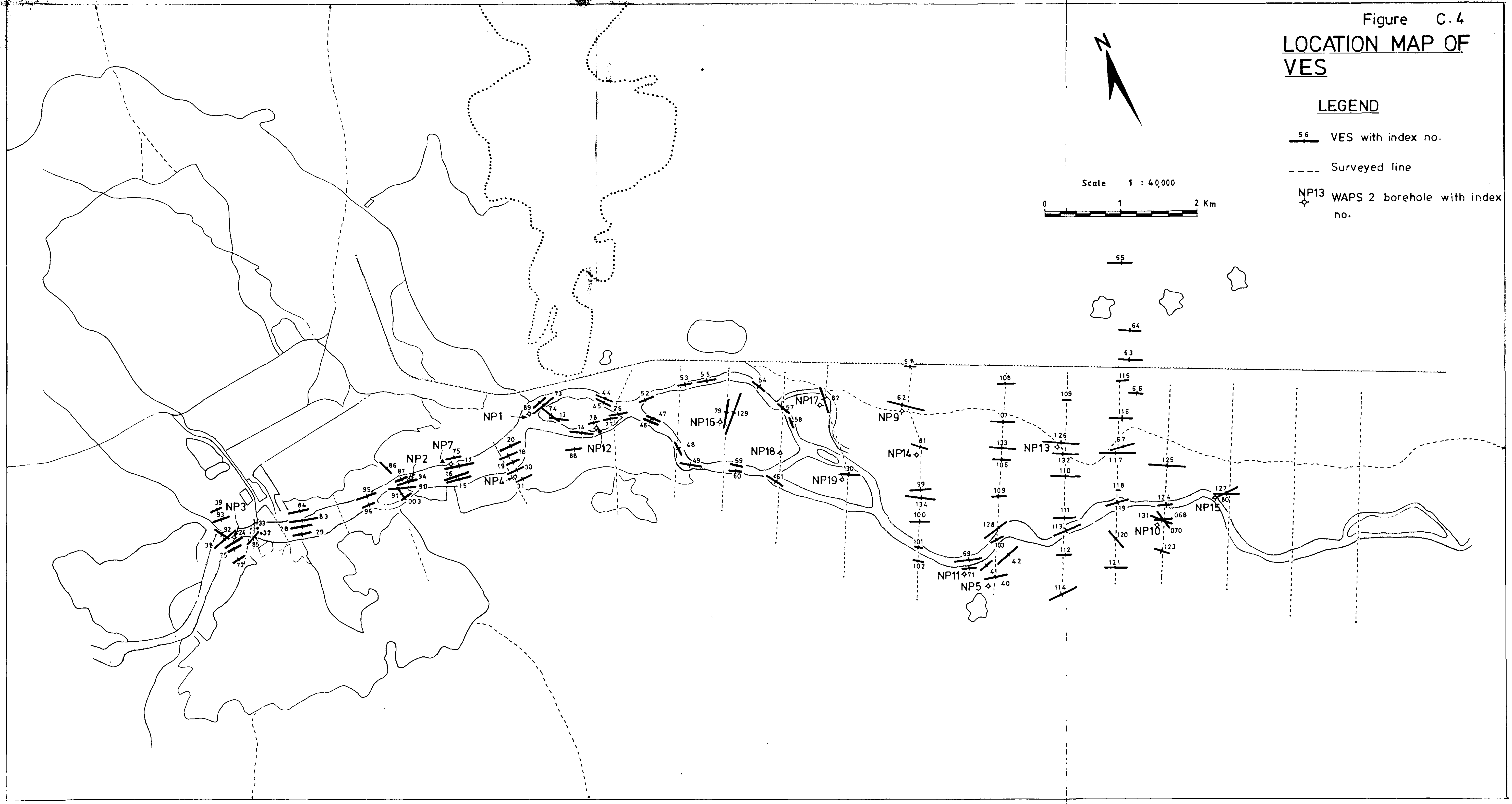
The location of a sounding is defined as the midpoint of the electrode configuration. Such a point will be called station (or measuring point). By increasing the distance between the outer, current electrodes, the vertical apparent resistivity distribution below the station is measured. The final distance between the two current electrodes (A and B in figure C.1) is called the total spread length of a VES. The distance between the potential electrodes M and N remains unchanged unless ΔV becomes too small to be accurately read. Then the spacing between the potential electrodes is increased.
For the measuring of vertical soundings, the Schlumberger array has been used.
For horizontal profiling, the Wenner array has been applied. The distance between two successive measurements along a profile line is called station (or measuring) interval.

Possible sources of errors are:

a. natural or spontaneous ground potentials (SP). They are caused by electrochemical effects or mechanical activity and are compensated in the field by a SP compensator, built in the instrument.
b. cultural noise i.e. electrical power lines, pipelines, reinforced concrete. It causes strong SP fluctuations or shortcut currents through metallic conductors. In many cases it shows as an irregularity in the field curve.
c. lateral inhomogeneities in the near surface layers in between the current electrodes. This mostly shows as an irregular variation in the apparent resistivity curve with increasing L/2 distance. This type of curve cannot be interpreted quantitatively.

Figure C.4

LOCATION MAP OF VES



C.4 Data Acquisition and Processing

A total number of 134 vertical electrical soundings has been made, for the major part located on or near surveyed profile lines. The total spread length L generally was between 200 and 300 m. The VES locations are shown on the map of figure C.4; the map also shows the spread directions and spread lengths on scale. A list of the soundings is given in table C.3.

Before the EM34-3 instrument became available 7 horizontal electrical profiles (HEP's) have been made with a total length of 44 km. The resistivity profiles were measured with a Wenner array, mostly with a = 30 m and with a station interval of 15 m.

Sources of error during the data acquisition are:

a. error in the location of a VES or a station of a HEP. The difference between the measuring point in the field and its indication on the map is considered to be no more than 50 m;
b. measurements which are located at a site which is not at a safe distance from cultural noises (see section C.3).

The processing of the electrical resistivity data mainly takes place in the field. With the VES-technique the apparent resistivity ρ_a vs. L/2 distances are plotted on double logarithmic paper; the relationship usually shows as a smooth curve, and is called a VES curve. With the HEP method, the field data are plotted on semilogarithmic paper, with the apparent resistivity data along the vertical, logarithmic axis, and the location of the stations on the horizontal scale. The main advantage of processing of resistivity data in the field is the quality control of the measurement. If a sounding curve is distorted, several checks in the field can be made to find out the cause of the distortion.
Because of the close agreement of the results of the HEP and the EM survey (see figure B.5.(a)) it was decided to continue solely with the EM method, because of its much higher speed of operation.

Table C.3 List of Vertical Electrical Soundings (VES's)

VES no.	Profile no.	Type of curve 1)	Spread length L (m)	Resistivity of top layer(Ωm)	Minimum apparent resistivity(Ωm)	S-value (Siemens) 2)	Notes
003	D1	KH	250	250	34	1.80	
013	D4	QH	170	1600	16	1.35	
014	D4	QH	300	230	32	2.00	
015	D2	H	350	560	40	1.60	
016	D2	KH	350	850	45	1.60	
017	D2	H	400	1100	43	0.75	
018	D2	KH	250	200	33	1.75	
020	D3	H	300	1800	30	1.45	
021	D3	H	250	2050	80	0.58	
022	D3	H	300	1900	30	1.70	
024	U4	KH	250	600	175	0.48	
025	U4	KH	200	630	46	1.20	
028	U2	KH	300	1000	132	0.64(?)	
029	U2	H	250	3500	20	0.70	
030	D3	HA	250	50	15	0.46	
031	D3	KH	250	20	75	0.50	
032		H(?)	350	600(?)	15(?)	-	near borehole BH 23
033		H(?)	300	300	85(?)	-	near borehole BH 23
034		H	200	20	9	0.70	Romalliya area
035		H	300	100	8	1.05	Romalliya area
036	D2	KH	250	30	22	1.00	
037	D2	KH	200	160	58	1.00	
038	U4	KH	400	850	70	0.52	
039	U4	A	170	22	-	0.25(?)	
040		H	300	30	10	1.50	near borehole NP 00
041		HKH	250	350	145,90	0.55	
042		HA	350	80	12	1.60	
043		KH(?)	60	50(?)	-	-	not completed
044		KH	250	20	62	0.55	
045		H	200	1400	95	0.42	
046		H	200	1100	40	1.10	
047		KH	250	480	70	0.66	
048		H	200	1450	48	0.60	
049		KHKH	300	600	170,310	0.30	
050		KH	200	440	28	1.00	
051		KH	200	300	70	0.66	
052		KH	200	280	36	0.90	
053		KH	200	120	22	1.30	
054		(K)H	250	500	16	2.00	
055		H	250	420	54	0.14	
056		H	200	180	12	1.10	
057		?	350	?	?	?	
058		KH	200	200	76	0.73	
059		H	170	900	48	0.75	
060		H	170	800	25	1.60	
061		H	300	1900	38	0.97	
062		H	400	35	12	2.15	near borehole NP 009
063		H	350	35	13	1.90	near Kalma village
064		H	300	55	10	2.80	near Kalma village
065		H	300	40	17	0.88	near Kalma village

(cont.) Table C.3 List of Vertical Electrical Soundings (VES's)

VES no.	Profile no.	Type of curve 1)	Spread length L (m)	Resistivity of top layer(Ωm)	Minimum apparent resistivity(Ωm)	S-value (Siemens) 2)	Notes
066		H	200	150	60	3.00	near Kalma village
067		KH	300	60	36	0.12	
068		KH	200	95	27	1.80	near borehole NP 010
069		KH	350	600	75	0.46	
070		KH	250	95	40	1.20	near borehole NP 010
071		KH	300	45	45	1.10	
072	U4	A	150	14	-	0.38(?)	
073	D4	QH	300	1650	52	0.44	
074	D4	H	300	1300	51	0.64	
075	D3	KH	250	500	33	1.20	
076		H	250	620	52	0.90	
077		H	200	1150	22	1.50	
078		KH	250	900	22	1.35	near borehole NP 012
079		NKH	400	75	45,58	1.70	near borehole NP 016
080		QH	350	650	58	1.30	near borehole NP 016
081		KH	200	14	12	0.80(?)	near borehole NP 014
082		HKH	400	530	48	1.80	near borehole NP 017
083	U2	H	400	800	185	0.18	
084	U2	KH	300	40	140	0.36(?)	
085		KH	250	300	137	0.31	50 m east of Mekkah Br.
086	D1	HKH(?)	250	23	22	1.20	
087	D1	H	200	1040	28	1.40	near borehole NP 002
088		H	200	20	16	1.50	
089	D4	KH	200	800	40	0.73	near borehole NP 001
090	D1	KH	350	660	71	1.00	
091	D1	KH	200	800	37	1.30	
092	U4	H(?)	250	530	113	0.34	
093	U4	H	200	30	18	0.64	
094		QH	300	600	85	0.56	near borehole BH 26
095		H	250	1600	50	0.52	
096		H	200	1750	30	0.88(?)	
097		H	350	1300	85	1.10	
098	D10	H	140	420	58	0.33	
099	D10	KH	250	165	75	0.80(?)	
100	D10	QH(?)	250	9500	85	0.75(?)	
101	D10	KH	120	750	27	1.00	
102	D10	H	140	100	14	1.63	
103	D11	H	200	1700	48	1.20	
104		KH	200	130	35	1.30	
105	D11	HA	250	62	48	0.72	
106	D11	KHKH	250	170	59,160	0.80	
107	D11	KH	250	38	50(?)	1.50	
108	D11	H	250	50	10	2.30	
109	D12	H	120	45	78	1.42	
110	D12	Q	400	18	61	1.10	
111	D12	HKH	300	340	44	1.55	
112	D12	KH	200	25	21	1.90	
113	D12	KH	350	750	47	1.50	
114	D12	HA(?)	400	250	29	1.20	
115	D13	H	200	900	67	0.29	
116	D13	H	350	360	25	1.70	

(cont.) Table C.3 List of Vertical Electrical Soundings (VES's)

VES no.	Profile no.	Type of curve 1)	Spread length L (m)	Resistivity of top layer(Ωm)	Minimum apparent resistivity(Ωm)	S-value (Siemens) 2)	Notes
117	D13	HKH	500	100(?)	46,72	1.00	
118	D13	KH	250	150	49	1.30	
119	D13	H(?)	350	2500	28	1.45	
120	D13	H(?)	300	310	87	1.55	
121	D13	H	300	500	97	0.14	
122	D14	-	-	-	-	-	not completed
123	D14	H	170	45	14	1.75	
124	D14	KH	200	490	33	1.12	
125	D14	HKH	500	150	36,77	1.25	
126	D12	HKH	500	100	100	0.85	near borehole NP 013
127	D15	?	350	950	40	1.90(?)	near borehole NP 015
128	D11	KH	400	60	75	1.20(?)	
129	D10	HKH	600	50	65	2.00	near borehole NP 014
130	D9	KH	250	100	155	0.34	near borehole NP 019
131	D14	KH	300	175	65	1.15	near borehole NP 010
132	D12	?	350	125	70(?)	1.10(?)	
133	D11	KH	350	95	85	0.70	
134	D10	KH	400	125	60	1.20	

1) A : three layer curve with $\rho_1 < \rho_2 < \rho_3$

H : three layer curve with $\rho_1 > \rho_2 < \rho_3$

HA : four layer curve with $\rho_1 > \rho_2 < \rho_3 < \rho_4$

KH : four layer curve with $\rho_1 < \rho_2 > \rho_3 < \rho_4$

QH : four layer curve with $\rho_1 > \rho_2 > \rho_3 < \rho_4$

HKH : five layer curve with $\rho_1 > \rho_2 < \rho_3 > \rho_4 < \rho_5$

KHKH : six layer curve with $\rho_1 < \rho_2 > \rho_3 < \rho_4 > \rho_5 < \rho_6$

2) S-value graphically determined from field curve.

C.5 Interpretation

Quantitative interpretations in most cases are not possible because of a combination of unfavourable conditions which prevail in the area under study. These conditions are:

a. high initial resistivity values on many locations caused by dry, sandy top layers, which mask information of the immediately underlying layers;
b. small values for the relative thickness of the alluvial layers, that consequently do not show up on the resistivity curve (principle of suppression);
c. relatively small resistivity contrasts between wet clayey and sandy layers in the aquifer. The saturated alluvium is 'sandwiched' between the resistive dry top layer and the resistive Basement Complex. Reliable layer model interpretations are arduous to perform.
d. rapid facies change in the alluvial fill of the wadi. In such an anisotropic medium interpretation will give erroneous values for the depth to alluvial interfaces and to the Basement Complex.

Because of the conditions mentioned above the major part of the resistivity soundings has been analysed qualitatively. After the preliminary results of the EM-survey became available, it was clear that in most cases the VES locations did not satisfy the condition of lateral homogeneity within the spread length of the sounding. This was confirmed by boreholes and jetting profiles drilled during the WAPS-2 project.

From the VES field curves the following qualitative information about the alluvium is deduced:

a. The resistivity of the top layer;
b. the minimum apparent resistivity of H-type curves. It indicates the maximum value for the resistivity of the saturated part of the alluvium;
c. the S-value.

For some soundings in the phase II Downstream Area, a proper application of the combined use of the VES technique and the EM 34-3 system could be performed which makes it possible to apply the quantitative VES layer model interpretation technique. After the EM

survey was completed and an iso-resistivity contour map was compiled, only a small amount of VES's could be selected on locations where the spread did not cross large lateral resistivity variations. Futhermore over the spreads of these selected soundings an additional EM-profile was measured to check in detail the condition of lateral homogeneity of the sounding location.
The selected soundings for the layer model interpretation are listed in table C.4. Use was made of a programme on a HP85 desktop computer. The results of the calculated layer models are presented in figure C.5. To limit the problem caused by equivalence, the computer programme was extended with an option to calculate the EM 34-3 system responses of the VES layer model. By comparing the calculated EM34-3 responses with the EM field data, the range of acceptable models could be narrowed. For an example of this procedure see figure C.3. The list of the selected soundings (table C.4) also shows the interpreted layer models and the corresponding calculated EM 34-3 responses, together with the measured EM 34-3 values.

VES no. 118 has a lower interpreted value for the layer just above the Basement Complex (9 Ωm) than is expected based on the analyses of the EM profiles. No plausible explanation can be given for this feature.

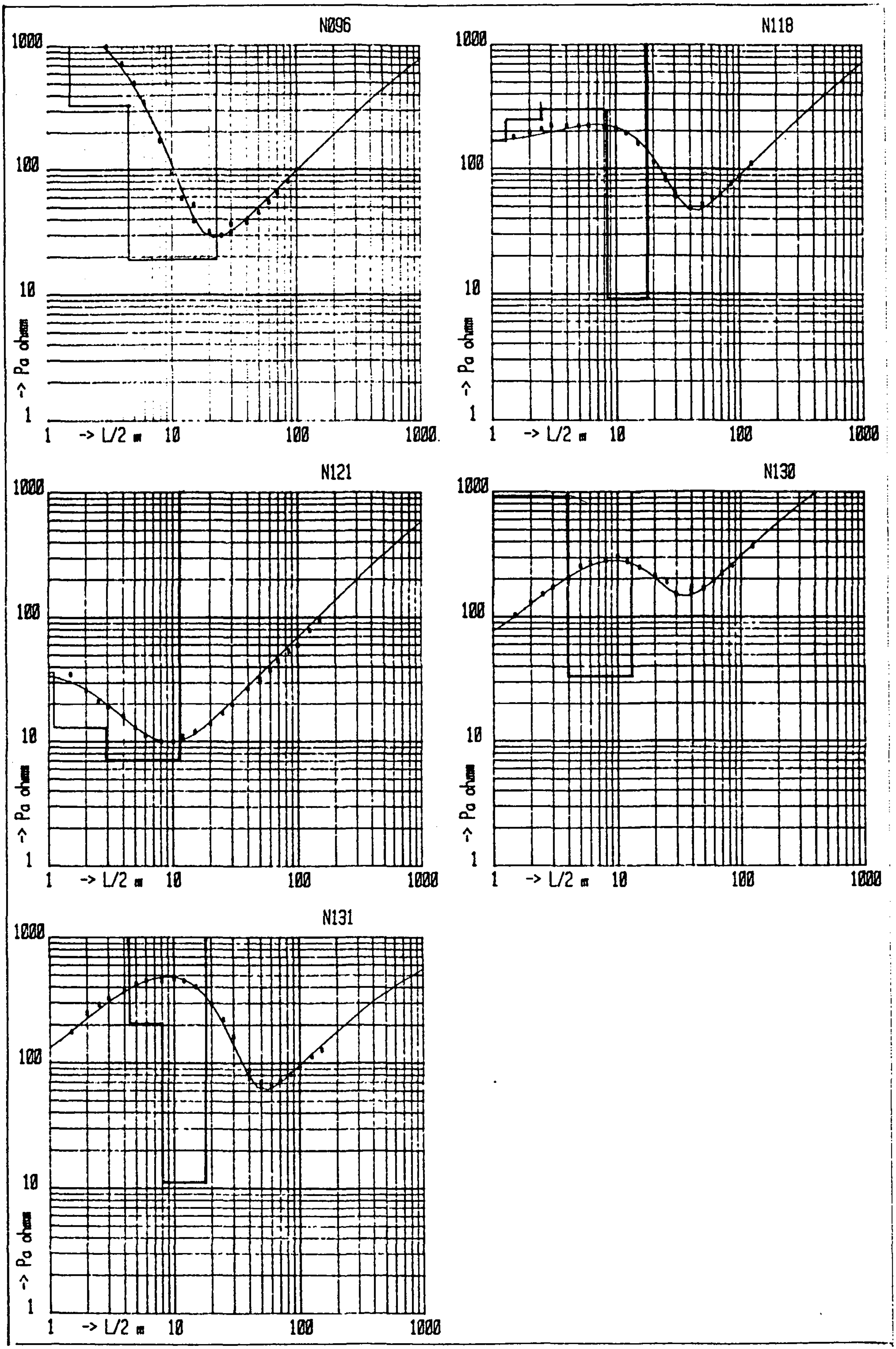
To apply this procedure, both the VES and the EM34-3 data must have been acquired in the same season, because the difference in groundwater level in the dry and the wet season affects the measured apparent resistivity values; see section B.1.

Table C.4 List of Selected Soundings for Layer Model Interpretation

VES no.	EM Profile no.	Layer model Depth (m)	Res. (Ωm)	Em 34-3 Responses (in Ωm) s (m)	mode	calculated	measured
096	100 m W of 051	0.0- 1.5	1650	20	VL	41.9	42.6
		1.5- 4.5	330		HL	36.5	40.8
		4.5-23.0	19				
		23.0- ∞	3000				
118	D13	0.0- 1.3	165	10	VL	54.6	46.5
		1.3- 2.5	250		HL	35.1	33.4
		2.5- 8.5	300	20	VL	40.2	38.6
		8.5-18.0	9		HL	31.6	32.3
		18.0- ∞	3000	40	VL	39.2	52.6
					HL	49.5	51.8
121	D13	0.0- 1.1	36	10	VL	12.9	16.3
		1.1- 2.9	13		HL	12.8	15.2
		2.9-11.5	7	20	VL	14.3	15.5
		11.5- ∞	3000		HL	20.9	20.8
				40	VL	19.9	27.4
					HL	52.4	55.6
130	D9 (near NP019)	0.0- 0.7	59	10	VL	83.9	90.9
		0.7- 1.0	150		HL	74.9	64.5
		1.0- 4.0	900	20	VL	84.0	95.2
		4.0-13.0	33		HL	100.1	95.2
		13.0- ∞	3000	40	VL	106.3	200.0
					HL	216.4	250.0
131	D14 (near NP010)	0.0- 0.6	83	20	VL	45.4	45.5
		0.6- 4.4	1160		HL	36.0	37.7
		4.4- 8.0	200				
		8.0-18.0	11				
		18.0- ∞	1000				

PLOT OF SELECTED VES

Figure C.5



APPENDIX D

WELL AND BOREHOLE DATA

Table D.1 Well Inventory Summary Nyala

Well no.	Well Dia. (m)	Well Depth (m)	Water depth S.W.L (m)	D.W.L (m)	Water quality EC. (µS/cm)	pH	Pump Inst?	Pump Yield (m³/h)	Annual yield Total (m³)	Irrig. (m³)	Domestic (m³)	Condition of well	Remarks
1													PE & WC-covered with zinc sheets.
14	3.75	8.22	6.00	-	380	?	yes	16.8	40300	40300	-	fair	Nurserey-well.
15	3.07	8.20	5.90	-	480	?	yes	13.1	37728	27728	-	fair	
16	1.75	7.80	-	7.50	?	?	yes	15.5	16275	-	16275	good	It gets dry when pumping
17	1.70	5.70	-	4.70	220	7.9	yes	?	?	?	2920	fair	Motor is out of order.
18	2.00	7.70	4.40	-	?	?	no	-	-	-	-	bad	Out of use.
19	3.00	8.50	-	5.94	360	?	yes	24.9	64000	35000	29000	good	Two motors were installed one out of use
20	1.75	4.95	4.28	-	450	8.7	no	-	-	-	-	good	Depth to B.C. (2.00 m.)
21	3.00	8.10	5.63	-	700	?	yes	?	?	-	?	good	In brick yard.
22	4.70	5.10	3.88	-	860	?	no	-	-	-	-	fair	Of not nice smell.
23	1.50	9.00	4.90	-	520	?	no	-	-	-	-	fair	They use it during dry season.
24	1.50	6.20	-	5.00	520	?	no	-	1460	-	1460	fair	Used for drinking.
25	-	-	-	-	-	-	-	-	-	-	-	-	Buried (old inventory).
26	-	-	-	-	-	-	-	-	-	-	-	-	Buried (previous inventory).
28	3.70	7.40	4.40	-	?	?	yes	-	-	-	-	good	The motor out of order.
29	4.04	5.90	-	5.00	320	?	yes	25.2	18144	18144	-	good	
30	?	?	?	?	?	?	?	?	?	?	?	?	Not found in the field.
31	-	-	-	-	-	-	-	-	-	-	-	-	It used as W.C. (in a house)
32	1.50	9.55	9.20	-	?	?	yes	-	-	-	-	fair	It contains not enough water.
33	1.20	3.22	dry	-	?	?	no	-	-	-	-	not good	The well was collapsed.
34	1.50	7.86					no	-	-	-	-	good	Out of use.
35	?	?	dry	-	?	?	no	-	-	-	-	not good	Out of use.
36	1.20	4.50	dry	-	?	?	no	-	-	-	-	not good	Out of use.
37		2.70					no	-	-	-	-	not good	Not actual depth.
38	1.60	6.50	?	?	?	?	no	-	-	-	-	good	Out of use.
39	1.20	6.30	dry	-	-	-	no	-	-	-	-	good	It contains water during wet season.
40	1.35	8.90	dry	-	-	-	no	-	-	-	-	not good	It gets wet during wet season.
41	2.50	6.84	dry	-	-	-	no	-	-	-	-	fair	Out of use.
42	1.50	5.80	dry	-	-	-	no	-	-	-	-	not good	Out of use.
43	3.15	2.64?	dry	-	-	-	no	-	-	-	-	good	Not actual depth. It doesn't contain water during kharif.
44	1.20	5.10	?	?	?	?	no	-	-	-	-	not good	Out of use.
45	-	-	-	-	-	-	-	-	-	-	-	-	Buried.
46	?	?	?	?	?	?	?	?	?	?	?	?	In a house.
47	2.50	9.50	7.68	-	?	?	no	-	-	-	-	not good	Out of use.
48	1.00	7.50	7.00	-	?	?	no	-	-	-	-	fair	The pump was removed.
49	-	-	-	-	-	-	-	-	-	-	-	-	Buried.
50	-	-	-	-	-	-	-	-	-	-	-	-	Well not found.
51	?	8.70	5.50	-	400	?	yes	?	?	?	?	good	Out of use for long time.
52	-	-	-	-	-	-	-	-	-	-	-	-	Buried (old inventory file)
53	-	-	-	-	-	-	-	-	-	-	-	-	Buried.
54	-	-	-	-	-	-	-	-	-	-	-	-	Washed by the wadi.
55	4.00	10.00	-	9.60	800	?	yes	?	?	?	?	not good	No fuel to run the motor.
56	2.10	8.05	6.30	-	640	?	yes	?	?	-	?	good	No one to run the motor.
57	1.50	8.85	7.75	-	510	?	yes	?	?	?	?	good	It contains not enough water.
58	2.60	9.15	7.70	-	720	?	yes	18.2	20000	?	13000	good	It is used also for drinking.
59	3.50	7.45	-	-	-	-	yes	-	-	-	-	fair	The well is dry in April 1985.
60	3.00	5.25	4.90	-	270	?	yes	?	?	?	-	not good	Out of use due to the motor.
61	2.00	5.95	5.65	-	540	?	no	-	-	-	-	good	Out of use.
62	1.50	4.75	dry	-	-	?	no	-	-	-	-	not good	It contains water during wet season only.
63	1.50	7.60	6.00	-	360	?	yes	12.6	45360	-	45360	fair	
64	1.50	3.63	dry	-	-	-	no	-	-	-	-	not good	It floods by the wadi.
65	-	-	-	-	-	-	-	-	-	-	-	-	Buried (old inventory file).
66	1.50	7.42	7.08	-	440	?	no	-	-	-	-	not good	Out of use.
67	2.00	5.92	4.33	-	300	?	yes	?	?	?	?	not good	Out of use due to the motor.
68	1.50	5.18	dry	-	-	-	no	-	-	-	-	not good	It contains water during wet season.
69	3.50	8.30	6.27	-	400	?	yes	?	?	?	-	not good	
70	2.22	7.00	4.54	-	240	?	yes	15.6	42120	42140	-	good	
71	1.90	7.00	-	6.50	280	?	yes	18.6	20088	20088	-	good	It floods by surface water.
72	3.00	7.00	4.08	-	640	?	no	-	-	-	-	good	Water not enough.
73	1.40	6.60	-	-	-	8.3	yes	-	-	-	-	good	Information from old file!! not found in the field.

Table D.1 (cont.)

Well no.	Well Dia. (m)	Well Depth (m)	Water depth S.W.L (m)	Water depth D.W.L (m)	Water quality EC. ($\mu S/cm$)	Water quality pH	Pump Inst?	Pump Yield (m^3/h)	Annual yield Total (m^3)	Annual yield Irrig. (m^3)	Annual yield Domestic (m^3)	Condition of well	Remarks
74	2.80	8.35	4.86	-	400	?	yes	27.2	53856	53856	-	fair	
75	3.50	7.00	4.54	-	260	?	yes	-	-	-	-	fair	Motor is out of order.
76	?	6.90	-	5.90	320	?	yes	21.8	31392	31392	-	fair	
77	?	5.48?	4.68	-	240	?	yes	?	?	?	-	fair	It floods by the wadi.
78	1.3	9.00	?	?	-	8.3	no	?	?	?	?	?	Old inventory 1979, not found in field!!
79	2.20	5.50	4.96	-	-	-	yes	13.1	7074	7074	-	fair	It contains not enough water during dry season.
80	3.00	6.60	5.02	-	310	7.8	yes	?	?	?	-	!	Not pumped.
81	1.20	6.30	5.90	-	340	7.7	yes	8.2	6642	6642	-	good	Reconstructed this year.
82	3.00	6.50	-	5.36	300	8.1	yes	16.6	18225	18225	-	?	
83	3.00	-	-	-	-	-	-	-	-	-	-	-	Burried.
84	1.30	6.4	4.00	-	-	-	no	-	-	-	-	good	Old inventory 1979. Not found in the field now.
85	2.50	5.55	-	5.30	400	7.4	yes	?	?	?	-	fair	
86	1.80	5.22	4.64	-	-	-	yes	?	?	?	-	good	Not pumped.
87	3.00	6.97	5.65	-	?	?	no	-	-	-	-	not good	Out of use.
88	1.50	8.30	6.20	-	400	7.3	yes	16.4	26568	26568	-	good	
89	3.25	9.75	7.65	-	500	7.2	yes	-	-	-	-	good	Not pumped.
90	-	-	-	-	-	-	-	-	-	-	-	-	Burried.
91	2.85	6.35	dry	-	-	-	yes	-	-	-	-	?	Out of use.
92	3.00	9.69	7.74	-	440	7.7	yes	?	?	?	-	good	Not pumped.
93	3.00	6.30	5.67	-	500	7.7	yes	?	?	?	-	fair	Not pumped.
94	3.50	?	dry	-	-	-	no	-	-	-	-	?	Abandoned.
95	2.75	7.40	6.00	-	?	?	yes	?	?	?	-	fair	
96	1.30	6.00	4.76	-	320	7.8	yes	16.4	22140	22140	-	good	
97	3.00	7.54	6.14	-	?	?	yes	?	?	?	-	good	Not pumped.
98	1.95	9.80	6.90	-	270	7.8	yes	21.8	41202	41202	-	good	
99	3.00	7.65	6.35	-	?	?	yes	?	?	?	-	?	Not pumped.
100	1.50	4.20	4.15	-	?	?	no	-	-	-	-	?	It floods by the wadi.
101	2.17	7.27	-	-	-	-	yes	-	-	-	-	fair	Old inventory file not found now.
103	3.75	6.90	6.50	-	300	7.8	yes	?	?	?	-	not good	Not pumped.
104	4.00	5.49	1.43	-	?	?	yes	?	?	?	-	good	No fuel to run the motor.
105	-	-	-	-	-	-	-	-	-	-	-	not good	Burried.
106	2.60	7.20	6.57	-	-	-	yes	18.2	4914	4914	-	good	It gets dry after short period of pumping.
107	3.00	5.00	2.30	-	360	?	yes	21.8	62784	62784	-	fair	
108	3.00	7.32	3.15	-	520	?	yes	16.4	39852	39852	-	fair	
109	3.50	8.00	3.34	-	600	?	yes	?	?	?	-	fair	Not pumped, well dry.
111	-	-	-	-	-	-	-	-	-	-	-	-	Abandoned.
112	3.00	6.40	4.90	-	420	7.8	yes	?	?	?	-	good	Not pumped.
113	3.00	8.20	6.65	-	380	7.8	yes	18.2	19656	19565	-	good	
114	1.30	!	dry	-	-	-	no	-	-	-	!		
115	1.80	6.98	6.43	-	660	7.7	yes	?	?	?	-	good	Not pumped.
116	2.75	3.25	2.70	-	-	-	no	-	-	-	-	fair	Old inventory file (1979) out of use.
117	2.30	4.90	-	3.75	-	-	no	-	-	-	-	fair	Old inventory file not found in the field.
118	4.05	4.00	dry	-	-	-	no	-	-	-	-	good	
119	5.00	4.00	2.65	-	-	-	yes	-	-	-	-	good	Old inventory file now not found in the field.
120	5.80	!	dry	-	-	-	no	-	-	-	-	!	
121	2.00	4.45	4.41	-	-	-	no	-	-	-	-	fair	Gets dry during dry season.
122	2.00	7.30	-	5.70	320	7.6	yes	13.6	73636	73636	-	fair	
123	3.30	6.31	6.06	-	2300	7.8	no	-	-	-	-	fair	Pump was moved.
124	-	-	-	-	-	-	-	-	-	-	-	-	Not found in the field.
125	2.00	6.70	-	6.55	460	-	yes	16.4	23564	23564	-	good	
126	1.20	7.30	-	6.90	420	-	yes	16.4	22090	22090	-	fair	
127	2.75	6.20	5.11	-	400	7.8	yes	?	?	?	-	good	
128	2.50	dry	-	-	-	-	-	-	-	-	-	good	Dry.
129	2.50	5.65	-	5.60	360	7.8	yes	21.8	11781	11781	-	good	
130	2.50	6.78	-	6.20	540	7.6	yes	?	?	?	-	good	
131	2.50	6.67	5.55	-	-	-	yes	18.2	14742	14742	-	fair	Gets dry during dry season.
132	2.85	6.11	-	6.05	500	7.7	yes	16.4	22090	22090	-	good	
133	2.75	9.88	-	7.70	680	7.6	yes	13.1	3537	3537	-	good	Depth to B.C. 5.20 m.
201	1.50	7.50	7.00	-	540	?	yes	21.8	39240	13080	26160	new	
202	-	-	-	-	-	-	-	-	-	-	-	-	Collapsed (immediately) after construction
203	-	-	-	-	-	-	-	-	-	-	-	-	" "
204	!	!	!	!	!	?	yes	16.0	57600	-	57600	renewed	Under construction.
205	2.50	7.00	6.00	-	405	?	yes	?	?	?	-	fair	The motor is out of order.
206													Not found.
207	2.50	8.00	5.50	-	!	!	no	-	-	-	-	fair	Out of use.
208	2.00	9.00	6.85	-	440	6.7	yes	15.0	60000	23000	37000	good	
209	2.00	11.10	-	8.10	480	6.7	yes	21.8	78480	52320	26160	good	It use for drinking & irr.
210	2.50	8.60	4.50	-	400	6.6	yes	15.0	59000	34000	25000	fair	

Table D.1 (cont.)

Well no.	Well Dia. (m)	Well Depth (m)	Water depth S.W.L (m)	Water depth D.W.L (m)	Water quality EC. (µS/cm)	Water quality pH	Pump Inst?	Pump Yield (m^3/h)	Annual yield Total (m^3)	Annual yield Irrig. (m^3)	Annual yield Domestic (m^3)	Condition of well	Remarks
211	3.00	10.00	5.50	-	440	7.7	yes	?	?	?	-	good	No fuel.
212	3.00	7.40	?	?	360	7.1	yes	21.8	65160	43440	21720	good	Use for drinking & irr.
213	1.50	6.00	5.50	-	200	6.7	no	-	-	-	-	good	This well of square shape.
214	?	6.60	5.50	-	340	6.7	yes	21.8	31392	20928	10464	fair	Used for irr. & drinking.
215	2.00	6.10	5.50	-	600	7.6	no	-	-	-	-	fair	Doesn't contain water during dry season.
216	?	?	?	?	?	?	?	?	?	?	?	new	Under construction.
217													Not found.
218													Not found.
219	1.8	7.80	3.70	-	350	7.3	yes	32.7	35316	34316	1000	fair	
220	?	?	?	?	?	?	?	?	?	?	?	?	Collapsed.
221	2.00	6.20	3.00	-	230	7.3	yes	32.7	47088	15696	31392	fair	
222	4.00	7.40	4.40	-	240	7.4	yes	?	?	?	-	fair	No fuel.
223	2.50	8.20	4.00	-	280	7.4	no	-	-	-	-	fair	Out of use.
224	3.00	10.20	6.00	-	290	6.7	yes	13.1	18864	18864	-	fair	They forced a pipe into the B.C.length 10.00 m.
225	?	?	?	?	220	7.1	yes	10.9	39240	13080	26160	fair	A side of the well collapsed.
226													Not found, in 1979 used as W.C (old inventory).
227	-	-	-	-	-	-	-	-	-	-	-	-	Collapsed.
228	3.50	7.20	3.30	-	640	7.3	no	-	-	-	-	good	-
228(A)	1.50	9.40	4.05	-	640	7.3	no	-	-	-	-	good	Out of use.
229	2.50	8.70	6.40	-	1100	6.9	yes	?	?	?	-	good	No fuel.
230	3.00	9.00	5.00	-	1500	8.0	no	-	-	-	-	bad	Out of use.
231	2.43	8.77	6.03	-	?	?	no	-	-	-	-	fair	
232	2.50	7.00	4.40	-	620	7.3	no	-	-	-	-	good	Out of use.
233	2.00	7.40	4.30	-	420	7.4	no	-	-	-	-	bad	Out of use.
234	?	6.50	3.60	-	?	?	no	-	-	-	-	good	Out of use.
235	3.50	7.00	4.50	-	330	7.3	yes	21.8	35316	35316	-	fair	During dry season it gets dry after short period of pumping.
236	-	-	-	-	-	?	?	?	?	?	?	?	Collapsed.
237	3.50	7.60	3.30	-	260	7.1	yes	16.4	17712	17712	-	fair	It floods with the wadi.
238	2.00	5.28	4.05	-	1500	7.6	no	-	-	-	-	not good	Out of use.
239	-	-	-	-	-	-	-	-	-	-	-	-	Not found.
240	3.00	8.50	4.30	-	240	7.3	yes	16.4	26568	26568	-	fair	Floods with the wadi.
241	3.00	8.00	dry	-	-	-	no	-	-	-	-	fair	
242	1.00	6.00	3.80	-	640	7.2	yes	-	-	-	-	-	The motor is out of order.
243	3.00	6.70	4.00	-	520	7.4	no	-	-	-	-	-	Out of use.
244	?	4.00	1.50	-	360	7.6	no	-	-	-	-	not good	Flooded by the wadi.
245	?	6.00	-	3.20	380	7.2	yes	13.1	10611	10611	-	fair	Flooded by the wadi.
246	3.00	9.00	-	8.00	640	7.1	yes	16.4	11808	11808	-	good	It contains not enough water.
247	2.50	8.70	5.70	-	420	7.1	no	-	-	-	-	fair	Motor is removed.
248	4.00	4.40	2.50	-	240	7.3	yes	21.8	23544	23544	-	good	Flooded by the wadi.
249	3.00	8.00	dry	-	-	-	-	-	-	-	-	good	
250	2.00	4.30	2.30	-	680	6.9	no	-	-	-	-	good	Out of use.
251	3.00	6.00	2.80	-	?	?	yes	?	?	?	-	fair	No fuel.
252	?	8.00	4.40	-	?	?	no	-	-	-	-	good	
253	3.00	7.15	6.40	-	?	?	yes	18.2	13104	13104	-	good	It gets dry after short period of pumping.
254	3.75	6.00	3.50	-	?	?	no	-	-	-	-	fair	Out of use.
255	?	?	?	?	300	7.0	yes	21.8	11772	11772	-	fair	Constructed in a big hole.
256	?	?	?	?	?	?	yes	?	?	?	?	?	Constructed in a big hole.
257	3.00	4.60	1.40	-	240	7.5	yes	21.8	17658	17658	-	fair	Floods with the wadi.
258	?	5.00	2.00	-	?	?	yes	?	?	?	-	fair	No fuel.
259	?	5.80	1.40	-	200	7.4	yes	?	?	?	-	good	The engine is not O.K.
260	1.50	6.00	4.00	-	?	?	yes	?	?	?	-	good	No one to run the motor depth to B.C. 6.00 m.
261	2.00	6.50	2.50	-	300	7.1	yes	?	?	?	-	fair	Motor is not O.K.
262	1.25	4.50	3.30	-	800	7.5	no	-	-	-	-	good	Out of use.
263	2.00	6.00	-	5.00	320	7.4	yes	13.1	23580	15720	7860	not good	Used for irrg.& drinking
264	3.00	5.00	2.50	-	340	6.8	yes	21.8	31392	16464	20928	good	Uses for domestic & irrg.
265	2.00	6.70	3.00	-	475	7.8	no	-	-	-	-	not good	It gets dry after short period of pumping.
266	2.50	6.00	2.80	-	920	7.5	yes	21.8	39240	39240	-	fair	
267	3.50	6.00	5.50	-	2200	7.9	no	-	-	-	-	good	Depth to B.C. 3.75 m.
268	2.00	6.50	1.60	-	700	7.1	yes	?	?	?	?	not good	The motor not O.K.
269	2.00	8.00	4.10	-	800	6.9	yes	9.3	41460	13820	27640	fair	Used for drinking & irrig.
270	-	-	-	-	-	-	-	-	-	-	-		Covered with some woods.
271	2.00	4.20	3.60	-	540	-	no	-	-	-	-	bad	Flooded by the wadi.
272	1.00	7.60	3.50	-	360	-	no	-	?	-	?	fair	Dirty around the well.
273	?	7.00	3.80	-	200	-	no	-	-	-	-	fair	Out of use.
274	?	5.50	3.60	-	260	-	yes	16.4	8856	8856	-	fair	Flooded by the wadi.
275	Not found in the field											-	Not found.
276	Not found in the old inventory file.											-	Not found.
277											-	-	Not found.

Table D.1. (cont.)

Well no.	Well Dia. (m)	Well Depth (m)	Water depth S.W.L (m)	Water depth D.W.L (m)	Water quality EC. (μS/cm)	Water quality pH	Pump Inst?	Pump Yield (m^3/h)	Annual yield Total (m^3)	Annual yield Irrig. (m^3)	Annual yield Domestic (m^3)	Condition of well	Remarks
278	2.50	8.30	3.25	–	400	7.1	yes	12.8	11772	11772	–	fair	It gets dry after short period of pumping during dry season.
279	2.50	6.00	5.50	–	400	6.8	yes	26.2	7074	7074	–	fair	It gets dry after short period of pumping.
280											–	–	Not found.
281	1.00	8.00	4.80	–	820	6.8	yes	21.8	2943	2943	–	fair	It gets dry after short period of pumping.
282	2.50	7.80	3.40	–	460	7.1	yes	26.2	21222	21222	–	fair	
283	2.50	6.50	–	4.80	200	–	yes	6.5	3510	3510	–	fair	
284	1.50	4.10	3.20	–	320	–	no	–	–	–	–	fair	Out of use.
285	1.50	5.60	4.50	–	440	–	no	–	–	–	–	fair	Out of use.
286	2.00	6.50	–	6.00	300	–	yes	?	?	?	–	fair	No one to run motor.
287	–	–	–	–	–	–	–	–	–	–	–	–	Buried.
288	1.50	6.30	5.20	–	980	8.3	no	–	–	–	–	–	Out of use.
289	5.00	8.46	6.35	–	520	7.3	yes	?	?	?	–	good	No fuel.
290	2.00	9.90	6.70	–	540	7.1	yes	?	?	?	–	fair	Motor is out of order.
291	2.00	9.40	8.20	–	1100	8.1	no	–	–	–	–	good	For long time it is out of use.
292													Not found.
293													Not found.
294	?	7.90	–	7.40	?	–	yes	16.4	11808	11808	–	fair	It gets dry after short period of pumping.
295	1.00	7.00	6.30	–	740	–	no	–	–	–	–	fair	Out of use.
296													Not found.
297	1.00	6.80	6.40	–	680	7.5	yes	?	?	?	–	good	No one to run the motor.
298	1.50	–	–	–	–	–	–	–	–	–	–	–	Buried.
299	1.00	7.80	–	7.78	580	7.1	yes	21.8	5886	5886	–	good	It gets dry after short period of pumping.
300	–	–	–	–	–	–	–	–	–	–	–	–	Buried.
301	1.50	8.35	5.80	–	–	–	no	–	–	–	–	not good	Out of use.
302	2.50	7.10	6.42	–	–	–	yes	16.3	8836	–	–	good	Used for bricks making.
303	–	6.00	–	–	–	–	no	–	–	–	–	fair	Dry - out of use.
304	3.48	9.40	–	9.14	790	?	yes	16.4	23616	–	23616	good	Depth to B.C. 7.40 m.
305	3.50	11.80	–	9.60	?	?	yes	4.0	5691	–	5691	good	It gets dry after short period of pumping.
309	2.50	9.00	6.07	–	100	?	no	–	–	–	–	not good	
310	1.80	10.60	7.68	–	620	?	no	–	–	–	–	good	Used for domestic.
311	2.44	14.13	11.60	–	540	?	no	–	–	–	–	good	Used for domestic.
312	1.20	11.70	9.85	–	560	?	no	–	1825	–	1825	good	Domestic.
313	2.50	8.00	7.68	–	240	7.2	yes	12.7	27220	20000	7220	good	Used for drinking & irrig.
314	1.50	7.00	?	?	440	7.4	yes	32.7	61803	60000	1803	good	For drinking & irrigation.
315	1.50	7.00	6.30	–	520	6.9	yes	32.7	86328	86328	–	good	
316	3.00	6.80	6.50	–	820	7.1	yes	10.9	52363	40000	12363	good	
317	2.30	7.00	–	6.90	400	7.7	yes	16.4	28990	13990	15000	good	Drinking & irrigation.
318	2.75	7.15	–	6.70	400	?	yes	16.4	17712	17712	–	good	
319	6.00	?	?	?	?	?	no	–	–	–	–	?	Dry.
320	?	7.63	7.57	–	800	7.9	no	–	–	–	–	–	Under construction.
400	2.29	–	–	–	–	–	no	–	–	–	–	–	Buried.
401	3.00	6.50	–	6.34	?	?	yes	21.8	41202	–	41202	good	They planned to dig deeper.
402	2.00	10.26	7.82	–	350	?	yes	16.4	22140	–	22140	good	3 meters in the B.C.
403	3.50	10.10	9.55	–	–	?	yes	32.7	9800	–	9800	not good	For livestock.
404	2.00	5.60	–	4.80	220	7.6	yes	16.7	60120	50120	10000	fair	
405	4.35	6.96	–	4.66	260	7.6	yes	13.1	18864	18864	–	fair	
406	3.00	6.47	4.60	–	520	?	no	–	–	–	–	good	Out of use.
407	?	6.20	–	5.00	280	?	yes	13.1	18148	4000	14148	good	
408	3.00	8.27	4.83	–	320	?	yes	27.6	33200	19200	14000	good	
409	2.41	8.56	2.90	–	530	?	yes	27.3	–	–	–	new	Out of use!!!!
410	1.50	5.85	4.91	–	550	?	yes	15.6	21060	–	21060	good	
411	?	7.82	?	?	?	?	?	?	?	?	?	new	Under construction.
412	3.00	7.50	4.95	–	520	?	no	–	–	–	–	good	
413	1.00	–	–	–	–	–	no	–	–	–	–	–	Buried.
414	?	8.85	6.15	–	?	?	no	–	–	–	–	good	Pipe forced in this dugwell.
415	?	7.13	5.82	–	600	?	yes	–	–	–	–	good	Out of use.
416	1.00	–	–	–	–	–	–	–	–	–	–	not good	Out of use, buried.
417	?	?	?	?	?	?	?	?	?	?	?	?	Coverde with zinc sheets.
418	2.50	9.90	6.55	–	?	?	no	–	–	–	–	good	
419	1.50	5.92	5.73	–	160	?	no	–	–	–	–	good	
420	1.45	8.25	–	7.60	340	?	yes	11.9	8568	568	8000	good	It gets dry after short period of pumping.
421	1.20	5.93	–	–	–	–	no	–	–	–	–	not good	Dry.
422	–	–	–	–	–	–	–	–	–	–	–	–	Buried.
423	?	9.35	–	5.11	360	?	yes	10.2	5510	5510	–	new	
424	?	4.87	–	–	–	–	no	–	–	–	–	new	Dry.
425	4.00	6.20	3.50	–	500	?	yes	26.2	35370	35370	–	good	Reconstructed in 1984.
426	1.24	8.48	6.66	–	540	?	no	–	–	–	–	fair	Not used.
427	1.00	6.14	dry	–	–	–	no	–	–	–	–	fair	It contains water during dry season.
428	1.25	7.20	6.35	–	780	7.1	yes	16.4	8856	8856	–	good	Depth to B.C. 5.00 m.
429	1.50	6.20	4.00	–	940	8.0	no	–	–	–	–	fair	They want to dig deeper.

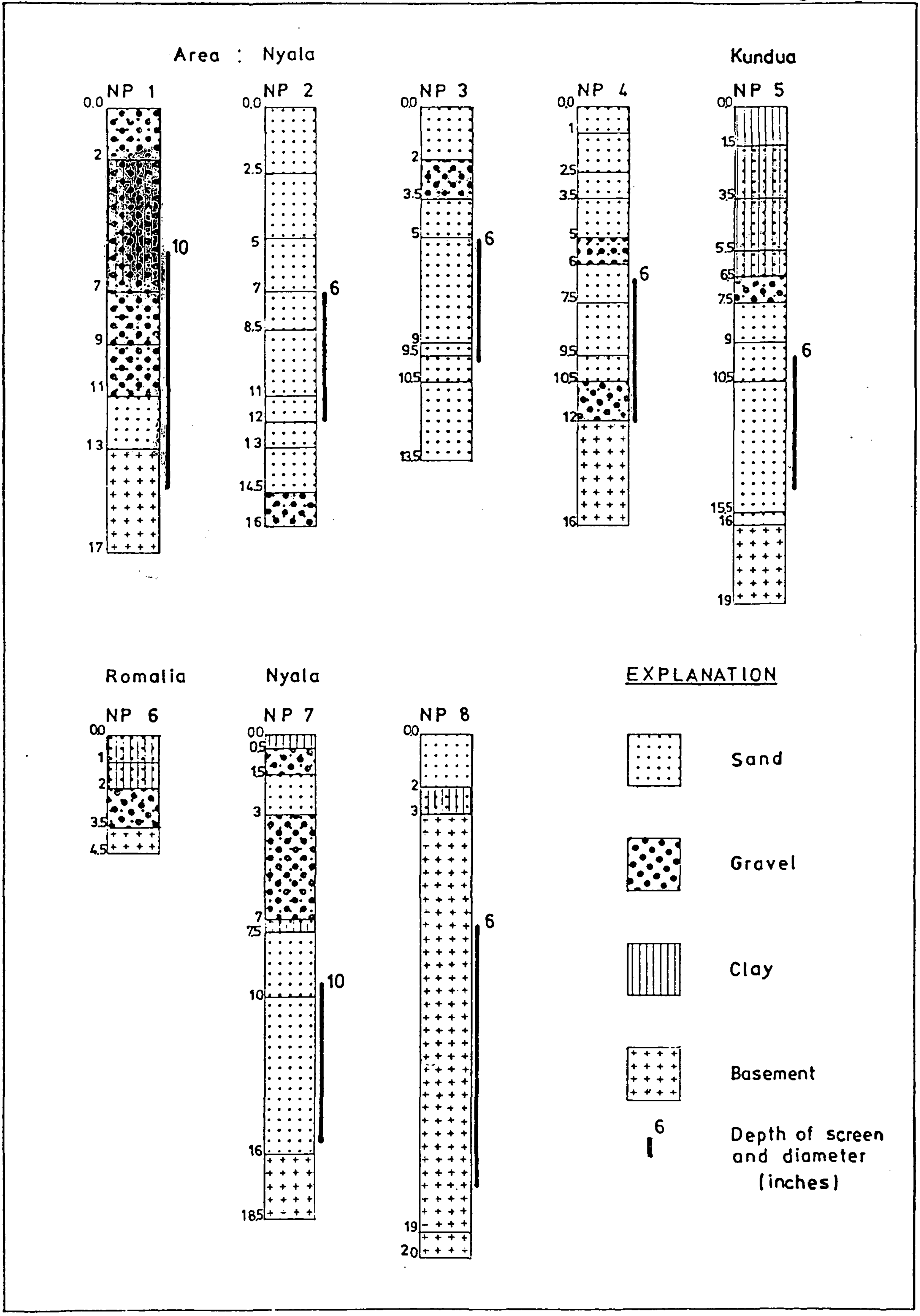
Table D.1 (cont.)

Well no.	Well Dia. (m)	Well Depth (m)	Water depth S.W.L (m)	D.W.L (m)	Water quality EC. (µS/cm)	pH	Pump Inst?	Pump Yield (m^3/h)	Annual yield Total (m^3)	Irrig. (m^3)	Domestic (m^3)	Condition of well	Remarks
431	2.00	8.59	7.85	-	-	-	yes	-	-	-	-	good	Out of use due to the engine.
432	2.00	?	?	?	1100	7.1	yes	16.4	41328	41328	-	good	They are building a new wall!
433	?	?	?	?	?	?	yes	?	?	?	?	?	Constructed in a big and deep hole.
434										?	?	?	Not found.
435	2.00	6.70	4.00	-	460	7.1	yes	?	?	?	?	fair	No fuel to run the motor.
436													Not found.
437	3.50	6.48	3.70	-	720	7.10	yes	13.1	21222	21222	-	good	
438													Not found.
439	3.50	9.00	7.00	-	360	7.00	yes	16.4	6642	6642	-	new	45 min. pumping it gets dry.
440	4.00	6.10	5.15	-	330	7.40	no	-	-	-	-	new	Out of use.
442	?	9.00	5.50	-	280	7.10	yes	16.4	41328	41328	-	good	Boulders, gravels were found during digging.
445	1.50	12.00	5.50	-	400	7.6	yes	21.8	41202	41202	-	good	
446	?	?	?	?	?	?	?	?	?	?	?	?	Dangerous to come near the well.
448	1.50	9.71	8.22		380	-	yes	13.1	23580	-	23580	new	
449	-	9.69	6.99		400	-	yes	16.4	29520	-	29520	new	
450	1.00	7.10	5.90	-	480	7.7	yes	21.3	8829	8829	-	new	Floods with the wadi.
452	2.50	5.15	1.40	-	380	7.2	yes	13.1	8842	8842	-	fair	
456	?	3.40	1.80	-	400	!	yes	-	-	-	-	fair	Motor is out of order.
500	1.00	7.60	5.85	-	300	7.5	yes	16.4	4428	4428	-	good	It flooded by the wadi.
501	2.00	6.90	5.67	-	-	-	yes	16.4	13254	13254	-	good	Enough water to be pumped.
502	2.50	6.65	4.81	-	280	7.4	yes	21.8	8829	8829	-	new	
503	1.50	5.50	1.50	-	600	7.9	yes	13.6	29376	29376	-	good	
504	?	?	?	?	?	?	?	?	?	?	?	?	The door is locked.
505	2.75	6.33	6.00	-	600	7.9	yes	-	-	-	-	good	The motor is out of order.
506	2.50	4.90	4.60	-	420	7.2	no	-	-	-	-	fair	It gets dry during dry season.
507	4.00	5.40	4.60	-	380	7.5	no	-	-	-	-	fair	Out of use.
508	1.25	4.50	4.21	-	-	-	-	-	-	-	-	fair	Out of use.
510	5.00	6.30	-	5.60	420	7.2	yes	16.4	17712	17712	-	fair	
511	1.50	3.00	2.50	-	-	-	yes	?	?	?	-	fair	Out of use due to the engine.
512	?	6.60	4.80	-	300	6.6	yes	13.1	10611	10611	-	fair	
513	2.50	6.17	-	6.37	480	7.5	yes	16.4	17672	17672	-	good	
514	1.50	5.15	4.75	-	?	?	no	-	-	-	-	fair	It gets dry during dry season.
515	2.50	5.81	4.77	-	280	7.5	yes	-	-	-	-	fair	Out of use due to the engine.
516	3.00	6.03	5.14	-	420	7.6	yes	13.1	7074	7074	-	fair	
517	1.25	5.43	3.25	-	280	-	yes	16.4	8856	8856	-	good	Flooded by the wadi.
518	2.00	6.99	5.02	-	360	-	yes	13.1	5305	5305	-	fair	
519	2.00	6.07	4.69	-	450	-	yes	-	-	-	-	fair	Out of use due to the engine.
520	2.50	5.71	5.34	-	300	-	yes	21.8	11772	11772	-	new	Gets dry after short period of pumping.
521	?	7.37	5.57	-	490	-	yes	13.1	17685	17685	-	good	3 pipes installed deeper.
522	?	6.31	3.89	-	280	-	yes	21.8	35316	35316	-	fair	
523	2.50	7.12	4.61	-	475	-	yes	21.8	54936	54935	-	good	It gets dry during dry season.
524	2.00	7.35	6.35	-	-	-	yes	21.8	17658	17658	-	good	It gets dry during dry season.
525	2.50	7.29	3.61	-	420	-	yes	32.7	70632	70632	-	fair	It gets dry during dry season.
526	0.75	11.61	4.49	-	530	-	yes	13.1	14148	14148	-	fair	It gets dry, running sands are present.
527	1.18	6.92	4.22	-	500	-	yes	21.8	47088	47088	-	good	It gets dry after short period of pumping.
528	2.25	6.00	5.50	-	-	-	yes	16.4	12000	12000	-	good	
529	2.50	?	3.52	-	420	-	yes	?	?	?	-	fair	The engine is out of order.
530	2.00	6.42	5.02	-	390	-	no	-	-	-	-	fair	Out of use.
531	1.00	7.70	6.50	-	360	7.7	yes	21.8	72619	72619	-	new	
532	1.10	6.50	6.25	-	-	-	no	-	-	-	-	good	Out of use.
533	1.86	9.44	6.39	-	320	-	yes	18.2	52416	52416	-	good	
534	2.00	7.14	5.97	-	500	-	no	-	-	-	-	not good	
535	3.50	8.08	6.27	-	325	-	yes	21.9	47304	47304	-	fair	
536	2.50	7.95	6.60	-	-	-	yes	16.4	17712	17712	-	fair	
537	-	-	-	-	-	-	-	-	-	-	-	-	Buried.
538	-	8.60	8.07	-	-	-	no	-	-	-	-	fair	Out of use due to the engine.
539	2.00	8.45	7.90	-	600	7.6	yes	12.8	17658	17658	-	new	4 pipe installed, length 8.00 m.
540													Under construction.

Table D.1 (cont.)

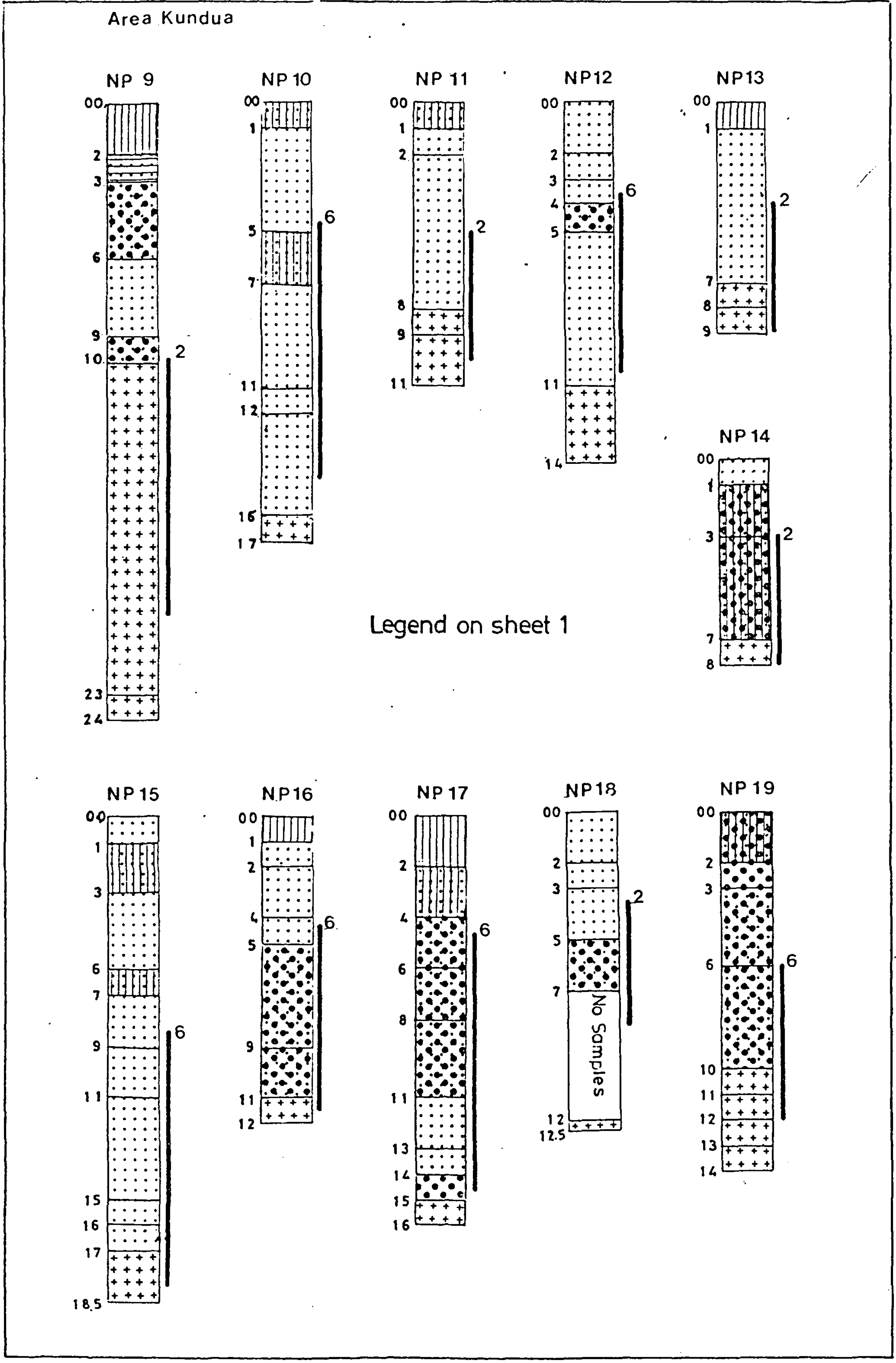
Well no.	Well Dia. (m)	Well Depth (m)	Water depth S.W.L (m)	Water depth D.W.L (m)	Water quality EC. (μS/cm)	Water quality pH	Pump Inst?	Pump Yield (m^3/h)	Annual yield Total (m^3)	Annual yield Irrig. (m^3)	Annual yield Domestic (m^3)	Condition of well	Remarks
600	2.00	11.25	9.15	-	-	-	yes	16.4	6642	6642	-	new	
601	-	8.80	-	7.95	-	-	yes	13.1	7074	7074	-	fair	It gets dry after short period of pumping.
602	-	8.40	7.23	-	-	-	yes	18.2	14742	14742	-	fair	
603	0.50	7.00	5.87	-	-	-	no	-	-	-	-	good	Out of use.
604	0.75	8.00	6.46	-	-	-	no	-	-	-	-	good	Out of use.
605	-	7.50	-	7.83	-	-	yes	13.1	21222	14148	7074	good	Enough water to be pumped.
606	-	7.90	6.06	-	-	-	yes	18.2	14742	14742	-	good	It gets dry after short period of pumping.
607	-	5.85	5.80	-	-	-	no	-	-	-	-	fair	It gets dry after short period of pumping.
608	1.50	9.60	8.70	-	-	-	yes	16.4	8856	8856	-	new	It gets dry after short period of pumping.
609	-	9.60	8.60	-	-	-	yes	13.1	7074	7074	-	good	After 15 m. it gets dry during dry season.
610	-	10.00	0.30	-	-	-	yes	16.4	8836	8836	-	good	After 15 m. it gets dry during dry season.
611	?	?	?	-	-	-	yes	11	5890	5890	-	fair	Very low to go down.
612	?	?	?	-	-	-	yes	16.4	8836	8836	-	good	Very low to go down.
613	0.50	?	?	?	-	-	yes	13.1	17685	17685	-	fair	Covered with some wood.
614	3.00	9.00	7.50	-	-	-	yes	9.4	5049	5049	-	good	Not enough water.
615	0.75	7.00	5.00	-	-	-	yes	18.7	15148	15148	-	new	4 steel pipe to 6.00 m from the bottom
616	1.00	?	?	?	-	-	yes	?	?	?	-	new	No one to run the motor.
617	?	?	?	?	-	-	yes	-	-	-	-	new	No one to run the motor.
618	0.50	7.00	6.90	-	-	-	no	-	-	-	-	new	Not enough water to be pumped.
(Kun.1)	1.15	10.50	dry	-	-	-	no	-	-	-	-	good	They removed the pump.
(Kun.2)	3.40	10.55	dry	-	-	-	yes	-	-	-	-	good	Out of use due to the motor.

LITHOLOGICAL PROFILES BOREHOLES WAPS-2 Figure D.1



LITHOLOGICAL PROFILES BOREHOLES WAPS-2

Figure D.1 (cont.)



Borehole Inventory Summary - Wadi Nyala   Table D.2

Borehole No.		Date drilled	Total depth (m)	Depth to BC (m)	Diameter casing (inches)	Length of plain casing (m)	Length of screen (m)	Screen type and remarks
Nyala	NWC Kht							
1		1959	13.4	6	(4 mtr)	-	-	
2			16	14.9	42	-	-	
3	1136?	1960	19.8	17.1	13 3/8	-	-	
4			?	?	-	-	-	Destroyed
5	3601A?	1970	18.3	15.9	10 3/4	-	-	
6	3601B?	1970	16.8	16.8	10 3/4	-	-	
7	6261	1974	17.7	-	10 3/4	10.1	8.2	
8	6260	1974	23.2	-	6 5/8	8.2	14.9	Destroyed
9	8071	1978	18.9	18.3	8 5/8	8.4	10.2	Destroyed
10	5674A	1972	14.6	-	10 3/4	4	10.7	Slotted
11	8069?	1978	16.8	13.7	8 5/8	6.4	10.4	Br.slott.
12	5674B	1972	16.5	16.4	10 3/4	5.8	10.7	
13	3603?	1970	16.2	-	8 5/8	6.1	10.1	
14	9702	1979	18.3	16.8	8 5/8	9.2	8.9	Johnson
15	9699	1979	19.8	17.7	8 5/8	10.7	8.9	Johnson
16	5437	1971	18.3	-	10 3/4	8.8	10.7	
17	3602?	1970	13.7	-	10 3/4	1.8	12.2	Br.slott.
18	7907	1977	18.9	15.2	8 5/8	3.5	15.2	Br.slott.
19	7906	1977	21.3	19.8	8 5/8	3.2	-	Destroyed
20	7905	1977	19.8	18.3	10 3/4	3.5	9.6	Slotted &
							7.8	Br.slott.
21	5895	1973	14.6	13.7	10 3/4	8.2	6.4	Slotted
22	-	1981	17.1	15.2	6 5/8	11.6	10.3	Abandoned
23	-	1981	16.8	15.2	6 5/8	11.9	10.1	Br.slott.
24	6092	1973	15.2	13.1	10 3/4	-	-	
25	8070?	1978	12.2	?	8 5/8	-	-	
26	-	1980	33.5	27.4?	8 5/8	24.4	12.2	Br.slott.
27	-	?	?	?	6 5/8	-	-	
28	-		?	-	6 5/8	-	-	Buried
29	-		?	-	6 5/8	-	-	Destroyed
30	-	1984	-	15.3	10 3/4		12.2	Johnson
31	-	1984	14.6	13.7	10 3/4	8.2	9.2	Johnson

Table D.2 (cont.)

Borehole Inventory Summary - Wadi Nyala

WAPS-2 exploratory boreholes drilled 1983-1984

Bore-hole nr.	Total depth drilled (m)	Depth to BC (m)	Casing diameter (inches)	Length of plain casing (m)	Length of screen (m)	Depth of screen (m)	Remarks
NP 01	17.00	13.00	10	7.2	9.0	5.4-14.4	Destroyed
NP 02	16.00	-	6	7.0	5.0	5.0-10.0	Buried
NP 03	13.50	-	6	5.5	5.0	5.0-10.0	
NP 04	16.00	12.00	6	6.5	5.0	6.5-11.5	
NP 05	19.00	16.00	6	10.0	5.0	9.5-14.5	Buried
NP 06	4.50	3.50	6	-	-	-	No casing
NP 07	18.50	16.00	10	9.5	6.0	9.5-15.5	Pumped
NP 08	20.00	3.00	6	8.0	10.0	7.5-17.5	N of Nyala
NP 09	24.00	10.00	2	10.0	10.0	10.0-20.0	
NP 10	17.00	16.00	6	5.0	10.0	4.5-14.5	
NP 11	11.00	8.00	2	5.0	5.0	4.8- 9.8	
NP 12	14.00	11.00	6	6.0	7.0	3.5-10.5	
NP 13	9.00	7.00	2	5.0	5.0	4.0- 9.0	Buried
NP 14	8.00	7.00	2	5.0	5.0	3.0- 8.0	Dry
NP 15	18.50	17.00	6	8.0	10.0	8.0-18.0	
NP 16	12.00	11.00	6	5.0	7.0	4.5-11.5	
NP 17	16.00	15.00	6	5.0	10.0	4.5-14.5	Buried
NP 18	12.50	12.00	2	5.0	5.0	3.5- 8.5	Buried
NP 19	14.00	13.00	6	8.0	6.0	6.0-12.0	

Table D.3

Lithological Description of Boreholes Wadi Nyala

Remark: Descriptions found in NWC files at Nyala.

BH No.	Thickness (m)	Lithological Description
BH 9	00.0-06.1	Sand.
	06.1-06.4	Sand and gravel.
	06.4-16.8	Coarse sand with pebbles.
	16.8-18.3	Coarse sand.
	18.3-18.6	Mica.
BH 11	00.0-04.6	Sand.
	04.6-09.2	Coarse sand.
	09.2-12.2	Pebbles with little clays.
	12.2-13.7	Pebbles.
	13.7-17.1	Basement Complex.
BH 13	00.0-04.6	Medium sand.
	04.6-06.1	Coarse sand.
	06.1-09.2	Silt with sand.
	09.2-10.7	Coarse sand.
	10.7-13.8	Sand & gravel.
	13.8-14.7	Basement Complex.
BH 14	00.0-01.5	Fine to medium sand.
	01.5-03.1	Medium to coarse brownish sand with gravels.
	03.1-04.6	Fine to medium sand with angular quartz pebbles
	04.6-06.1	Fine reddish sand.
	06.1-07.7	Medium sand.
	07.7-09.2	Fine to coarse subrounded sand & gravels.
	09.2-10.7	Medium to coarse sand.
	10.7-13.8	Medium to coarse sand with few muscovites.
	13.8-16.9	Coarse sand & gravels.
	16.9-18.4	Green schists (B.C).
BH 15	00.0-01.5	Fine to medium sand, whitish in colour.
	01.5-03.1	Fine to medium sand some boulders & pebbles.
	03.1-06.1	Clayey sand fine to medium with some gravels and pebbles.
	06.1-07.7	Clayey sand fine to medium.
	07.7-09.2	Clayey sand fine to medium.
	09.2-10.7	Pebbles & gravels with fine to medium sand.
	10.7-12.2	Medium to coarse sand with gravels & pebbles.
	12.2-17.8	Medium to coarse sand with gravels, pebbles & boulders.
	17.8-19.9	Basement Complex.
BH 18	00.0-03.1	Coarse sand.
	03.1-07.7	Sandy clay.
	07.7-10.7	Pebbles.
	10.7-13.8	Clay.
	13.8-15.3	Coarse sand.
	15.3-19.0	Basement Complex.
BH 19	00.0-01.5	Sand.
	01.5-04.6	Clay.
	04.6-07.7	Pebbles.
	07.7-10.7	Coarse sand.
	10.7-13.8	Sandy clay.
	13.8-16.9	Pebbles.
	16.9-19.9	Clay.
	19.9-21.5	Basement Complex.

Table D.3 (cont.)

BH No.	Thickness (m)	Lithological Description
BH 20	00.0-07.7	Sand.
	07.7-18.4	Gravels & Pebbles.
	18.4-19.9	Basement Complex.
BH 21	00.0-07.1	Sand clay.
	07.1-13.8	Gravels & Pebbles
	13.8-14.9	Basement Complex.
BH 22	00.0-01.5	Sand coarse grained yellowish.
	01.5-03.1	Sand, gravelly, angular coarse grained yellow brownish.
	03.1-04.6	Coarse sand, pebbly brownish.
	04.6-07.7	Boulders, gravels rounded to subrounded, yellowish.
	07.7-09.2	Sands, gravels angular, intercalated by clays, greyish.
	09.2-15.3	Gravels, sandstone coarse grained & yellowish.
	15.3-17.2	Basement Complex.
BH 23	00.0-01.5	Sands coarse grained yellowish.
	01.5-03.1	Sands, medium coarse angular yellow brownish.
	03.1-04.6	Pebbly, sand coarse brownish.
	04.6-07.7	Sands, gravelly rounded to subrounded yellowish coarse.
	07.7-09.2	Sands, gravels angular intercalcated by clays.
	09.2-15.3	Gravelly sands coarse grained yellowish.
	15.3-16.9	Basement Complex.
BH 24	00.0-09.2	Sandy clay.
	09.2-13.2	Sand & gravels.
	13.2-15.3	Basement Complex.
BH 26	00.0-01.5	Sands, medium coarse grained brownish in colour.
	01.5-04.6	Coarse sands, brownish.
	04.6-06.1	Clay, greyish in colour.
	06.1-07.7	Fine medium sands, whitish in colour.
	07.7-12.3	Sandstone coarse grained, brownish in colour.
	12.3-13.8	Mudstone, sandstone coarse grained greenish.
	13.8-15.3	Mudstone brownish in colour.
	15.3-24.5	Sandstone gravels coarse grained, brownish.
	24.5-27.6	Gravels, sands rouded to subrounded, brownish.
	27.6-32.2	Weathered Basement Complex.
	32.2-33.7	Fresh Basement Complex.
BH 31	00.0-03.1	Fine to coarse grained sands with some gravels and clay.
	03.1-06.1	Very coarse sand, large gravels, pinkish in colour.
	06.1-12.2	Very coarse sands and boulders brownish in colour.
	12.2-13.7	Very coarse sands and boulders, whitish in colour.
	13.7-14.9	Basement Complex.

Table D. 4

Lithological Description of NP Boreholes

BH No.	Thickness (m)	Lithological Description
NP 01	00.0-02.0	Medium to coarse sands with gravel
	02.0-07.0	Medium to coarse sand with some clays and gravel
	07.0-09.0	Medium to coarse sand with gravel
	09.0-11.0	Very coarse sand with a lot of gravels
	11.0-13.0	Medium to coarse sands
	13.0-17.0	Weathered Basement
NP 02	00.0-02.0	Medium to coarse sands
	02.0-05.0	Medium to fine sands, grey
	05.0-07.0	Fine to medium sands
	07.0-08.5	Fine sands
	08.5-11.0	Coarse sands
	11.0-12.0	Very coarse sands
	12.0-13.0	Medium to coarse sands
	13.0-14.5	Very fine sands (pinkish)
	14.5-16.0	Very fine sands with gravel
NP 03	00.0-02.0	Medium to coarse sands with gravels
	02.0-03.5	Fine to medium sands with gravels
	03.5-05.0	Coarse sands
	05.0-09.0	Medium to coarse sands
	09.0-09.5	Fine to medium sands
	09.5-10.5	Very coarse sands
	10.5-13.5	Medium to coarse sands
NP 04	00.0-01.0	Clayey sands
	01.0-02.5	Sandy clay
	02.5-03.5	Fine to medium sands
	03.5-05.0	Fine to medium sands with gravels
	05.0-06.0	Yellow coarse sands
	06.0-07.5	Fine to coarse sands
	07.5-09.5	Very coarse sands
	09.5-10.5	Medium to coarse sands
	10.5-12.0	Grey coarse sands with gravels
	12.0-16.0	Weathered Basement
NP 05	00.0-01.5	Sticky clay (dark)
	01.5-03.5	Sandy clay (brown)
	03.5-05.5	Clayey sands
	05.5-06.5	Medium to coarse sands with few clay
	06.5-07.5	Coarse sands with few gravels
	07.5-09.0	Medium sands
	09.0-10.5	Fine sands (yellowish)
	10.5-15.5	Fine sands (whitish)
	15.5-16.0	Coarse sands
	16.0-19.0	Weathered Basement
NP 06	00.0-01.0	Sandy clay (brown)
	01.0-02.0	Clayey sands with gravels
	02.0-03.5	Mixture of grits, gravels and sands
	03.5-04.5	Crushed granitic rock (B.C.)

Table D.4 (continued)

B.H.No.	Thickness (m)	Lithological Description
NP 07	00.0-00.5	Clay
	00.5-01.5	Medium to coarse sands
	01.5-03.0	Fine to medium sands
	03.0-07.0	Medium to coarse sands with gravels
	07.0-07.5	Clayey sands
	07.5-10.0	Coarse sands
	10.0-16.0	Fine to coarse sands
	16.0-18.5	Weathered Basement
NP 08	00.0-02.0	Sands
	02.0-03.0	Clayey sands
	03.0-19.0	Weathered Basement
	19.0-20.0	Fresh Basement rock
NP 09	00.0-02.0	Silt and clays
	02.0-03.0	Sandy sticky clays
	03.0-06.0	Sands with gravels
	06.0-09.0	Coarse to medium sands
	09.0-10.0	Coarse sands with gravels
	10.0-23.0	Weathered Basement
	23.0-24.0	Fresh Basement
NP 10	00.0-01.0	Sandy clays
	01.0-05.0	Fine to medium sands
	05.0-07.0	Clayey sands
	07.0-11.0	Very fine sands
	11.0-12.0	Medium to coarse sands
	12.0-16.0	Fine to medium sands
	16.0-17.0	Weathered Basement
NP 11	00.0-01.0	Clayey sands
	01.0-02.0	Very fine sands
	02.0-08.0	Medium to coarse sands
	08.0-09.0	Weathered Basement
	09.0-11.0	Fresh Basement
NP 12	00.0-02.0	Fine to medium sands
	02.0-03.0	Medium to coarse sands
	03.0-05.0	Coarse sands with gravels
	05.0-11.0	Fine to medium sands
	11.0-14.0	Weathered Basement
NP 13	00.0-01.0	Sticky clays
	01.0-07.0	Fine to medium sands
	07.0-08.0	Weathered Basement
	08.0-09.0	Fresh Basement
NP 14	00.0-01.0	Sandy clays
	01.0-03.0	Clays with gravels
	03.0-07.0	Very sticky clays with gravels
	07.0-08.0	Basement rocks

Table D.4 (cont.)

B.H.No.	Thickness (m)	Lithological Description
NP 15	00.0-01.0	Fine to medium sands
	01.0-03.0	Sandy clays
	03.0-06.0	Fine to medium sands
	06.0-07.0	Clayey sands
	07.0-09.0	Fine to medium sands
	09.0-11.0	Coarse sands
	11.0-15.0	Coarse sands
	15.0-16.0	Fine to medium sands
	16.0-17.0	Very coarse sands
	17.0-18.5	Basement rocks
NP 16	00.0-01.0	Clay and silts
	01.0-02.0	Sandy clays
	02.0-04.0	Medium to coarse sands
	04.0-05.0	Fine to medium sands
	05.0-09.0	Very coarse sands with a lot of gravels
	09.0-11.0	Medium to coarse sands with gravels
	11.0-12.0	Basement rocks (fresh)
NP 17	00.0-02.0	Sticky clays
	02.0-04.0	Clayey sands
	04.0-06.0	Medium to coarse sand with gravels
	06.0-08.0	Coarse sands with gravels
	08.0-11.0	Fine to coarse sands with few gravels and clays
	11.0-13.0	Medium sands
	13.0-14.0	Medium to coarse sands
	14.0-15.0	Fine gravels
	15.0-16.0	Fresh Basement
NP 18	00.0-02.0	Very fine to medium grained sand
	02.0-05.0	Fine to medium grained sand
	05.0-07.0	Fine to coarse grained sand with pebbles
	07.0-12.0	(No samples)
	12.0-12.5	Slightly weathered Basement
NP 19	00.0-00.5	Sandy clay (top soil)
	00.5-02.0	Heterogeneous layer of sands, clay and gravels
	02.0-03.0	Gravels, rounded to subrounded
	03.0-06.0	Coarse sand and gravel
	06.0-10.0	Very coarse sand and gravel
	10.0-11.0	Weathered Basement, whitish coloured fine sand
	11.0-12.0	Gravels (probably derived from upper layers)
	12.0-13.0	Sands and gravels, product of weathering of B.C.
	13.0-14.0	Weathered Basement

Table D.5

Grain Sizes, Uniformity and Sorting Coefficients of Drilling Samples taken at Depth of Screen Face

U_c = Uniformity Coefficient = D40/D90 U_s = Sorting Coefficient = √ D25/D75

Bore-hole	Depth (m)	D25 (mm)	D40 (mm)	D75 (mm)	D90 (mm)	U_s	U_c
NP 01	7.0- 9.0	1.50	1.00	0.50	0.25	1.70	4.00
	9.0-11.0	3.50	3.00	1.50	0.90	1.50	3.30
	11.0-13.0	1.90	1.30	0.70	0.30	1.60	4.30
NP 02	2.5- 5.0	0.80	0.65	0.34	0.22	1.53	2.96
	7.0- 8.5	0.80	0.65	0.35	0.25	1.50	2.60
	8.5-11.0	1.40	1.10	0.80	0.60	1.32	1.83
	11.0-12.0	0.42	0.35	0.24	0.14	1.32	2.50
	12.0-13.0	0.54	0.42	0.25	0.20	1.47	2.10
NP 03	6.0- 7.0	1.50	0.90	0.55	0.30	1.65	3.00
	7.0- 9.0	1.00	0.80	0.55	0.22	1.65	3.63
	9.0- 9.5	0.80	0.80	0.60	0.40	1.22	2.00
	9.5-10.5	1.75	1.50	0.75	0.60	1.52	2.50
	10.5-11.5	0.60	0.45	0.20	0.14	1.73	3.20
	11.5-13.0	0.85	0.75	0.40	0.25	1.46	3.00
	13.0-13.5	0.70	0.60	0.30	0.20	1.53	3.00
NP 04	5.0- 6.0	1.25	0.90	0.60	0.24	1.44	3.75
	6.0- 7.5	0.95	0.80	0.49	0.22	1.39	3.63
	7.5- 9.5	1.60	1.00	0.66	0.36	1.56	2.77
	9.5-10.5	0.60	0.46	0.30	0.23	1.41	2.00
	10.5-12.0	1.80	1.70	0.80	0.50	1.50	3.40
NP 05	5.5- 7.0	1.50	1.00	0.50	0.20	1.70	5.00
	7.0- 9.0	1.00	0.80	0.50	0.25	1.40	3.20
	9.0-10.5	0.80	0.70	0.50	0.25	1.30	2.80
	10.5-15.5	0.80	0.75	0.50	0.25	1.26	3.00
	15.5-16.0	1.60	1.50	0.80	0.45	1.41	3.30
NP 07	3.0- 7.0	0.90	0.70	0.50	0.20	1.30	3.50
	7.0- 7.5	0.60	0.50	0.30	0.20	1.40	2.50
	7.5-10.0	0.50	0.40	0.25	0.15	1.40	2.70
	10.0-11.0	0.50	0.40	0.20	0.15	1.60	2.70
	11.0-12.0	0.70	0.65	0.50	0.22	1.18	2.95
	12.0-16.0	0.23	0.20	0.19	0.13	1.10	1.54
NP 10	5.0- 7.0	0.99	0.77	0.43	0.25	1.50	3.08
	7.0-11.0	0.72	0.65	0.35	0.19	1.43	3.42
	11.0-12.0	1.50	1.00	0.50	0.27	1.73	3.70
	12.0-16.0	0.70	0.60	0.46	0.25	1.23	2.40
NP 12	5.0-11.0	1.20	1.00	0.80	0.50	1.22	2.00
NP 15	7.0- 9.0	0.95	0.80	0.50	0.28	1.37	2.85
	9.0-11.0	1.75	1.60	0.75	0.43	1.50	3.70
	11.0-15.0	1.65	1.50	0.65	0.30	1.59	5.00
	15.0-16.0	0.70	0.60	0.39	0.22	1.34	2.70
	16.0-17.0	1.60	1.20	0.85	0.60	1.37	2.00

Table D.5 (cont.)

U_c = Uniformity Coefficient = D 40/90 U_s = Sorting Coefficient = √ D25/D75

Bore-hole	Depth (m)	D25 (mm)	D40 (mm)	D75 (mm)	D90 (mm)	U_s	U_c
NP 16	5.0- 9.0	3.00	2.50	1.50	0.80	1.40	3.13
	9.0-11.0	1.90	1.60	0.70	0.35	1.60	4.60
	11.0-12.0	1.70	1.55	0.90	0.60	1.37	2.60
NP 17	4.0- 6.0	1.50	1.20	0.60	0.25	1.58	4.80
	6.0- 8.0	2.30	1.80	1.00	0.70	1.52	2.57
	8.0-11.0	>4.00	3.50	0.90	0.50	>2.10	7.00
	11.0-13.0	0.80	0.60	0.25	0.20	1.79	3.00
	13.0-14.0	1.50	1.20	0.65	0.30	1.52	4.00
	14.0-15.0	3.00	2.30	1.40	0.60	1.46	3.83
NP 18	5.0- 7.0	2.00	1.50	0.60	0.30	1.83	5.00
NP 19	6.0-10.0	2.25	2.00	1.60	0.90	1.19	2.22
	10.0-11.0	3.00	2.40	1.50	0.90	1.41	2.67
	11.0-12.0	>4.00	>4.00	3.00	2.00	>1.10	>2.00
BH 31	3.0- 6.0	2.00	1.50	0.70	0.30	1.69	5.00
	6.0-12.0	2.50	1.60	0.80	0.40	1.77	4.00
	12.0-13.5	1.50	1.20	0.80	0.50	1.37	2.40

Table D.6

Percentages of Sands and Gravels in Drilling Samples taken at Depth of Screen Face.

Bore-hole No	Depth (m)	Grain Size (mm)			
		<0.2 fine sands	0.2-0.6 medium sands	0.6-0.2 coarse sands	>2.0 gravels
NP 01	7.0- 9.0	8%	19.5%	62.5%	10%
	9.0-11.0	2	4	31	63
	11.0-13.0	6	16	58	20
NP 02	7.0- 8.5	7	53	40	-
	8.5-11.0	1	9	80	10
	11.0-12.0	17	71	12	-
	12.0-13.0	10	68	22	-
NP 03	6.0- 7.0	6	29	58	7
	7.0- 9.0	12	31	53	4
	9.0- 9.5	3	27	67	3
	9.5-10.5	2	10	80	8
	10.5-11.5	15	65	20	-
	11.5-13.0	7	38	55	-
NP 04	5.0- 6.0	4	21	70	5
	6.0- 7.5	5	35	56	4
	7.5- 9.5	3	19	73	5
	9.5-10.5	8	62	30	-
	10.5-12.0	2	13	73	12
NP 05	9.0-10.5	5	50	43	2
	10.5-15.5	7	25	68	-
	15.5-16.0	2	13	85	-
NP 07	7.5-10.0	40	58	2	-
	10.0-11.0	20	65	15	-
	11.0-12.0	9	23	68	-
	12.0-16.0	41	57	2	-
NP 10	5.0- 7.0	7	33	60	-
	7.0-11.0	10	45	45	-
	11.0-12.0	6	26	64	4
	12.0-16.0	7	53	40	-
NP 12	5.0-11.0	3	13	85	-
NP 15	7.0- 9.0	5	25	67	3
	9.0-11.0	2	15	72	11
	11.0-15.0	2	21	67	10
	15.0-16.0	2	8	87	3
NP 16	5.0- 9.0	-	3	50	47
	9.0-11.0	4	16	58	22
	11.0-12.0	2	8	81	9

Table D.7

Determination of Optimum Screen Slot Width
(all figures in mm)

Well nr.	WITH GRAVEL PACK					WITHOUT GRAVEL PACK	
	Minimum Grain Size Drilling Samples		Grain Size Gravel Pack		Screen Slot Width	Minimum Grain Size Drilling Samples	Screen Slot Width
	D40	D75	D75	D90		D50	
NP01	1.0	0.5	2.5	2.0	2.0	0.8	0.75
NP02	0.65	0.35	1.75	1.4	1.25	0.55	0.5
NP03	0.75	0.4	2.0	1.6	1.5	0.65	0.5 -0.6
NP04	0.8	0.5	2.5	2.0	2.0	0.7	0.5 -0.6
NP07	0.4	0.25	1.25	1.0	1.0	0.35	0.25-0.3
BH31	1.2	0.70	3.50	2.75	2.5	1.1	1.0
NP10	0.65	0.35	1.75	1.4	1.25	0.55	0.5
NP12	1.0	0.8	4.0	3.5	3.0	0.95	0.75-1.0
NP15	0.8	0.5	2.5	2.0	2.0	0.7	0.5 -0.6
NP16	1.5	0.7	3.5	3.0	3.0	1.3	1.25
NP18	1.5	0.6	3.0	2.5	2.5	1.2	1.0
NP19	2.0	1.6	no gravel		2.0	2.0	2.0

Remarks: - 1. The D75 of the required gravel was determined at 5 times the D75 of the sand. The screen slot width equals the D90 of the gravel, which should be about 80% of the D75 of the gravel.

2. The maximum discharge from a borehole (in m^3/hr) for each slot width is shown in the table below:

Casing Diameter (mm)	100				150				200				250			
Slot Width (mm)	0.25	0.5	1.0	2.0	0.25	0.5	1.0	2.0	0.25	0.5	1.0	2.0	0.25	0.5	1.0	2.0
Screen type																
Wire - wound:																
Open Area (m^2/m)	0.03	0.05	0.09	0.12	0.04	0.08	0.13	0.18	0.06	0.10	0.18	0.24	0.07	0.13	0.22	0.30
Max. Q (m^3/hr)	9	16	29	39	13	26	42	58	19	32	58	78	22	42	71	97
Vertical slots:																
Open Area (m^2/m)	.009	.019	.035	.063	.014	.028	.052	.094	.019	.038	.069	.126	.024	.048	.086	.157
Max. Q (m^3/hr)	3	6	11	20	5	9	17	30	6	12	22	41	7	15	27	50

The discharge is determined under the assumption that the entrance velocity is smaller than 3 cm/sec. and that the saturated thickness is 6 meter. A safety factor 2 was applied to account for clogging of slots.

It should be noted that for reasons of maximum allowable drawdown the maximum discharge should not be more than 30-40 m^3/hr.

APPENDIX E

PUMP TEST ANALYSIS

Table E.1

Description of Pump Test Analysis Results

Well no.	Description of pump test analysis results
2	From the chart of the waterlevel recorder the following data were obtained:

Date	Drawdown after 8hrs pumping (m)	Specific capacity (m^3/hr/m)	Saturated Thickness Aquifer D (m)	Trans-missivity T (m^2/day)	Permea-bility k (m/day)	Analysis method
May '83	1.48	21.9	5.30	445	84	Jacob
June'83	1.88	17.2	4.60	395	86	Jacob
July'83	0.58	56	14.50	835	58	Jacob
Oct '83	0.47	69	13.60	1186	87	Jacob
Nov '83	0.77	42	11.30	1016	90	Jacob
Jan '84	1.02	31.8	8.30	593	71	Jacob

The pumpdischarge was estimated at 32.4 m^2/hr. A change in slope on the drawdown curve indicates a boundary at 300-400 m. from the well.

Well no.	Description of pump test analysis results	T (m^2/day)	S
BH 7	23 HRS TEST: Q=32.7 m^3/hr		
	- pumped well: Jacob Theis is not possible, because curve is too flat.	850	$2x10^{-3}$
	- observation BH 28 (45 m): Theis (good fit)	1650	$1x10^{-3}$
	-recovery of pumped well	500	-
BH 14	10 HRS TEST : Q=32 m^3/hr		
	- pumped well: Jacob T>2000 m^2/day Theis not possible, because curve is too flat.		
	- piezometer (10.65 m.), Theis, poor curve	1055	-
	- piezometer (5.15 m.), Theis	1705	-
	- piezometer (5.10 m.), Theis	1450	-
	- recovery gives T>2000 m^2/day		
	Remark: boundary seems to influence results, no realistic S-values were determined.		
BH 16	STEPTEST The well was developing during the test, the first and second step indicated T-value; Jacob, 1st step	340	-
	Constant discharge test: data were lost.		

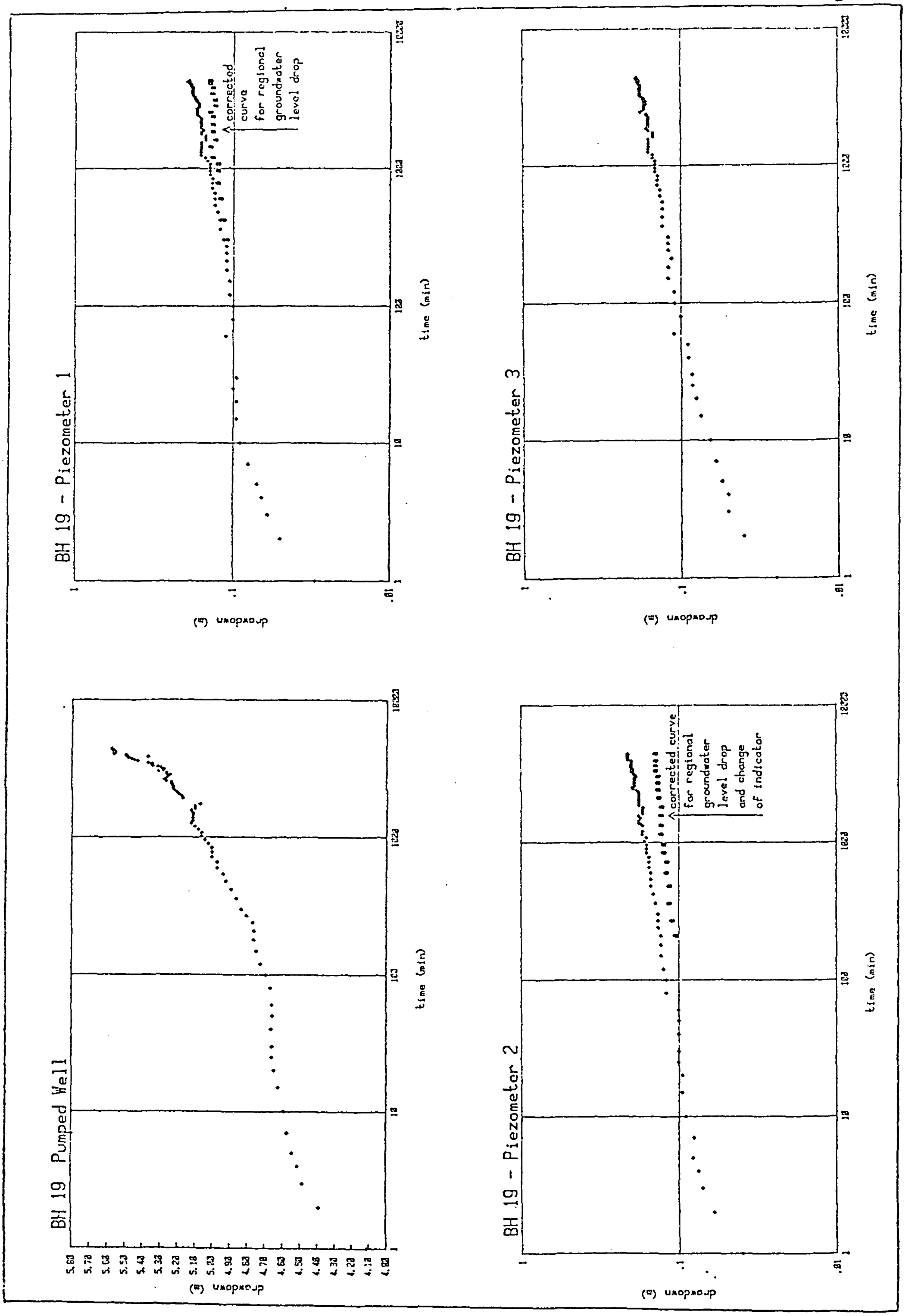
Table E.1 continued

Well no.	Description of pump test analysis results	T (m^2/day)	S
BH 19	<u>STEPTEST</u>: the steps show different values for T	(1000)	-
	<u>73 HRS TEST</u>: Q=14.7 m^3/hr.		
	- <u>pumped well</u>: <u>Jacob</u>, shows a change in slope at 200 min, indicating a boundary at 150 m.	400	-
	- <u>piezometer 1</u> (5.10 m): <u>Boulton</u>, good curve	1400	0.15
	- <u>piezometer 2</u> (5.10 m): <u>Boulton</u>, good curve	1340	0.15
	- <u>piezometer 3</u>(12.35 m): <u>Boulton</u>, good curve	1120	0.15
	Remark: Drawdown curves were corrected by 5 cm to account for drop in regional water level during the test; the analysis shows S-values in the range of 0.15 - 0.30		
BH 20	<u>STEPTEST</u>: the pumpdischarge was very irregular and also wrong discharge steps were used, therefore data not usable.		
	<u>72 HRS TEST</u>: Q=18.8 m^3/hr		
	- <u>pumped well</u>: <u>Jacob</u> shows a change in slope at 200 min, indicating a boundary at 100m.	660	-
	- <u>piezometer 1</u> (5.00 m): <u>Theis</u>-curve, correction of 7 cm for drop in regional waterlevel, T is high, S is reasonable.	2112	0.14
	- other piezometer (10.00 m) provided no good data.		
	- recovery shows T>2000 m^2/day.		
BH 30	<u>STEPTEST</u>: T-value determined from 4th and 5th step, but is confirmed by results of other steps.	750	0.044
	<u>2½ HRS.TEST</u>: Q=36.0 m^3/hr		
	Duration of test very short due to power cut.		
	- pumped well: <u>Jacob</u>	480	-
	<u>Recovery</u>	660	-
	No piezometers used in this test.		
BH 31	<u>STEPTEST</u>		
	- <u>pumped well</u>: step 6	660	-
	- <u>piezometer 1</u> (4.85 m): step 6	640	0.285
	<u>69 HRS. TEST</u>: Q=18.0 m^3/hr		
	- <u>pumped well</u>: <u>Jacob</u>, change in slope indicates boundary at 50-70 m.	530	-
	- <u>piezometer 2</u> (4.85 m): <u>Theis</u> (good fit)	520	0.394
	<u>Recovery</u>	660	-
	- other piezometers provided no good data.		
	Remark: drawdown during long test was corrected by 0-0.08 m to account for drop in regional water level.		

Well no.	Description of pump test analysis results	T (m^2/day)	S
NP 04	12 HRS.TEST: Q=20.0 m^3/hr - pumped well: Jacob, change in slope indicates boundary at about 40 m only. - piezometer (5.00 m): Boulton (delayed yield) - piezometer (10.00 m): Boulton (delayed yield) Remark: test duration too short to determine S, results of test are affected by partial penetration.	 975 1005 1105	 - - -
NP 07	STEPTEST: no results, due to improper execution of the test. 6 HRS TEST: Q=32.7 m^3/hr. - pumped well: data not usable. - piezometer (5.00 m): Theis - piezometer (10.00 m): Theis (doubtful result) Remarks: test result affected by partial penetration and boundary effects. The test duration is also too short.	 1280 2230	 0.38 -
NP 10	13 HRS TEST: Q=14.0 m^3/hr - pumped well: Jacob (poor curve) - piezometer 1 (5.00 m): Boulton - piezometer 2 (10.00 m): Boulton - piezometer 3 (5.00 m): Boulton Remark: test duration too short to determine value for S	 1400 820 780 900	 - - - -
NP 12	10 HRS TEST: Q=21.0 m^3/hr - pumped well: Jacob (poor curve) - piezometer (5.00 m): Boulton (poor curve) - piezometer (10.00 m): Boulton (poor curve) Remark: test duration too short to determine value for S	 1390 1740 1400	 - - -
NP 15	STEPTEST: well was developing, no good data 46 HRS TEST: Q=13.7 m^3/hr - pumped well: Jacob (poor curve) - piezometer: (10.37 m): Theis (reasonable curve)	 275 380	 - 0.14
NP 16	12 HRS TEST: Q=14.0 m^3/hr - pumped well: Jacob - piezometer 1 (5.00 m): Jacob Boulton (good curve) - piezometer 2 (10.00 m): Boulton Remark: delayed yield effect is clear in piezometer curves, but test duration is too short for accurate interpretation	 880 880 800 740	 - - 0.27 0.21

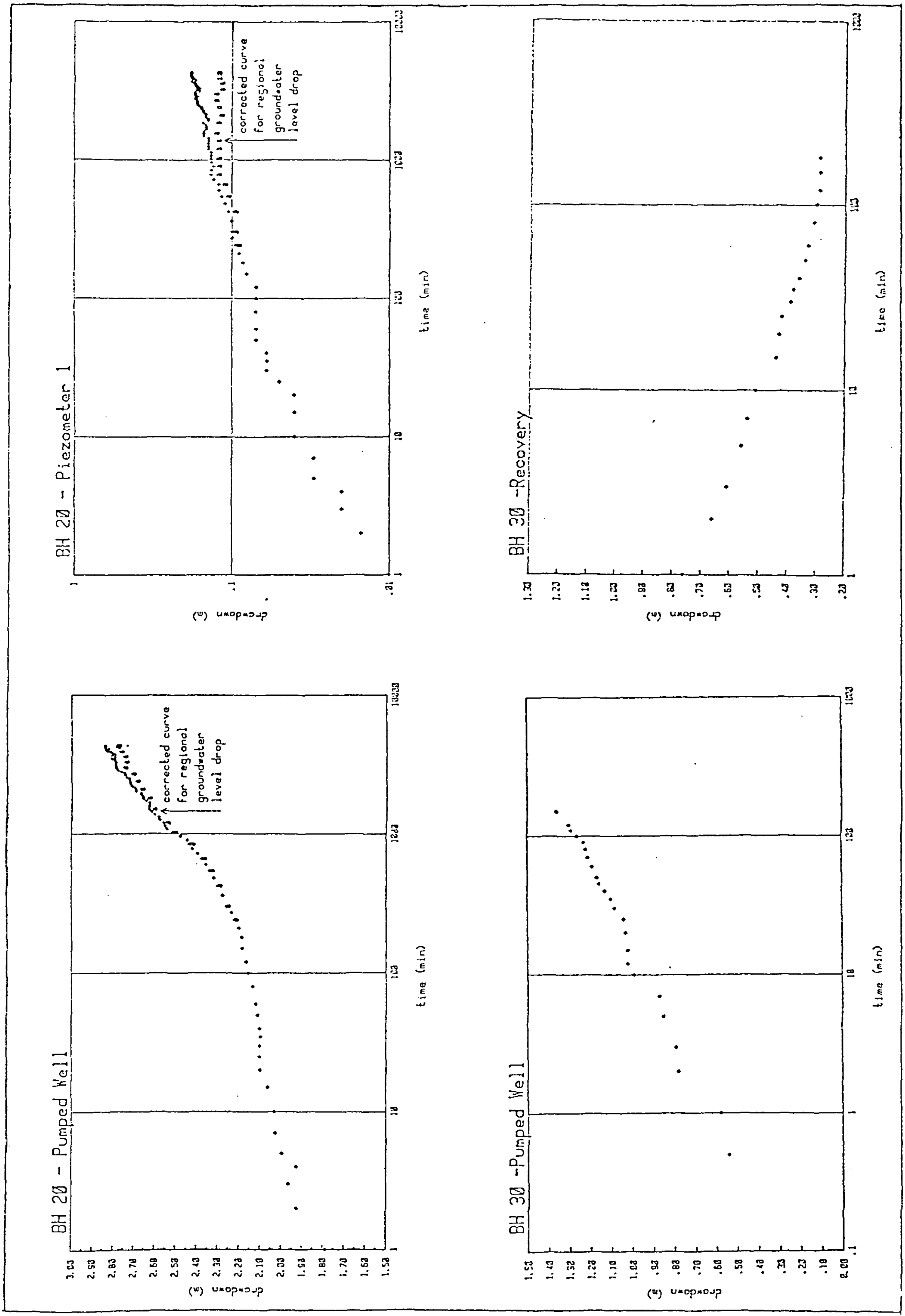
PUMP TEST CURVES

Fig. E.1



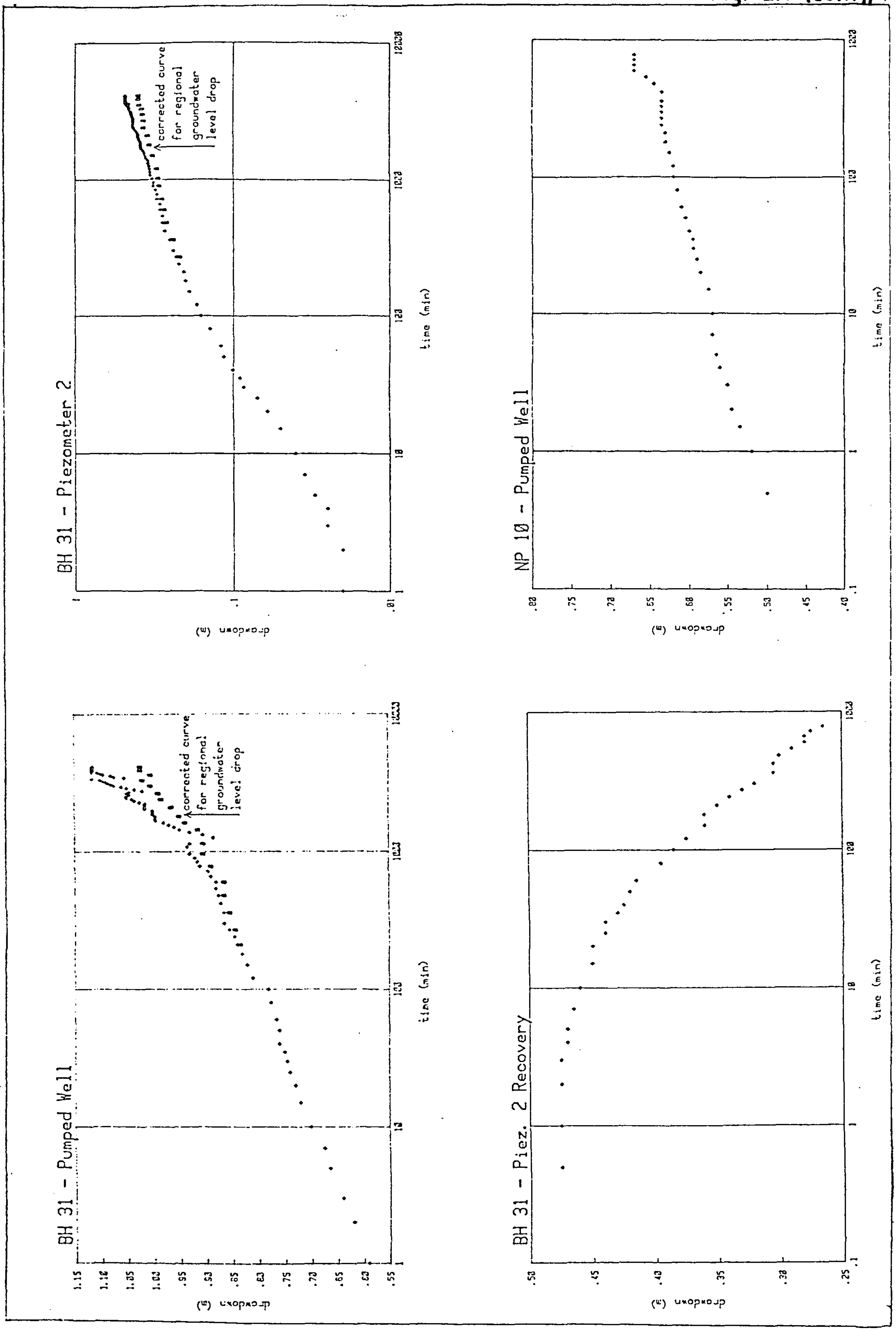
PUMP TEST CURVES

Fig. E.1 (cont.)



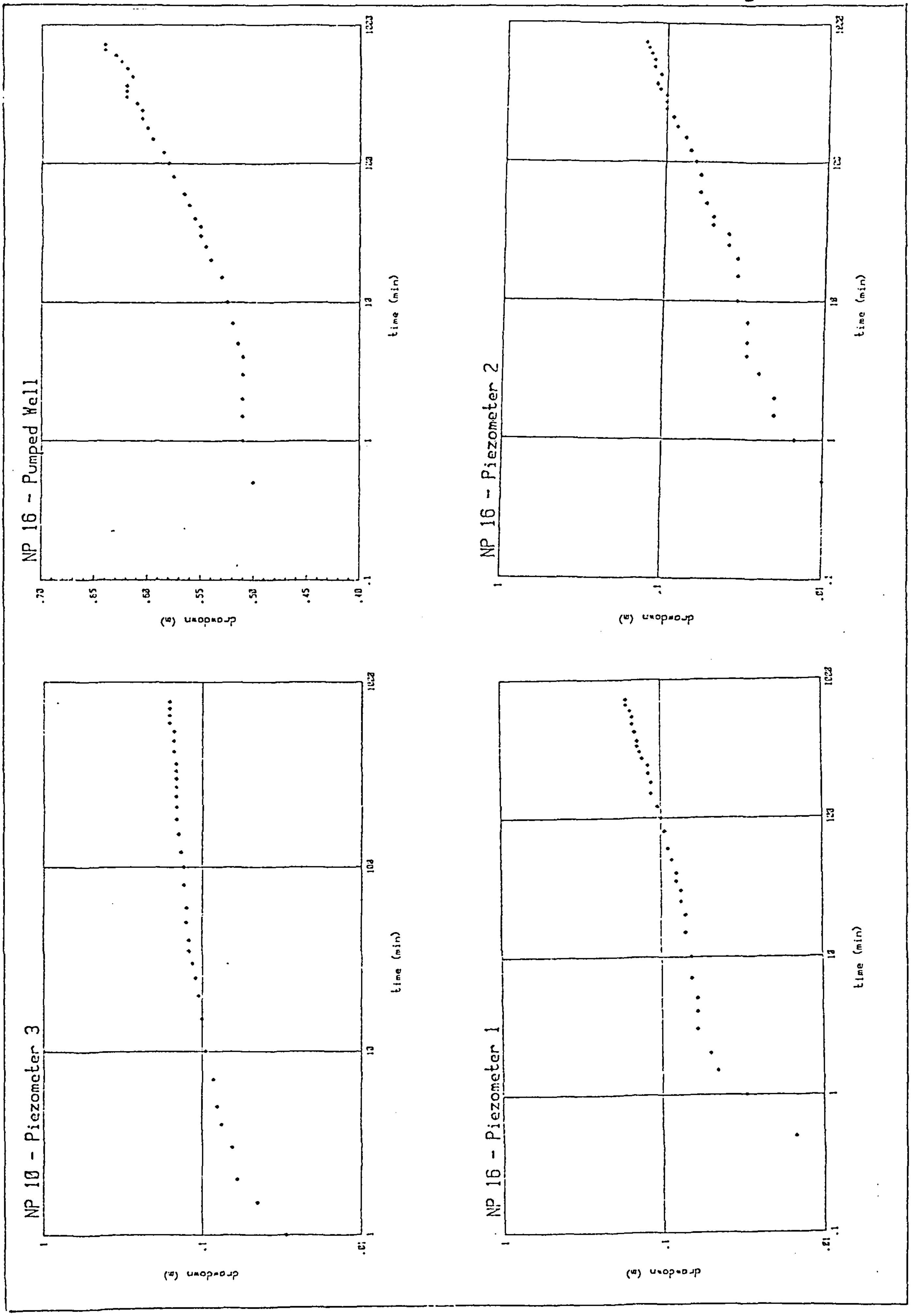
PUMP TEST CURVES

Fig. E.1 (cont.)



PUMP TEST CURVES

Fig. E.1 (cont.)



APPENDIX F

GROUNDWATER MODELS OF TOWN AREA AND DOWNSTREAM AREA

APPENDIX F GROUNDWATER MODELS OF TOWN AREA AND DOWNSTREAM AREA

F1. Description of the Model

F1.1 General

The groundwater model used is developed for the HP-85 micro-computer with a total memory of 32 kbytes (Schoute and Swenker, 1984). It is a finite difference polygonal one aquifer layer model, as described by Tyson and Weber (1963), Thomas (1973) and Boonstra and De Ridder (1981). The model can be applied to unconfined or confined aquifers, or to any combination of these, provided that one type passes laterally into the other.

The model allows wide variations to be taken into account in aquifer parameters as hydraulic conductivity and storage coefficient. Transient (unsteady) flow problems can be studied, provided that the flow is laminar and Darcy's law thus applies.

The model is devised for saturated flow only. This means that the processes of infiltration, percolation, and evaporation, which occur in the unsaturated zone of unconfined aquifers cannot be simulated. They must be calculated by hand and their algebraic sum prescribed to the model.
The method used by the model to solve the finite-difference equations is essentially that of Gauss-Seidel. It is an iterative calculation process that is continued as long as necessary, to obtain water-table elevations that are sufficiently accurate. Apart from the advantage of avoiding stability problems, this method requires little computer memory.

Incorporated in the model are the following features and restrictions:
- The aquifer is treated as a two-dimensional flow system.
- Both unsteady and steady state conditions can be simulated.
- Only one aquifer system can be modelled with one storage coefficient in vertical direction.

- The aquifer is bounded at the bottom by an impermeable layer.
- The upper boundary of the aquifer is an impermeable layer (confined aquifer) or the free water-table (phreatic or unconfined aquifer).
- Darcy's law (linear resistance to laminar flow) and Dupuit's assumptions (vertical flow can be neglected) are applicable in the aquifer.
- The aquifer has head-controlled, flow-controlled, and/or zero-flow boundaries; the first two may vary with time.
- For unconfined aquifers the transmissivity varies with time; the model adjusts the saturated thickness according to the calculated water-table elevation (non-linear conditions); only the hydraulic conductivity and the bottom of the aquifer must be prescribed.
- Limits, in between which the water-table in the aquifer is allowed to vary, can be prescribed. If the water-table exceeds a certain upper or lower limit, the model introduces an artificial flow rate that will keep the calculated water-table within that limit.
- The discharge or recharge from or to each node can be simulated by a constant flow rate or by a varying monthly flow rate prescribed seperately for each node.
- The processes of the infiltration and percolation of rain and surface water and of capillary rise and evapotranspiration, taking place in the unsaturated zone of the aquifer (above the water-table), cannot be simulated. This means that the net-recharge to the aquifer must be calculated manually and prescribed to the model.
- The length of the simulation period can be chosen freely. The simulation can be started on any day of the year, the calculation time step specified to any number of days.
- The model cannot simulate spatial and time variations of groundwater quality.

In its present version the computer programme can handle 100 polygonal nodes with a maximum of 300 interfaces between them.

Two models were prepared for the WAPS-2 study area at Nyala:

- one for the Town Area, between the Texas bridge and the Jebel Nyala; consisting of 60 nodes;
- one for the Downstream Area, with 38 nodes.

F1.2 General description of the input

The data required for each node are:

- bedrock elevation;
- upper water level limit;
- initial water level;
- nodal area;
- type of node (fixed or variable head);
- any recharge or discharge, which is constant during the simulated period;
- the number of the net-recharge function;
- the net-recharge factor;
- storage coefficient.

To each node is assigned one out of 10 (nrs. 0-9) different net-recharge /discharge scenarios. Each scenario consists of a series of twelve net-recharge/discharge values, that multiplied with the net-recharge factor for each month correspond to the mean daily flow rate (in mm/day).

In each node the groundwater head can be kept fixed or be variable, i.e. it is calculated by the model. It is also possible to keep it fixed at the upper water level limit for some time steps and variable for others.
In the latter case one of the net-recharge scenarios is used to indicate the months during which the fixed head conditions exist.

The nodal area is calculated seperately with a sub-programme after the coordinates of each node centre are provided.
Other data required by the model is an estimate of the aquifer permeability at each interface between the nodes.

F1.3 General description of the calibration

The model should be calibrated after selecting the input data by comparing the results of the simulation run with actually observed piezometric heads. The results can be presented in the form of groundwater level contour maps or groundwater hydrographs.
If the simulation is not satisfactory then those input data should be adjusted which has the lowest level of confidence. This is usually the estimate of discharge or recharge or the estimate of the aquifer parameters k and S.
If the simulation gives satisfactory results then a sensitivity analysis can be done by analysing the effect on the results by a change in one of the input data. This analysis should show the required accuracy of the input data.

F2. The Town Area Model

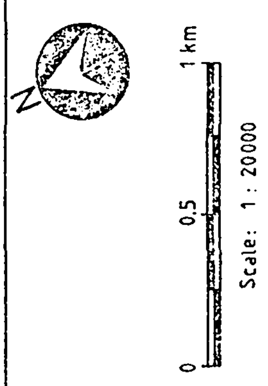
F2.1 Lay-out of the model

The model consists of 29 internal nodes and 31 external nodes (see figure F.1).
The interfaces between internal and external nodes correspond with the outer boundary of the aquifer as indicated on the alluvial aquifer map (map 3). The boundary between the sandy and clayey/sandy parts of the aquifer is also represented in the model, by interfaces between internal nodes.
The clayey/sandy aquifer is covered by 14 nodes, the sandy aquifer by 15 nodes. The areas of the nodes at the location of the Town Wells are smaller, because of the prevailing large groundwater table gradients and big variations in the depth to the Basement.

The upstream boundary of the Town Area model was chosen just upstream of the Texas bridge. Not included was an area of 0.4 km^2 between the runoff station and the bridge, which otherwise

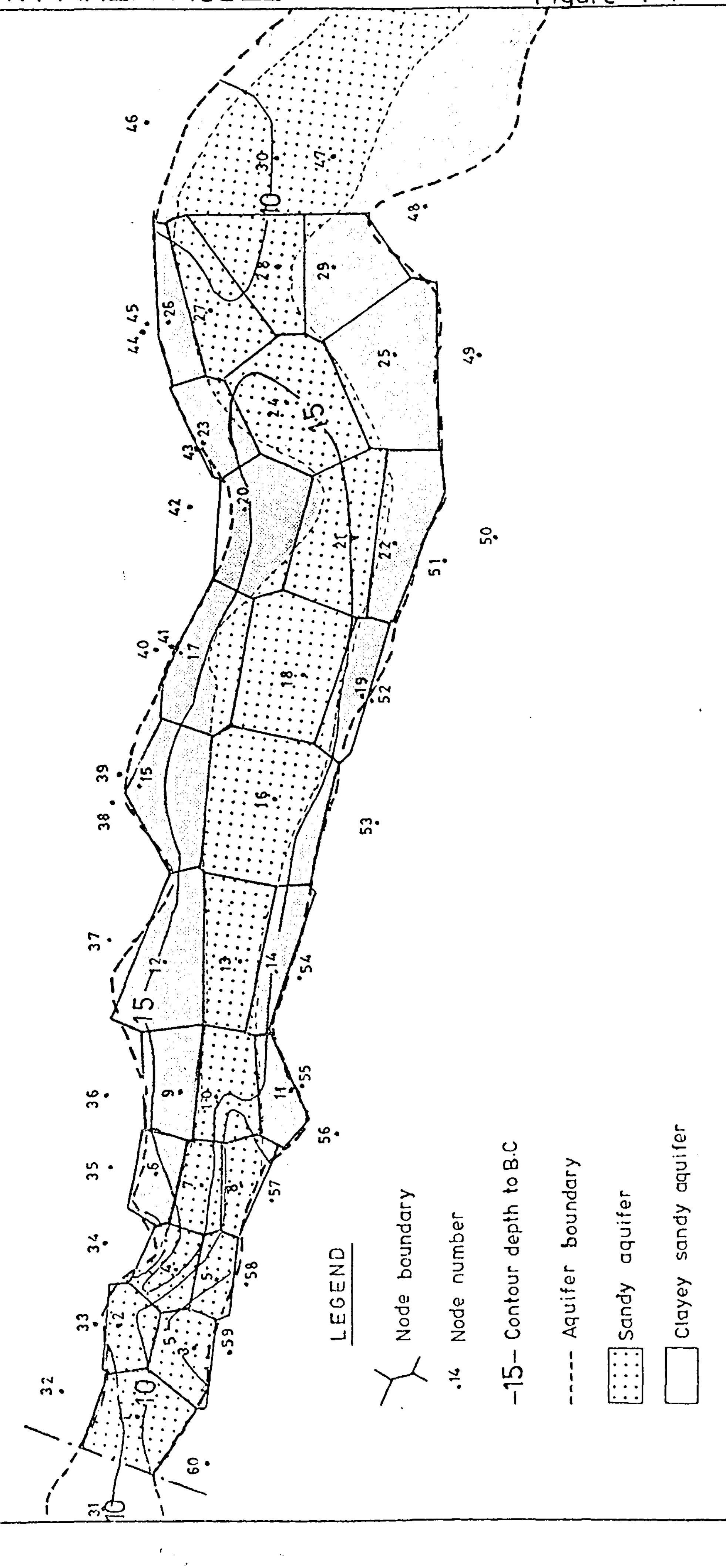
LAY-OUT TOWN AREA MODEL

Figure F.1



NFC026

NODE	X	Y
1	375.00	1535.00
2	700.00	1600.00
3	620.00	1325.00
4	900.00	1395.00
5	860.00	1245.00
6	1244.00	1465.00
7	1200.00	1300.00
8	1195.00	1160.00
9	1535.00	1375.00
10	1520.00	1250.00
11	1540.00	990.00
12	2000.00	1430.00
13	2000.00	1165.00
14	1965.00	1035.00
15	2625.00	1525.00
16	2580.00	1040.00
17	3110.00	1380.00
18	3020.00	940.00
19	2950.00	730.00
20	3615.00	1145.00
21	3520.00	760.00
22	3495.00	610.00
23	3855.00	1300.00
24	4000.00	1000.00
25	4170.00	620.00
26	4290.00	1420.00
27	4325.00	1270.00
28	4485.00	1040.00
29	4485.00	840.00
30	4880.00	1030.00
31	50.00	1650.00
32	465.00	1805.00
33	705.00	1680.00
34	1000.00	1640.00
35	1265.00	1620.00
36	1520.00	1640.00
37	2080.00	1630.00
38	2570.00	1630.00
39	2670.00	1595.00
40	3120.00	1460.00
41	3130.00	1420.00
42	3630.00	1350.00
43	3840.00	1330.00
44	4260.00	1510.00
45	4285.00	1500.00
46	5000.00	1500.00
47	4880.00	850.00
48	4695.00	515.00
49	4170.00	320.00
50	3520.00	260.00
51	3430.00	440.00
52	2940.00	705.00
53	2500.00	680.00
54	1940.00	960.00
55	1550.00	969.00
56	1395.00	820.00
57	1145.00	1050.00
58	845 00	1145.00
59	600.00	1200.00
60	200.00	1275.00



in this report is included in the Town Area.
The downstream boundary of the model is located near Jebel Nyala. Both boundaries are fixed flow boundaries. All other outer boundaries were assumed to be no-flow boundaries.

F2.2 Input data

The elevation of the upper and lower water level limit was determined equal to the elevation of the ground surface and the top of the Basement respectively. For each node the average elevation of the ground surface was estimated from a topographical map (prepared by the WAPS-2 project, but not represented in this report), and the average elevation of the top of the Basement from the aquifer geometry map.
The upper water level limit was determined equal to the water level of September 1984 for those nodes which have assigned a fixed water level in the rainy season. These are the nodes under the wadi course, where infiltration from surface water occurs.

The estimates for the aquifer parameters k and S were based on the results of the pumptests (section 7.3):
- k = 50 m/day at interfaces between two sandy aquifer nodes;
- k = 20 m/day at other interfaces;
- S = 0.25 at sandy aquifer nodes;
- S = 0.15 at clayey/sandy aquifer nodes.

(The value of S was changed after calibration, see section F2.3).

The groundwater discharge at each node consists of:
- evapotranspiration;
- pumping for domestic use (not all nodes);
- outflow across model boundary (not all nodes).

The groundwater losses by evapotranspiration were determined according to the procedure presented in appendix A2. The evaporation rates during the simulated period were not much different

from the mean monthly rates, except during the wet season of 1984. Then the actual evapotranspiration was bigger than normal, because of the low rainfall. Therefore the actual observed evaporation rates were only applied for the wet season. For the other months the mean rates were used.
The rainfall during 1984 was substracted in a similar way as explained in section 7.6, producing the following estimates of groundwater losses by evapotranspiration:

- dry season 1.4×10^6 m^3;
- wet season 0.3×10^6 m^3.

The evapotranspiration losses at each node were determined according to the land use at the node.

The pumping for domestic purposes by the PEWC was estimated, assuming that the variation in discharge observed from the metered wells applies for all wells. The total annual discharge by the PEWC during 1983 - 1984 was 1.4×10^6 m^3 or 70% of the normal annual total of 2.0×10^6 m^3.
The daily discharge from each borehole is included in table F.3. The pumping for domestic purposes from dug wells by private water vendors was also included. The total annual volume pumped from inside the model area was estimated at 0.35×10^6 m^3 and was assumed to be discharged at a constant rate during the year. (This quantity was changed after calibration, see section F2.3). The outflow across the model boundary was based on the estimate presented in section 7.6: 0.21×10^6 m^3/year. This outflow takes place at the nodes 28 and 29.

The recharge by infiltration of surface water was simulated by fixing the groundwater level in the wadi nodes at the upper water level limit during the three wet season months. This procedure corresponds well with the actual quick recovery of the water levels after surface runoff has occurred (see hydrograph of BH 2 in figure 7.4). Also the flow of groundwater from the wadi into the banks can thus be simulated satisfactorily, despite the limited number of calculation time steps (3 months) in the rainy season.

The recharge by inflow of groundwater across the aquifer boundary takes place only at node 1. The quantity was estimated at 20 000 m^3/year (section 7.5).

A total of 6 net-recharge functions were utilized (see table F.1):

- function 0: denotes the months with a fixed water level;
- function 1: specifies the monthly variation of the pump discharges of the PEWC wells;
- function 2: recharge function of node 1;
- function 3: recharge function of node 28;
- function 4: recharge function of node 29;
- function 5: specifies the monthly variation of the evapotranspiration.

The function 0 is used for nodes where recharge by infiltration from surface water takes place. These are the nodes in the wadi course. The recharge was assumed to be during the months July, August and September.

The variation in evapotranspiration is simulated with function 5, which is multiplied with the net-recharge factor of the node to obtain the mean daily water loss by evapotranspiration in that node. The net-recharge factor is equal to the total annual evapotranspiration minus the net rainfall and depends on the land use at the node.
A summary of the input data corrected after calibration is presented in table F.1.

Table F.1 Input Data Town Area Model Nyala

FILE NAME IS NPIN30

INTERFACE BETWEEN NODES		W-L	K
1	2	.4354	50
1	3	.69118	50
1	31	.74417	50
1	32	28151	0
1	60	999	0
2	3	.08356	50
2	4	578	50
2	32	.063772	0
2	33	3.8944	0
2	34	25369	0
3	4	.31335	50
3	5	44807	50
3	53	2.525	0
3	60	071712	0
4	5	1.7773	50
4	6	14259	20
4	7	.47244	50
4	34	83547	0
5	7	.13108	50
5	8	.19637	50
5	58	2.8763	0
5	59	.11831	0
6	7	1.7722	20
6	9	53957	20
6	34	.36323	0
6	35	1.7659	0
6	36	078094	0
7	8	2.2583	50
7	9	037474	20
7	10	.33457	50
8	10	36982	50
8	11	.22771	20
8	57	2.9573	0
8	58	010301	0
9	10	3.2363	20
9	12	.47913	20
9	13	.031192	50
9	36	1.2792	0
10	11	1.3008	20
10	13	.25193	50
10	14	071383	20
11	14	.14254	20
11	55	14.958	0
11	56	.644	0
11	57	030906	0
12	13	2.0834	40
12	15	.19975	20
12	16	.016384	20
12	36	.22035	0
12	37	2.609	0
13	14	4.0052	20
13	16	.47519	50
14	16	15692	20
14	57	043956	0
14	54	6.8381	0
14	55	0073665	0
15	16	97418	40
15	17	3217	20
15	38	2.7677	0
15	39	3.5563	0
16	17	11117	20
16	18	6841	50
16	19	.22018	20
16	53	1.2162	0
17	18	1.01	40
17	20	30306	20
17	39	059887	0
17	40	2.4558	0
17	41	7.4155	0
17	42	021407	0
18	19	2.1636	20
18	20	.17107	20
18	21	.51954	50
19	21	037716	20
19	22	.20071	20
19	51	.016903	0
19	52	19.739	0
19	57	.025773	0
20	21	1.0846	20
20	23	.599	20
20	24	48785	20
20	42	1.7528	0
21	22	3.9766	20
21	24	42613	50
21	25	11247	20
22	25	.23833	20
22	49	017779	0
22	50	46164	0
22	51	2.6837	0
23	24	.89934	20
23	26	.22978	20
23	27	.14393	20
23	42	064833	0
23	43	10.975	0
24	25	.99786	40
24	27	.57224	50
24	28	.20776	50
24	29	.13686	40
25	29	.94179	20
25	48	.20372	0
25	49	1.9278	0
26	27	3.7225	20
26	44	2.1181	0
26	45	4.8606	0
26	46	.080998	0
27	28	1.8945	50
27	46	.1197	0
28	29	2.155	20
28	30	.98442	50
28	46	.029189	0
29	47	.50985	20
29	48	.77167	0

FILENAME IS NPNODE

NODE	INIT.WATERL.[m]	FLOWRATE [m/DAY]	NODE TYPE	STORAGE COEFF.	BASEMENT ELEV.[m]	UPP.W.L.LIMIT [m]	NODAL AREA [m2]	NET-RECH.FUNCT.	NET-RECH.FACTOR
1	654.20	0.0000	0	.20	645.00	654.40	94012.00	2	1.00
2	652.60	0.0000	0	.20	643.50	653.20	51442.00	1	5.00
3	653.20	0.0000	0	.20	648.50	653.40	59027.00	5	337.00
4	651.80	0.0000	0	.20	640.30	653.30	59816.00	1	26.70
5	652.50	0.0000	0	.20	646.30	652.30	37048.00	5	86.00
6	650.80	0.0000	V	.10	641.00	655.00	50901.00	5	589.00
7	651.60	0.0000	0	.20	638.60	651.20	49460.00	1	7.90
8	651.80	0.0000	0	.20	645.30	651.60	47188.00	5	305.00
9	650.50	-.0011	V	.10	637.00	653.00	77265.00	5	680.00
10	650.80	0.0000	0	.20	637.50	650.50	75274.00	1	12.00
11	650.90	0.0000	V	.10	639.00	653.00	49522.00	5	524.00
12	649.70	-.0016	V	.10	636.80	651.80	127865.00	5	937.00
13	649.90	0.0000	0	.20	635.10	649.50	113541.00	1	7.20
14	650.20	0.0000	V	.10	637.40	651.40	60378.00	5	478.00
15	648.50	0.0000	V	.10	636.50	650.50	114867.00	5	1070.00
16	648.70	-.0006	0	.20	634.20	649.00	217472.00	1	6.80
17	647.40	-.0007	V	.10	634.00	649.00	119445.00	1	4.40
18	647.50	0.0000	0	.20	632.70	647.30	165872.00	1	4.20
19	647.60	0.0000	V	.10	637.50	649.50	64256.00	5	990.00
20	646.40	0.0000	V	.10	632.00	648.00	134463.00	5	276.00
21	646.50	0.0000	0	.20	632.80	646.00	148492.00	5	525.00
22	646.40	0.0000	V	.10	635.00	648.00	104603.00	5	1088.00
23	645.50	-.0012	V	.10	632.80	646.80	63734.00	5	944.00
24	645.70	0.0000	0	.20	632.00	645.60	166283.00	5	652.00
25	644.20	0.0000	V	.10	633.70	646.70	175549.00	5	1248.00
26	644.50	-.0019	V	.10	634.00	645.50	56686.00	5	503.00
27	644.60	0.0000	0	.20	633.80	645.00	107996.00	5	331.00
28	644.50	0.0000	V	.20	634.70	645.20	114200.00	3	1.00
29	644.40	0.0000	V	.10	632.60	644.60	113978.00	4	1.00

FILE NAME IS NPRE3C

Net-recharge in [mm/DAY]:

TIME STEP	NET-RECHARGE FUNCTION 0	NET-RECHARGE FUNCTION 1	NET-RECHARGE FUNCTION 2	NET-RECHARGE FUNCTION 3	NET-RECHARGE FUNCTION 4	NET-RECHARGE FUNCTION 5
JAN	0.0000	-.8000	-1.7000	-5.1000	-3.5000	-.0019
FEB	0.0000	-.7500	-1.6000	-5.1000	-3.6000	-.0022
MAR	0.0000	-.7000	-1.6000	-5.1000	-3.0000	-.0025
APR	0.0000	-.6000	-1.6000	-4.5000	-3.7000	-.0027
MAY	0.0000	-.5500	-1.5000	-4.2000	-3.7000	-.0031
JUN	0.0000	-.4500	-1.3000	-3.9000	-3.5000	-.0030
JUL	1.0000	-.4500	-1.0000	-4.3000	-3.9000	-.0033
AUG	1.0000	-.4000	-.5000	-5.6000	-4.4000	-.0033
SEP	1.0000	-.9000	-1.7000	-6.8000	-4.9000	-.0033
OCT	0.0000	-1.0000	-2.0000	-7.3000	-5.1000	-.0032
NOV	0.0000	-1.0000	-2.0000	-6.2000	-4.2000	-.0025
DEC	0.0000	-.9000	-1.8000	-5.4000	-3.7000	-.0020

F2.3 Calibration of the model

The groundwater model was calibrated using data from the period October 1983 until June 1985. The calculations were started with an initial water level determined from the groundwater level measurements of 20 October 1983.
The following adjustments were made to the original input data to improve the simulation:

- The flow rate in nodes 9 and 12 (corresponding with pumping from dug wells for domestic purposes) was reduced, changing the total pumping in the Town Area from 350 000 m^3/year to 250 000 m^3/year.
- The pumping in node 10 by BH 7 was increased from 190 000 m^3/year to 225 000 m^3/year.
- The permeability k was increased from 20 to 40 m/day at nodes 12, 15, 17 and 25 to improve the recovery of the groundwater level.
- The specific yield S was reduced to 20% for sandy aquifer nodes and to 10% for the clayey/sandy aquifer nodes.

The input data which suited best the conditions in the wadi aquifer are summarized in table F.1.
The result of the calibration is shown in figure F.2 in the form of the simulated groundwater contour maps of October 1984 and June 1985, and in figure F.3 in the form of the hydrographs of five different nodes. These figures show a good simulation of the actual situation by the groundwater model.

The groundwater storage fluctuation in the Town Area during the simulated period of October 1983 - June 1985 is shown in table F.2. It can be seen that the storage remaining at the end of the dry season is very limited, especially after the dry year 1984.

The actual variation of the groundwater storage during 1983 - 1985 is shown in figure 7.7. The model result corresponds well with the actual situation.

SIMULATED GROUNDWATER CONTOUR MAPS

Figure F.2

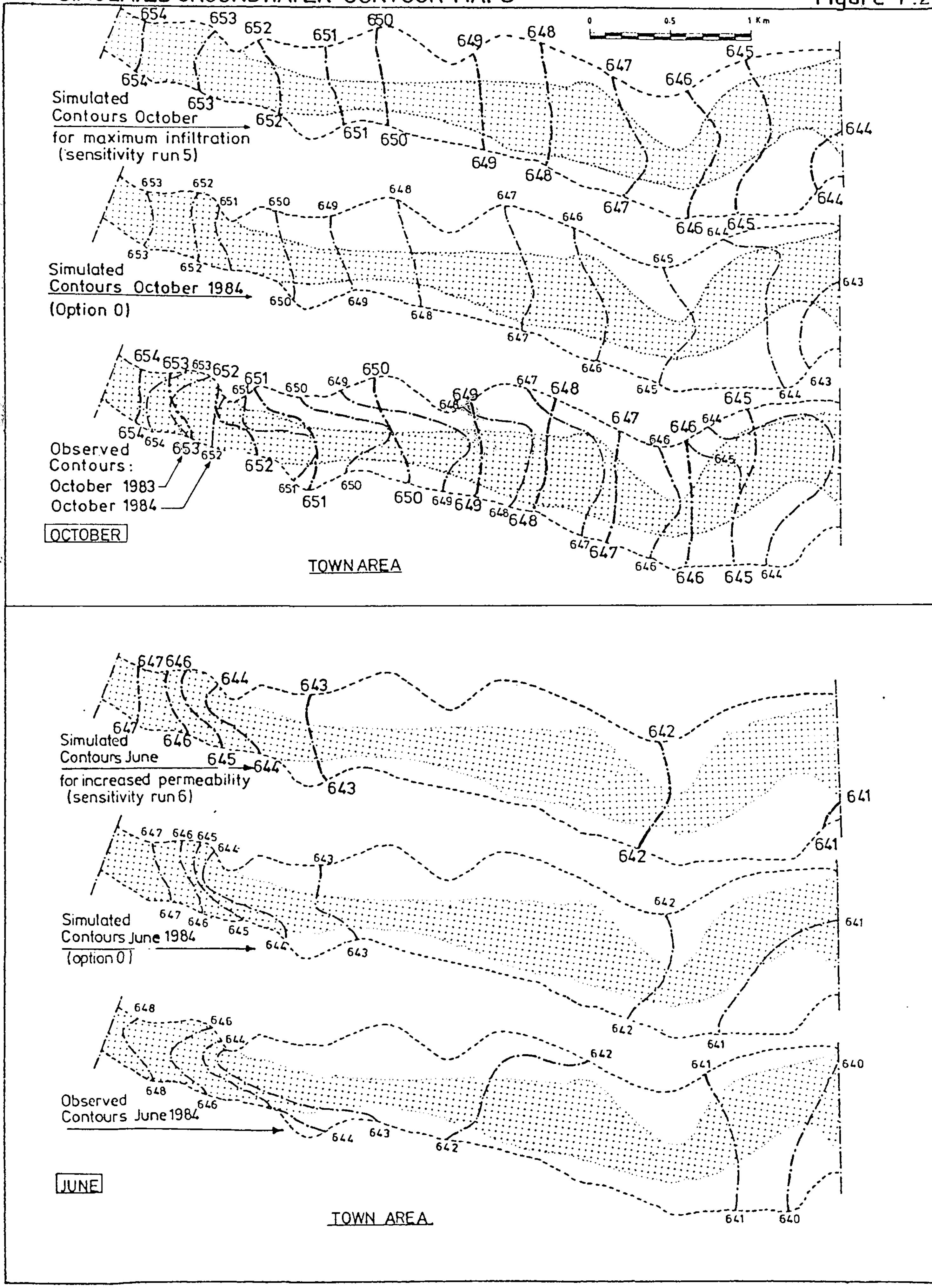


Table F.2 Simulated groundwater storage fluctuation in the Town Area during 1983 - 1985

INITIAL STORAGE OCTOBER 1983				5.3
Infiltration Groundwater inflow	- 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	1.3 0.9 0.2 0.2	
IN	0.0	OUT	2.6	-2.6
STORAGE JUNE 1984				2.7
Infiltration Groundwater inflow	3.0 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	0.3 0.3 0.0 0.0	
IN	3.0	OUT	0.6	+2.4
STORAGE SEPTEMBER 1984				5.1
Infiltration Groundwater inflow	- 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	1.4 1.1 0.2 0.2	
IN	0.0	OUT	2.9	-2.9
STORAGE JUNE 1985				2.2

F2.4 Sensitivity analysis

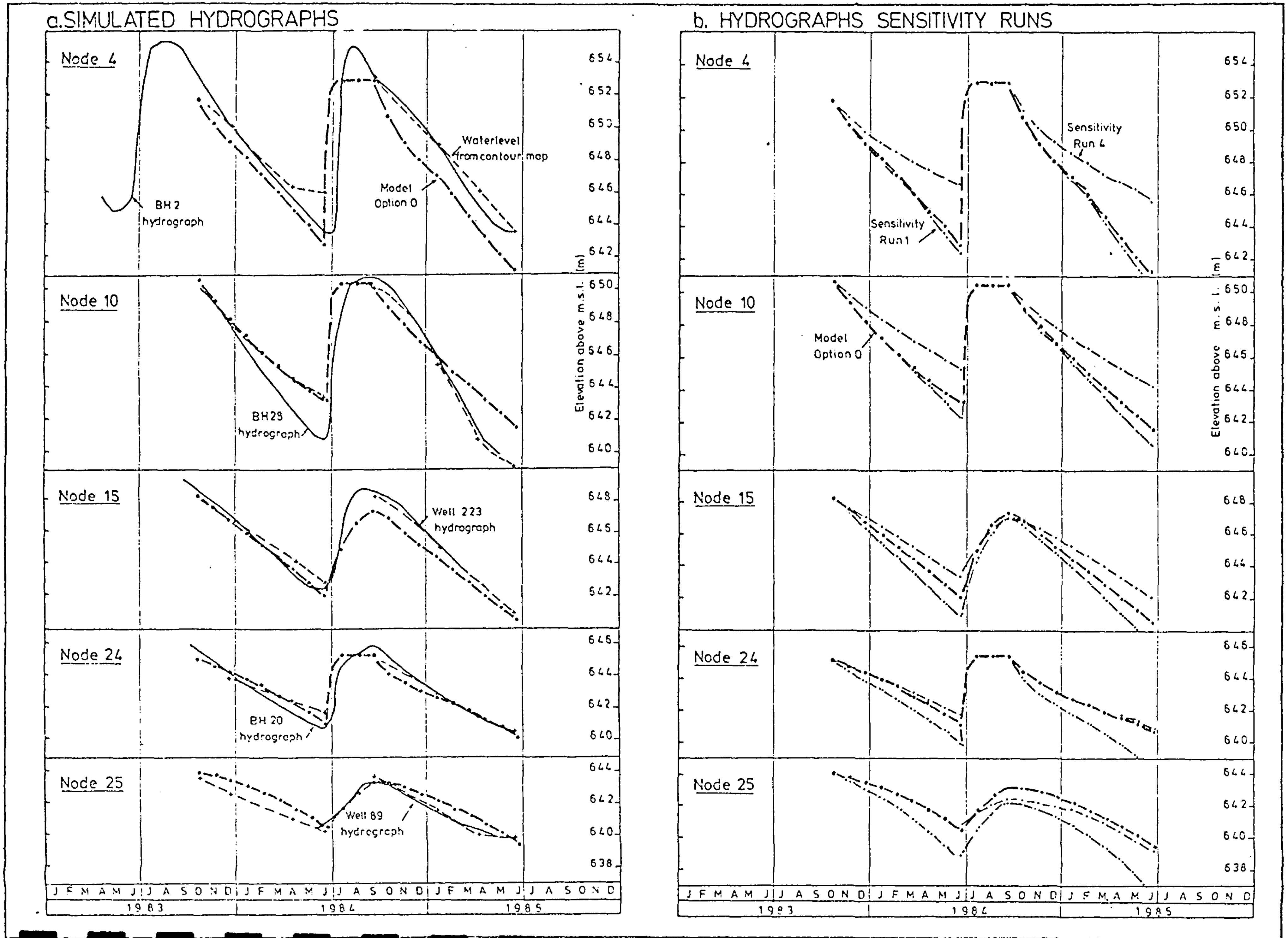
The sensitivity of the simulation to variations in the input data was tested to determine the accuracy of the model. Six runs were made changing the following data:

- The discharge by evapotranspiration was increased by 50%.
- The specific yield S was increased by 25%.
- The specific yield S was increased by 50%.
- The discharge by evapotranspiration and the specific yield S were both increased by 50%.
- The upper water level limit was raised to ground surface elevations at nodes in the wadi to obtain maximum infiltration rates.
- The aquifer permeability was doubled: to 90 m/day at interfaces between sandy aquifer nodes, to 50 m/day at interfaces between sandy and clayey/sandy aquifer nodes and to 30 m/day at interfaces between clayey/sandy aquifer nodes.

The results of the sensitivity runs are presented in figures F.2 and F.3.

The main conclusions from the sensitivity runs are:

- Any infiltration can be simulated if the appropriate upper water level limits are used.
- The value of k only has a small effect on the model result, due to the relatively small flows across the node boundaries. The steep groundwater table gradients in the area of the Town Wells are simulated well with the k-value of 50 m/day.
- The drawdown at node 4 is not simulated satisfactorily with a bigger estimate for S than 0.20. Assuming that the S-value is generally similar in the model area, this value is the correct estimate for the whole sandy aquifer.
- If accepted that the estimates of S and k are suitable, the evapotranspiration estimate should not be chosen to be bigger, otherwise too large drawdowns are simulated.



a. SIMULATED HYDROGRAPHS
b. HYDROGRAPHS SENSITIVITY RUNS
Node 4
Node 10
Node 15
Node 24
Node 25
BH 2 hydrograph
Waterlevel from contour map
Model Option 0
BH 28 hydrograph
Well 223 hydrograph
BH 20 hydrograph
Well 89 hydrograph
Sensitivity Run 4
Sensitivity Run 1
Elevation above m.s.l. (m)
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1983
1984
1985

Figure F.3

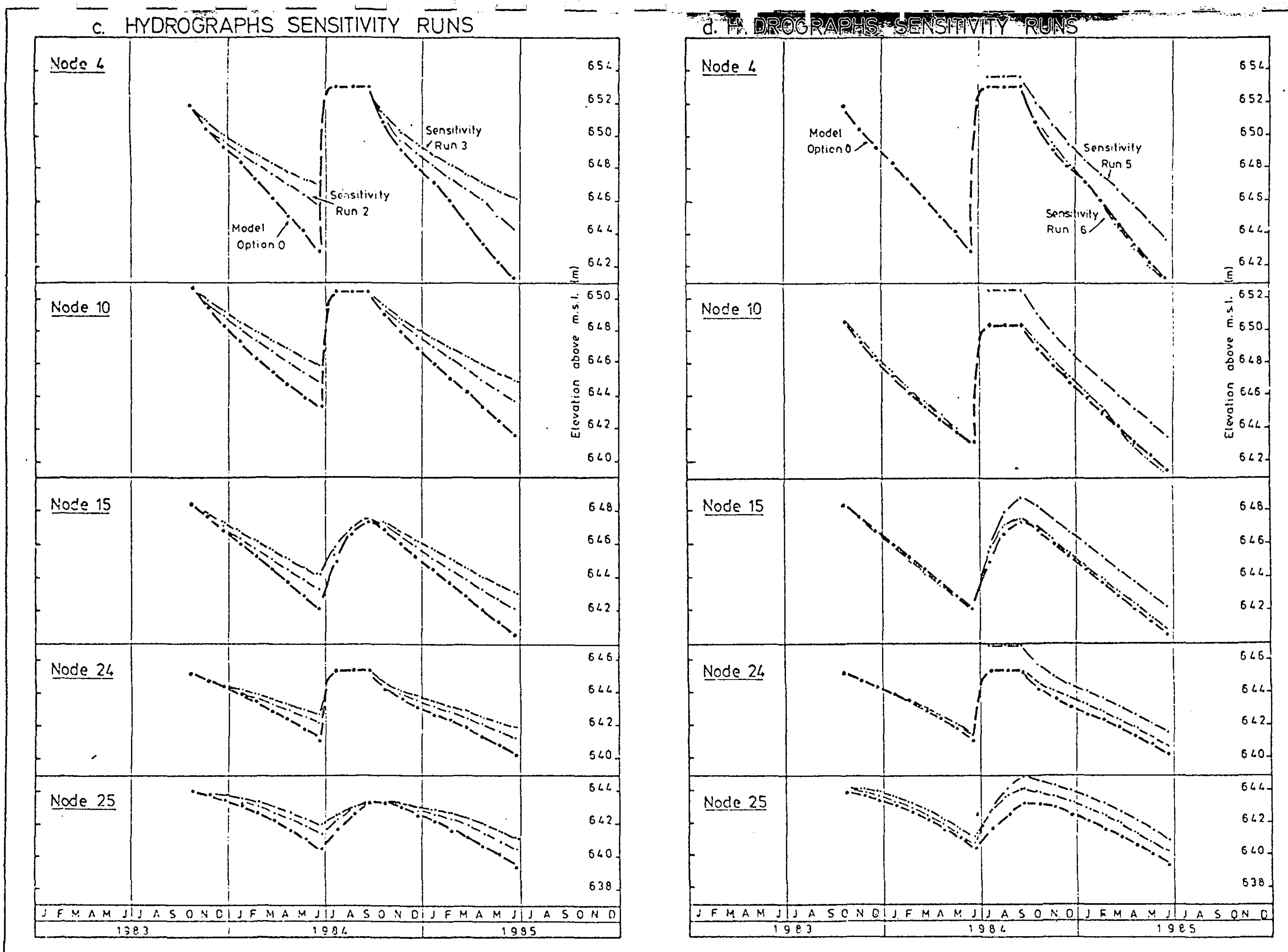


Figure F.3(cont.)

F2.5 Simulation of groundwater development options

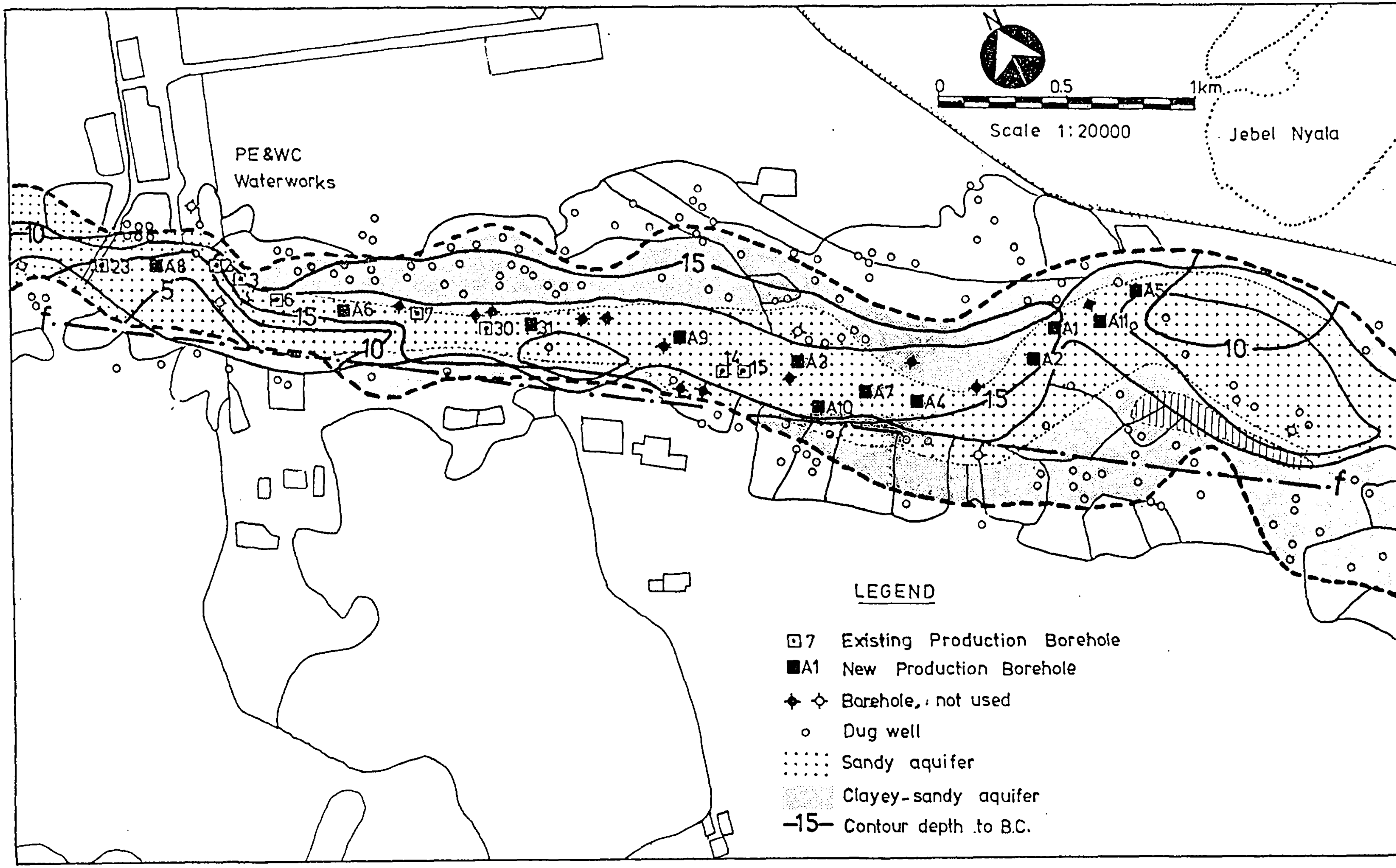
The model of the Wadi Nyala aquifer was used to study the effect on groundwater levels by an increase in pumping from new boreholes for the town water supply. The simulation of the present situation was used as the zero option, on which additional groundwater abstraction was superimposed.
The existing boreholes suitable to continue to be pumped are BH 2, BH 3, BH 6, BH 7, BH 30, BH 14 and BH 15. The efficiency of BH 23 is not known, but it is expected that a new well will be required at this location. Also BH 31 can be used in future.

The locations of the new wells were determined according to the following criteria:

- in the centre of the sandy part of the aquifer;
- sufficient depth of the aquifer;
- more drawdown of groundwater levels is allowed at the location;
- well spacing more than 200 metres;
- connection to pumphouse or storage tank at reasonable distance.

The locations of the wells are shown in figure F.4. It should be realized that these locations need to be evaluated during the final design of the town water distribution system.

The drawdown calculated by the model represents the average drawdown in the nodal area. The drawdown inside the pumped boreholes is bigger, due to the effect of the point abstraction. To ensure a continuing productivity of the boreholes this drawdown should not reach more than about 2 metres. Therefore an appropriate design of the well is required (see section 9.4).
The pumptests in newly constructed wells show that this requirement can be fulfilled (e.g. BH 30, test 30.05.1984; drawdown 1.35 m at 36 m^3/hour). The total depth of the borehole is bigger



LOCATION BOREHOLES DEVELOPMENT OPTIONS Figure F.4

by about 2 metres or more than the depth to Basement, as it was applied in the model. The nodal depth to Basement is an average, the boreholes are located where depth to Basement is maximum in the node area. This ensures that the drawdowns calculated by the model can be allowed in the planned new wells, without reducing the pumping rate.

The simulation of the development options was run for a period of 20 months, starting from October. The first dry season represents a normal year (conditions of 1983 - 1984). The wet season simulated is corresponding to the conditions of very low rainfall in 1984, and the following dry season therefore represents the conditions of a dry year.

The simulation was carried out for six different development options. A short description of the results is included below; the required well capacities of new and old boreholes are summarized in table F.3.

For reasons of well efficiency the maximum yield was determined at 625 m^3/day, which means a pump capacity of 30 to 35 m^3/hour for 18 to 21 pumping hours per day. The pump capacity should be limited to this rate to avoid too big drawdowns inside the well.

The pumping for domestic use was assumed to be constant during the year, because the variation in the water demand is insufficiently known.

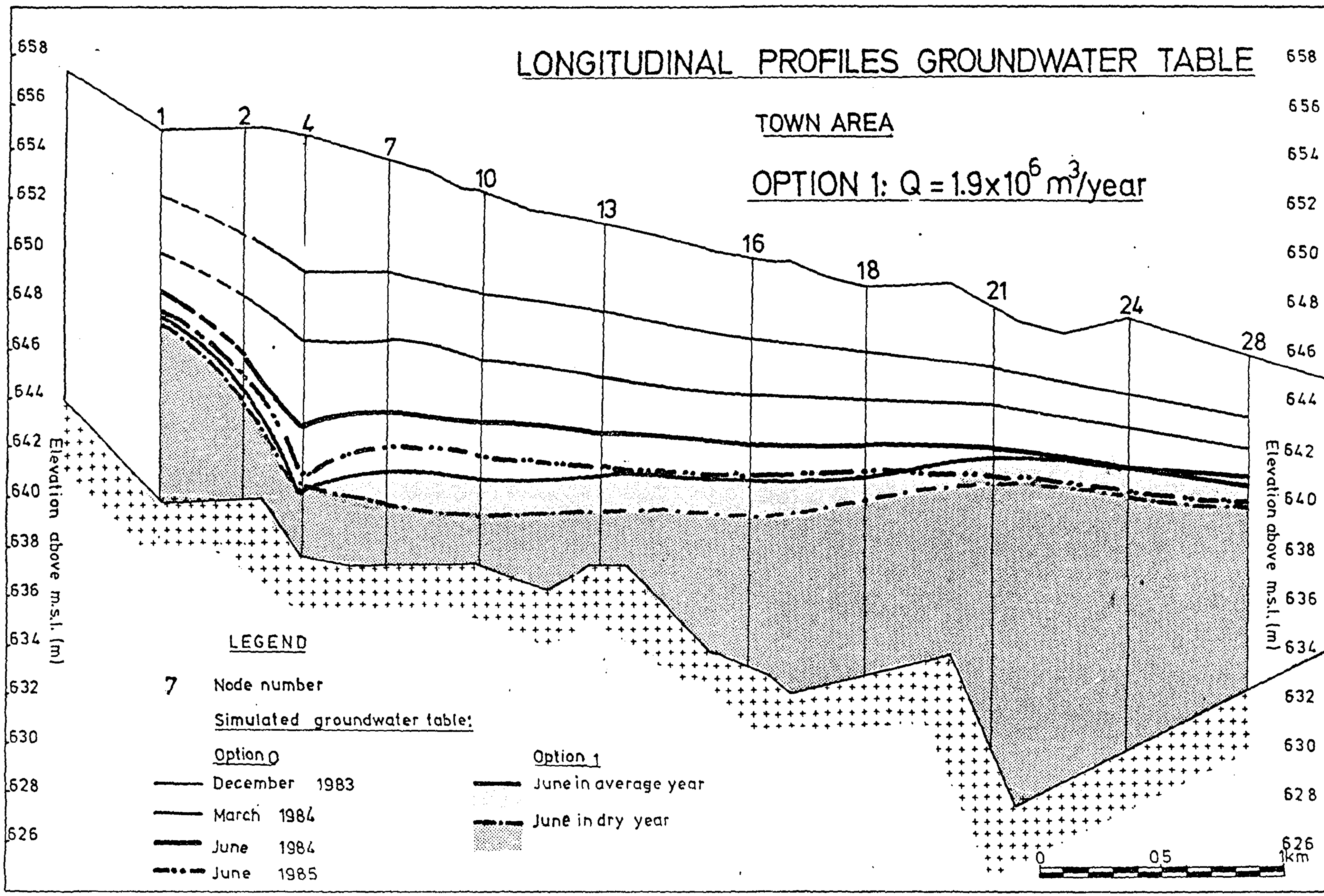
The present consumption of water from dug wells for domestic use (0.25×10^6 m^3/year) was included unchanged in volume in the development simulation runs. Also the consumptive use of agricultural and other areas was included unchanged from the present volumes.

The water loss by evapotranspiration and the outflow across the model boundary is the same in both simulated years, although in reality the lower groundwater levels in the second dry year will cause a reduction in these water losses.

Table F.3 Summary of Well Capacities for the Development Options

Well No.	Location of Well in Node number	Existing Situation Option 0	Pump Capacity (m³/day) Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
BH 23 (or new)	1	225	450	400	400	400	400	400
DW 1	2	225	-	-	-	-	-	-
BH 2	4	725	725	400	400	400	400	400
BH 3	4	450	450	400	400	400	400	400
BH 6	4,7	725	725	625	625	625	625	625
BH 7	10	740	725	625	625	625	625	625
BH 30	13	625	725	625	625	500	500	500
BH 31	13	-	-	-	-	625	625	625
BH 14	16	625	725	625	625	625	495	570
BH 15	16,18	625	725	625	625	625	625	625
BH 16/ NP 07	17,18	410	-	-	-	-	-	-
A1	24	-	-	400	400	400	400	400
A2	24	-	-	625	625	625	625	625
A3	18	-	-	-	475	475	475	525
A4	21	-	-	-	625	625	625	625
A5	27	-	-	-	400	625	625	625
A6	7,10	-	-	-	-	400	600	600
A7	21	-	-	-	-	(245)	445	695
A8	2	-	-	-	-	-	400	400
A9	16	-	-	-	-	-	400	625
A10	18	-	-	-	-	-	300	500
A11	24,27	-	-	-	-	-	-	600
Total (m³/day)		5375*	5250	5350	6850	8220	9590	10990
Total (10^6 m³/year)		1.4	1.9	2.0	2.5	3.0	3.5	4.0

* Note: the pump capacity in option 0 only used at 70% of total, i.e. 3760 m³/day.



LONGITUDINAL PROFILES GROUNDWATER TABLE
TOWN AREA
OPTION 1: Q = 1.9x10^6 m^3/year
658
656
654
652
650
648
646
644
642
640
638
636
634
632
630
628
626
Elevation above m.s.l. (m)
1
2
4
7
10
13
16
18
21
24
28
LEGEND
7 Node number
Simulated groundwater table:
Option 0
December 1983
March 1984
June 1984
June 1985
Option 1
June in average year
June in dry year
0
05
1km

Figure F.5

Option 1 - Pump Capacity 1.9 x $10^6 m^3$/year

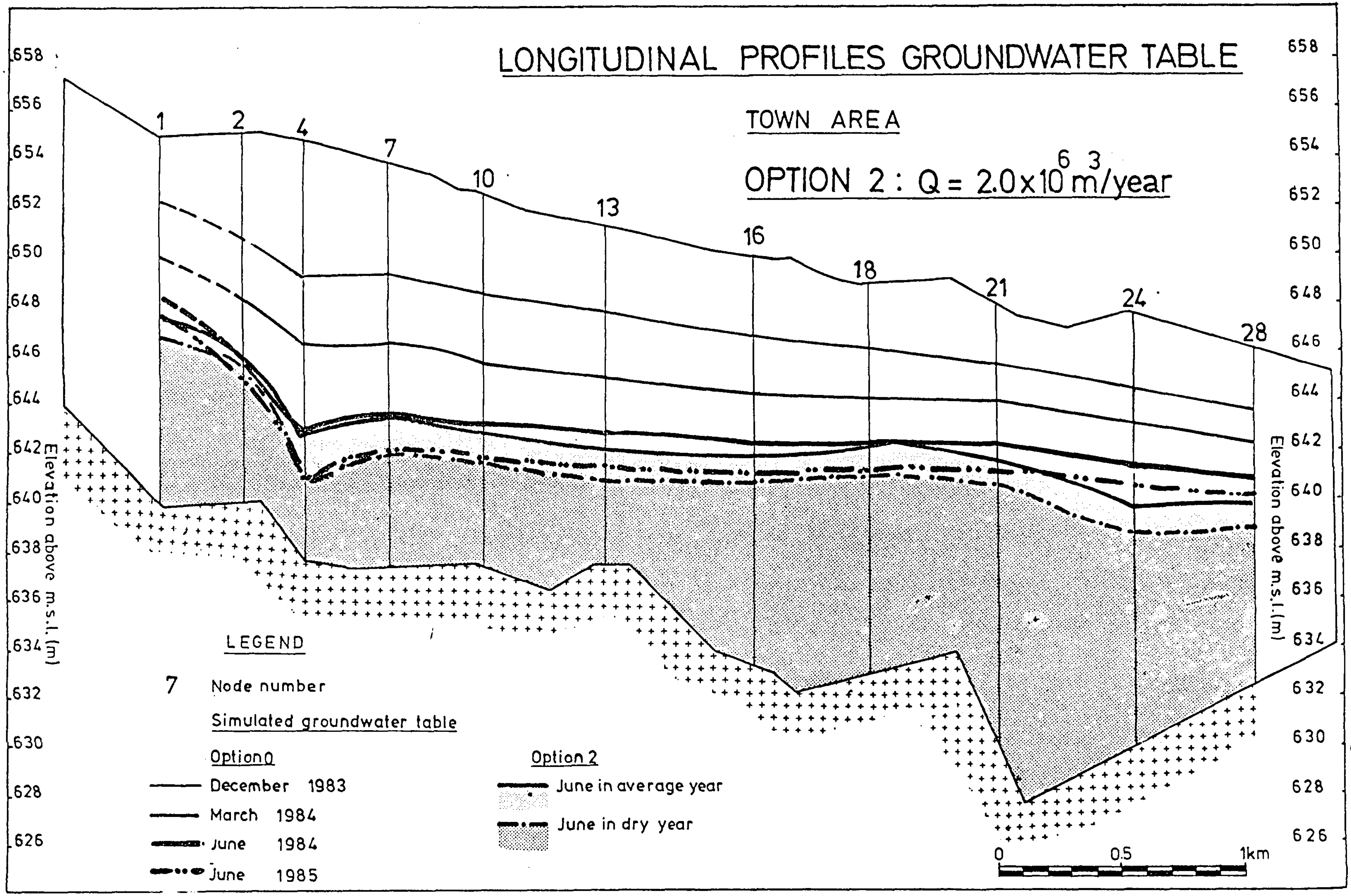
Pumping from existing boreholes only - 8 boreholes

Results (figure F.5):

The concentration of wells at the Town Wells causes excessive drawdown in node 4. The model indicates that the water level reaches the lower limit (B.C.) in May and June. Pumping in this period is of course not possible. In the dry year pumping has to be interrupted in April at the Town Wells.
The longitudinal profile (figure F.5) shows that the drawdowns are much less in the downstream part of the area.

AVERAGE YEAR:		INITIAL STORAGE OCTOBER		5.3
Infiltration	-	Consumptive use	1.3	
Groundwater inflow	0.0	Domestic use from boreholes	1.1*	
		Domestic use from dug wells	0.2	
		Groundwater outflow	0.2	
IN	0.0	OUT	2.8	-2.8
		STORAGE JUNE		2.5
Infiltration	3.4	Consumptive use	0.3	
Groundwater inflow	0.0	Domestic use from boreholes	0.5	
		Domestic use from dug wells	0.0	
		Groundwater outflow	0.0	
IN	3.4	OUT	0.8	+2.6
DRY YEAR:		STORAGE SEPTEMBER		5.1
Infiltration	-	Consumptive use	1.4	
Groundwater inflow	0.0	Domestic use from boreholes	1.3*	
		Domestic use from dug wells	0.2	
		Groundwater outflow	0.2	
IN	0.0	OUT	3.1	-3.1
		STORAGE JUNE		2.0

* Shortage 0.1 x 10^6 m^3 in domestic use due to excessive drawdowns in May and June at Town Wells.



LONGITUDINAL PROFILES GROUNDWATER TABLE
TOWN AREA
OPTION 2 : Q = 2.0 x 10⁶ m³/year
1
2
4
7
10
13
16
18
21
24
28
Elevation above m.s.l. (m)
658
656
654
652
650
648
646
644
642
640
638
636
634
632
630
628
626
LEGEND
7 Node number
Simulated groundwater table
Option 0
December 1983
March 1984
June 1984
June 1985
Option 2
June in average year
June in dry year
0
0.5
1km

Figure F.6

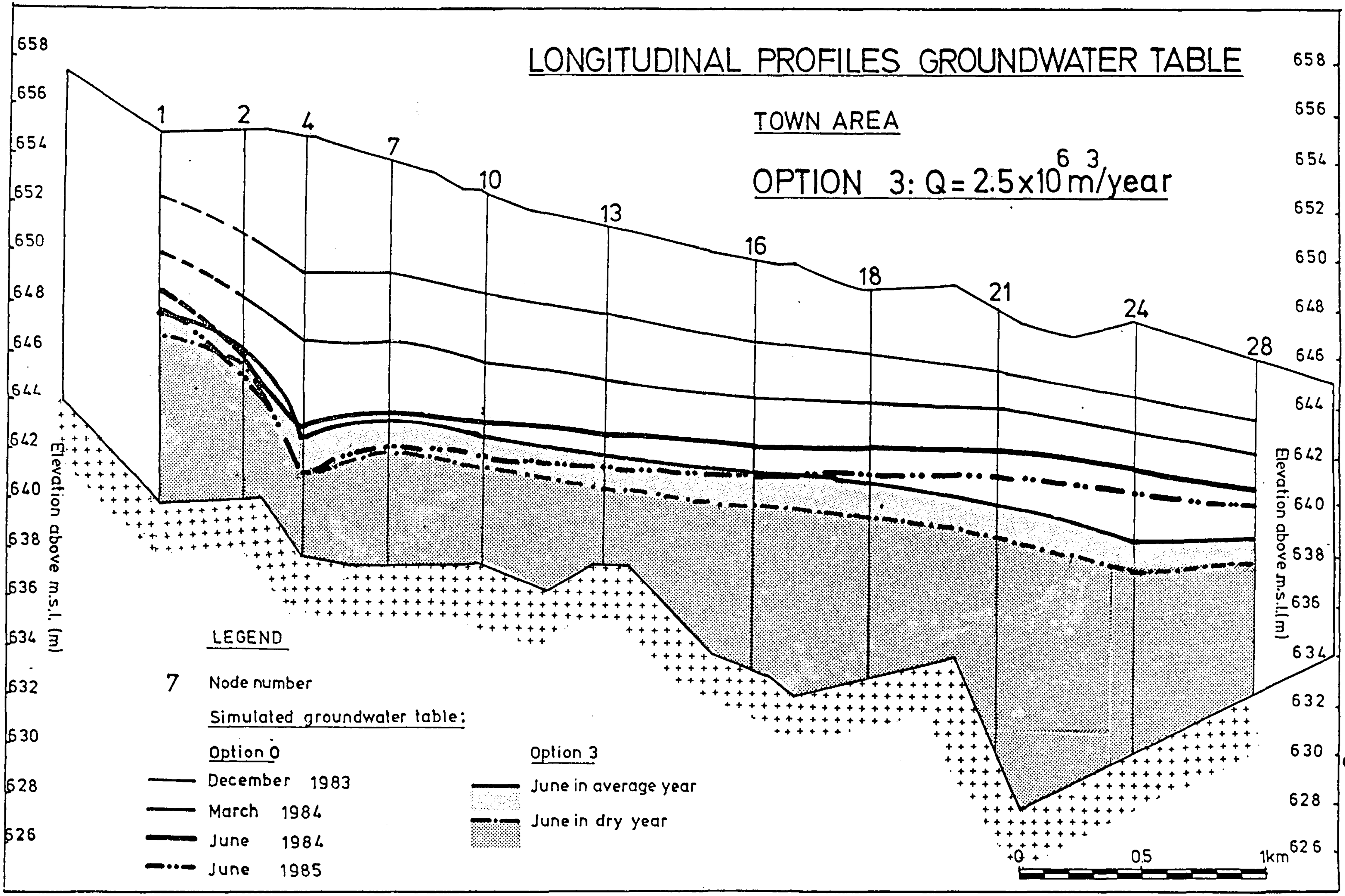
Option 2 - Pump Capacity 2.0 x $10^6 m^3$/year

Pumping from 10 boreholes

Results (figure F.6):

The reduction of the pump capacity at the Town Wells produces an acceptable drawdown. The drawdown at the location of the new boreholes A1 and A2 is limited.
After a dry year, excessive drawdowns do not occur, but conditions are similar to those prevailing in June 1985.

AVERAGE YEAR:	INITIAL STORAGE OCTOBER			5.3
Infiltration Groundwater inflow	- 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	1.3 1.2 0.2 0.2	
IN	0.0	OUT	2.9	-2.9
	STORAGE JUNE			2.4
Infiltration Groundwater inflow	3.6 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	0.3 0.5 0.1 0.0	
IN	3.6	OUT	0.9	+2.7
DRY YEAR:	STORAGE SEPTEMBER			5.1
Infiltration Groundwater inflow	- 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	1.4 1.5 0.2 0.2	
IN	0.0	OUT	3.3	-3.3
	STORAGE JUNE			1.8



LONGITUDINAL PROFILES GROUNDWATER TABLE
TOWN AREA
OPTION 3: Q = 2.5x10^6 m^3/year
1
2
4
7
10
13
16
18
21
24
28
658
656
654
652
650
648
646
644
642
640
638
636
634
632
630
628
626
Elevation above m.s.l. (m)
Elevation above m.s.l.(m)
LEGEND
7 Node number
Simulated groundwater table:
Option 0
December 1983
March 1984
June 1984
June 1985
Option 3
June in average year
June in dry year
0
0.5
1km

Figure F.7

Option 3 - Pump Capacity 2.5 x $10^6 m^3$/year

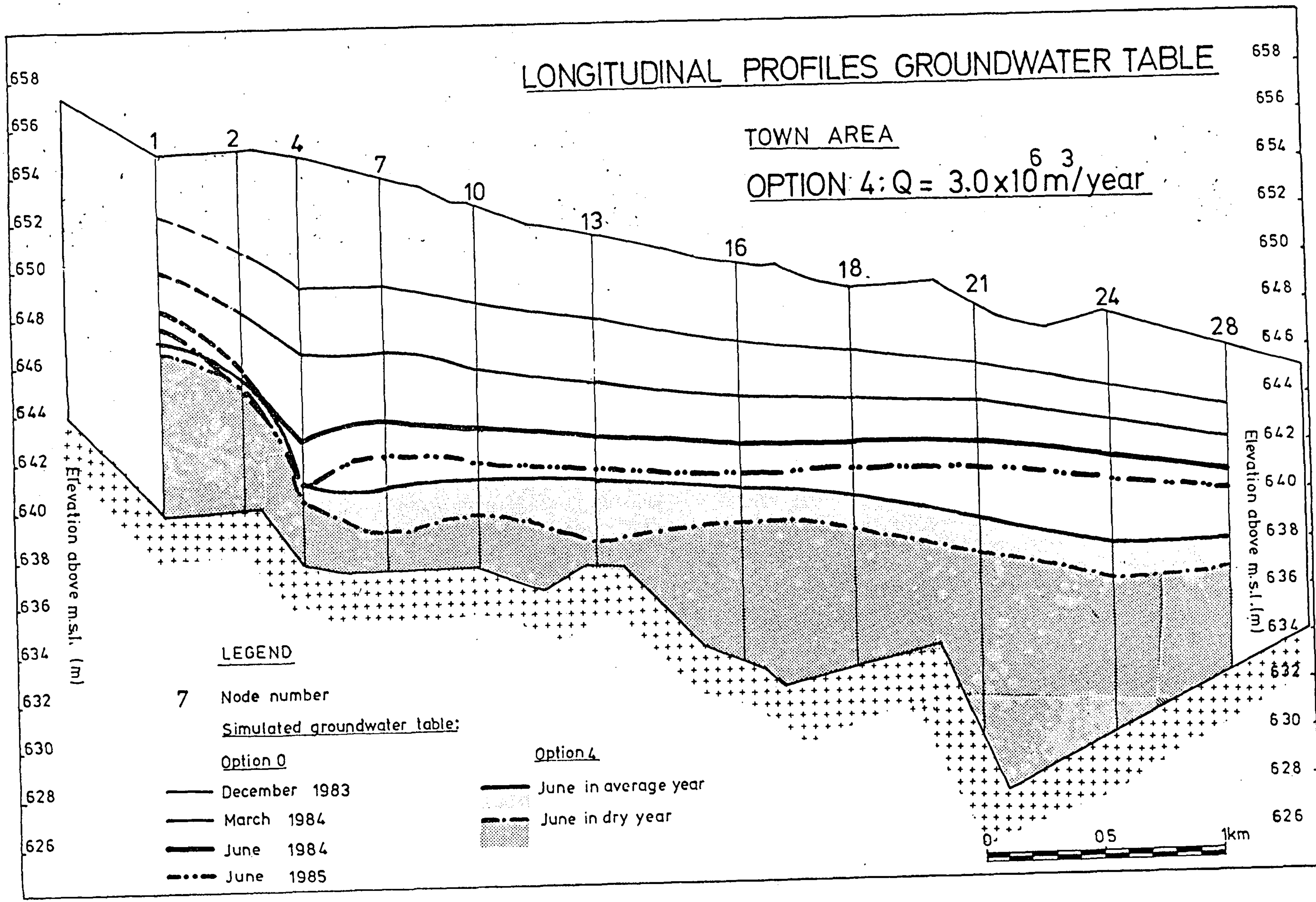
Pumping from 13 boreholes

Results (figure F.7):

The available groundwater storage downstream of the Railway Wells is now exploited more efficiently, without excessive drawdowns occurring.

Also after a dry year limitation in pumping from the boreholes is not encountered.

AVERAGE YEAR:	INITIAL STORAGE OCTOBER			5.3
Infiltration	-	Consumptive use	1.3	
Groundwater inflow	0.0	Domestic use from boreholes	1.6	
		Domestic use from dug wells	0.2	
		Groundwater outflow	0.2	
IN	0.0	OUT	3.3	-3.3
STORAGE JUNE				2.0
Infiltration	4.1	Consumptive use	0.3	
Groundwater inflow	0.0	Domestic use from boreholes	0.7	
		Domestic use from dug wells	0.0	
		Groundwater outflow	0.0	
IN	4.1	OUT	1.0	+3.1
DRY YEAR:	STORAGE SEPTEMBER			5.1
Infiltration	-	Consumptive use	1.4	
Groundwater inflow	0.0	Domestic use from boreholes	1.8	
		Domestic use from dug wells	0.2	
		Groundwater outflow	0.2	
IN	0.0	OUT	3.6	-3.6
STORAGE JUNE				1.5


LONGITUDINAL PROFILES GROUNDWATER TABLE
TOWN AREA
OPTION 4: Q = 3.0x10^6 m^3/year
1
2
4
7
10
13
16
18
21
24
28
Elevation above m.s.l. (m)
Elevation above m.s.l. (m)
658
656
654
652
650
648
646
644
642
640
638
636
634
632
630
628
626
LEGEND
7 Node number
Simulated groundwater table:
Option 0
December 1983
March 1984
June 1984
June 1985
Option 4
June in average year
June in dry year
0
05
1km
Figure F.8

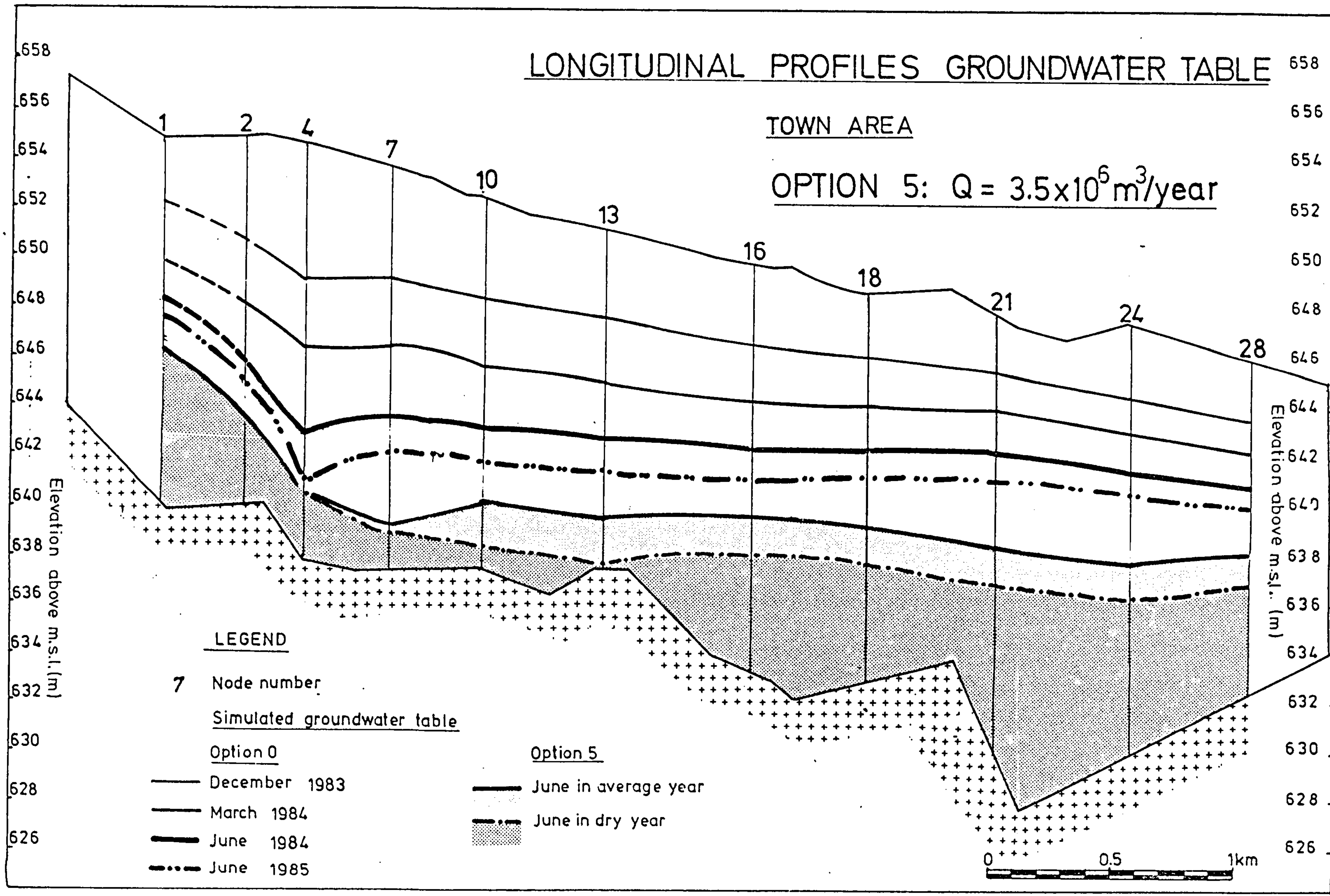
Option 4 - Pump Capacity 3.0 x $10^6 m^3$/year

Pumping from 15 boreholes

Results (figure F.8):

The groundwater storage in the Town Wells area is used extensively, due to the introduction of borehole A6 between BH 6 and BH 7. But there is no limitation in pumping during an average year.
After a dry year in June pumping has to be interrupted at the Town Wells because of excessive drawdowns, but the reduction in total pump yield is small.

AVERAGE YEAR:	INITIAL STORAGE OCTOBER			5.3
Infiltration Groundwater inflow	- 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	1.3 2.0 0.2 0.2	
IN	0.0	OUT	3.7	-3.7
	STORAGE JUNE			1.6
Infiltration Groundwater inflow	4.6 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	0.3 0.8 0.0 0.0	
IN	4.6	OUT	1.1	+3.5
DRY YEAR:	STORAGE SEPTEMBER			5.1
Infiltration Groundwater inflow	- 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	1.4 2.2 0.2 0.2	
IN	0.0	OUT	4.0	-4.0
	STORAGE JUNE			1.1



LONGITUDINAL PROFILES GROUNDWATER TABLE
TOWN AREA
OPTION 5: Q = 3.5x10^6 m^3/year
1
2
4
7
10
13
16
18
21
24
28
Elevation above m.s.l.(m)
658
656
654
652
650
648
646
644
642
640
638
636
634
632
630
628
626
LEGEND
7 Node number
Simulated groundwater table
Option 0
December 1983
March 1984
June 1984
June 1985
Option 5
June in average year
June in dry year
0
0.5
1km

Figure F.9

Option 5 - Pump Capacity 3.5 x $10^6 m^3$/year

Pumping from 19 boreholes

Results (figure F.9):

Pumping at this capacity produces excessive drawdowns in the Town Wells area during an average year. Partly this is due to the introduction of borehole A8.
It is therefore advisable not to drill more wells in this area apart from borehole A6 and not to use A8. Also considering water quality aspects it is advisable to construct the new wells in the area downstream near the Railway Wells.

AVERAGE YEAR:	INITIAL STORAGE OCTOBER			5.3
Infiltration Groundwater inflow	- 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	1.3 2.3 0.2 0.2	
IN	0.0	OUT	4.0	-4.0
		STORAGE JUNE		1.3
Infiltration Groundwater inflow	5.0 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	0.3 0.9 0.0 0.0	
IN	5.0	OUT	1.2	+3.8
DRY YEAR:	STORAGE SEPTEMBER			5.1
Infiltration Groundwater inflow	- 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	1.4 2.5* 0.2 0.2	
IN	0.0	OUT	4.3	-4.3
		STORAGE JUNE		0.8

* Shortage 0.1 x 10^6 m^3 in domestic use due to excessive draw-down in May and June at Town Wells.

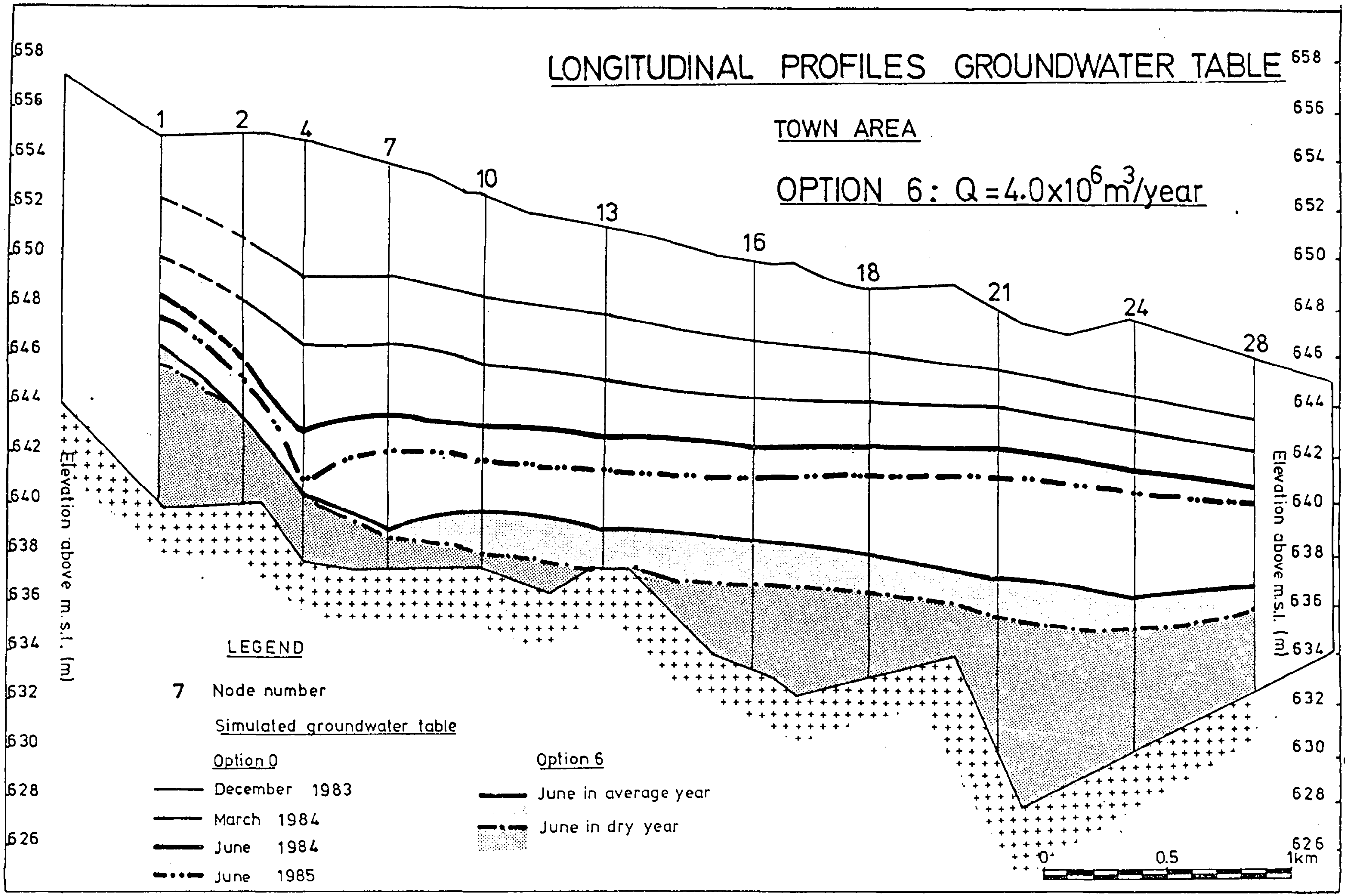

LONGITUDINAL PROFILES GROUNDWATER TABLE
TOWN AREA
OPTION 6: Q = 4.0x10^6 m^3/year
Elevation above m.s.l. (m)
Elevation above m.s.l. (m)
658
656
654
652
650
648
646
644
642
640
638
636
634
632
630
628
626
1
2
4
7
10
13
16
18
21
24
28
LEGEND
7 Node number
Simulated groundwater table
Option 0
December 1983
March 1984
June 1984
June 1985
Option 6
June in average year
June in dry year
0
0.5
1km

Figure F.10

Option 6 - Pump Capacity 4.0 x $10^6 m^3$/year

Pumping from 20 boreholes

Results (figure F.10):

The drawdown in the Railway Wells area and further downstream is about 1.5 metre more than in option 5, but it is still acceptable. After a dry year, however, only a limited storage is left in the last months of the dry season, and the water supply to the town will be severely disrupted. Under such conditions it is not advisable to pump at this rate, but to reduce the production during the whole dry season.

AVERAGE YEAR:	INITIAL STORAGE OCTOBER			5.3
Infiltration Groundwater inflow	- 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	1.3 2.6 0.2 0.2	
IN	0.0	OUT	4.3	-4.3
		STORAGE JUNE		1.0
Infiltration Groundwater inflow	5.5 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	0.3 1.0 0.1 0.0	
IN	5.5	OUT	1.4	+4.1
DRY YEAR:	STORAGE SEPTEMBER			5.1
Infiltration Groundwater inflow	- 0.0	Consumptive use Domestic use from boreholes Domestic use from dug wells Groundwater outflow	1.4 2.8* 0.2 0.2	
IN	0.0	OUT	4.6	-4.6
		STORAGE JUNE		0.5

* Shortage 0.2 x 10^6 m^3 in domestic use due to excessive drawdown in May and June at Town Wells.

F3. The Downstream Area Model

F3.1 Lay-out of the model

The groundwater level data in the Downstream Area is less numerous than in the Town Area. Especially downstream of Kundua Forest not much information is available, due to the limited number of (observation) wells.

A detailed simulation of the Downstream Area is therefore not possible and the model lay-out was kept simple. The nodes cover the full width of the aquifer and the node data represent the average of the sandy and clayey/sandy aquifer parameters for each node area. The node areas are related to the availability of groundwater level data, i.e. small areas in the upper part, where many data is available; large areas in the lower parts, where not many data is found (see figure F.11).

The model consists of 12 internal nodes and 26 external nodes. The external boundary of the model corresponds with the boundary between the clayey/sandy and clayey part of the aquifer. Small clayey areas inside the model boundaries have been considered as clayey/sandy.

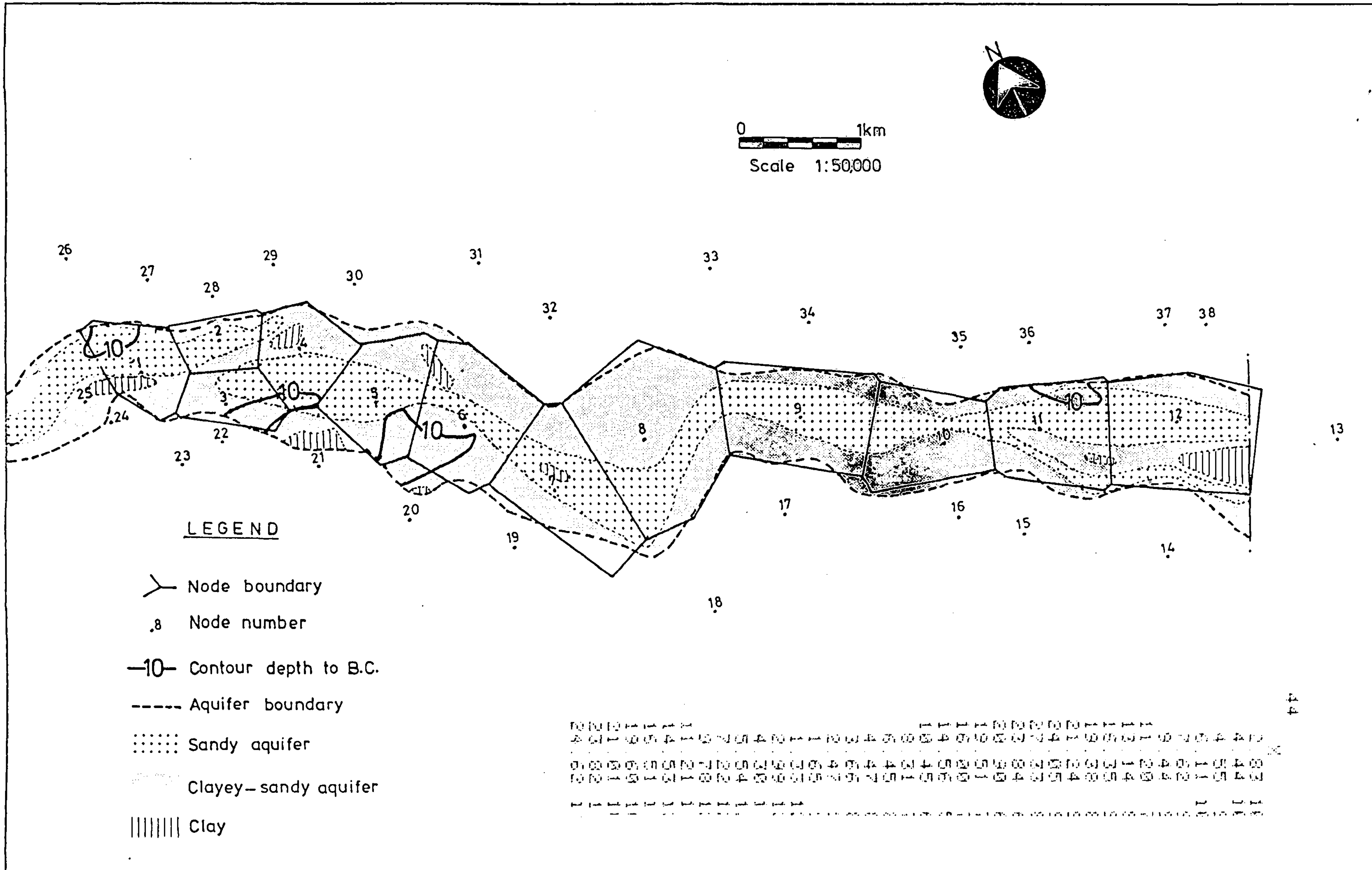
F3.2 Input data

The input data required for the Downstream Area Model was obtained by similar methods as for the Town Area model. For a description reference is made to section F2.2. A summary of the input data is presented in table F.4.

The large size of the nodes required average values for the aquifer parameters, which were chosen equal to the parameter values in the Town Area:

- k = 50 m/day and S = 20% for the sandy part of the aquifer;
- k = 20 m/day and S = 10% for the clayey/sandy part of the aquifer;

The inflow across the upstream model boundary was determined



LAY-OUT DOWNSTREAM AREA MODEL

Figure F.11

Table F.4 Input Data Downstream Area Model

FILE NAME IS NPIN4D

INTERFACE BETWEEN NODES		W/L	k
1	2	.59091	40
1	3	.44909	20
1	27	.13336	0
1	24	.95416	0
1	25	1.1665	10
1	26	.10754	0
1	27	.7931	0
2	3	1.098	30
2	4	.70345	20
2	27	.047105	0
2	28	1.8969	0
2	29	.058411	0
3	4	.55194	30
3	21	.19827	0
3	22	2.5134	0
3	23	.12037	0
4	5	.86419	30
4	21	.21265	0
4	29	.50367	0
4	30	.8292	0
5	6	1.3778	10
5	20	.21574	0
5	21	1.0212	0
5	30	.54698	0
5	31	.073432	0
6	7	.90097	15
6	19	.12612	0
6	20	.70127	0
6	31	.18903	0
6	32	.68143	0
7	8	1.5234	20
7	18	.21518	0
7	19	2.2914	0
7	32	.10015	0
8	9	.5831	15
8	17	.46535	0
8	18	.27247	0
8	32	.65875	0
8	33	.39572	0
9	10	.67228	20
9	17	1.3926	0
9	33	.048127	0
9	34	1.6429	0
9	35	.027584	0
10	11	.74359	15
10	16	1.5968	0
10	17	.1217	0
10	35	1.2745	0
10	36	.1653	0
11	12	.75905	20
11	14	.040176	0
11	15	.95569	0
11	16	.081585	0
11	35	.16772	0
11	36	1.1699	0
11	37	.024603	0
12	13	.63481	0
12	14	1.0276	0
12	37	.83214	0
12	38	.74795	0

FILENAME IS NPN04D

	NODE 1	NODE 2	NODE 3	NODE 4	NODE 5	NODE 6	NODE 7	NODE 8
INIT.WATERL.[m]	641.70	639.00	639.00	634.50	633.00	631.00	628.00	626.00
FLOWRATE [m/DAY]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NODE TYPE	2	2	2	V	V	2	2	2
STORAGE COEFF.	.14	.13	.12	.13	.13	.09	.13	.09
BASEMENT ELEV.[m]	635.50	632.00	633.00	630.30	628.20	624.50	620.50	618.50
UPP.W.L.LIMIT [m]	642.00	638.50	640.00	640.30	638.20	632.00	629.00	626.00
NODAL AREA [m2]	694872.00	488479.00	517318.00	770750.00	1023953.00	1337189.00	1316159.00	2138468.00
NET-RECH.FUNCT.	1	0	0	0	0	0	0	0
NET-RECH.FACTOR	1.00	734.00	819.00	830.00	749.00	695.00	645.00	656.00

	NODE 9	NODE 10	NODE 11	NODE 12
INIT.WATERL.[m]	622.00	618.40	614.40	610.00
FLOWRATE [m/DAY]	0.0000	0.0000	0.0000	0.0000
NODE TYPE	V	V	V	V
STORAGE COEFF.	.13	.12	.13	.09
BASEMENT ELEV.[m]	615.00	612.50	610.50	607.00
UPP.W.L.LIMIT [m]	628.00	625.50	622.50	619.00
NODAL AREA [m2]	1556015.00	1314807.00	1211424.00	1706559.00
NET-RECH.FUNCT.	0	0	0	0
NET-RECH.FACTOR	554.00	599.00	653.00	508.00

NPRE4B

NET-RECHARGE FUNCTION 0

TIME STEP	NET-RECHARGE [mm/DAY]
JAN	-.0019
FEB	-.0032
MAR	-.0025
APR	-.0027
MAY	-.0031
JUN	-.0030
JUL	-.0033
AUG	-.0033
SEP	-.0033
OCT	-.0032
NOV	-.0025
DEC	-.0020

NET-RECHARGE FUNCTION 1

TIME STEP	NET-RECHARGE [mm/DAY]
JAN	-.5000
FEB	-.7800
MAR	-1.0600
APR	-1.3900
MAY	-1.8200
JUN	-1.9100
JUL	-1.9950
AUG	-1.7000
SEP	-1.4200
OCT	-1.2000
NOV	-.8200
DEC	-.5300

NET-RECHARGE FUNCTION 2

TIME STEP	NET-RECHARGE [mm/DAY]
JAN	0.0000
FEB	0.0000
MAR	0.0000
APR	0.0000
MAY	0.0000
JUN	0.0000
JUL	1.0000
AUG	1.0000
SEP	1.0000
OCT	0.0000
NOV	0.0000
DEC	0.0000

equal to the groundwater outflow at the downstream boundary of the Town Area model. No groundwater outflow was simulated because the volume involved is insignificant compared with groundwater losses by evapotranspiration. The inflow was included for reasons of completeness, although the volume involved is negligible: 0.21 x 10^6 m^3/year.

Three net-recharge functions were applied:

- function 0: specifies the monthly variation of the evapotranspiration;
- function 1: recharge function of node 1;
- function 2: denotes the months with a fixed water level.

F3.3 Calibration of the model

The groundwater model was calibrated using data from the period December 1983 until June 1984. The calculations were started with an initial water level determined from the groundwater level measurements of 21 December 1983. The input data which suited the conditions in the wadi aquifer are summarized in table F.4.

The value of the aquifer permeability k could not be calibrated satisfactorily. The large size of the nodes produces inter-node groundwater flows, which are much smaller than the evapotranspiration losses per node. Therefore a change in the groundwater flow caused by a change in the permeability k, does not affect much the node groundwater level. Hence the calibration of k is not possible accurately.

The groundwater levels depend mainly on the value of S and the groundwater discharge consisting of the evaporation. A deviation of the calculated groundwater level from the observed groundwater level can be corrected by a change in either the S-estimate or the evapotranspiration estimate; however, the decision on which of the two to change is complicated, because the resulting change in groundwater level will be the same. Therefore also for these estimates an accurate calibration was not possible.

Due to the above mentioned arguments sensitivity runs were not carried out.

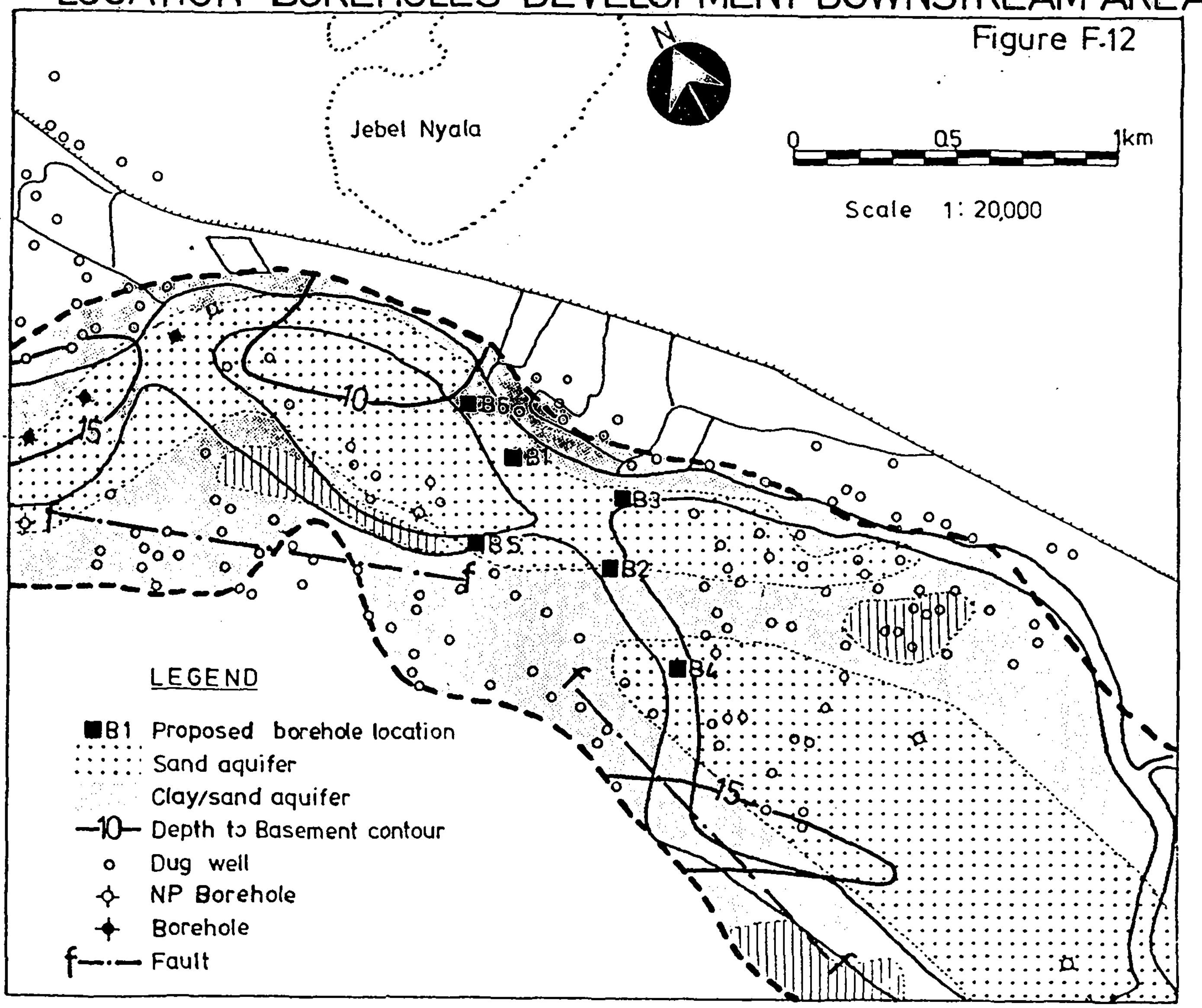
F3.4 Simulation runs of development option

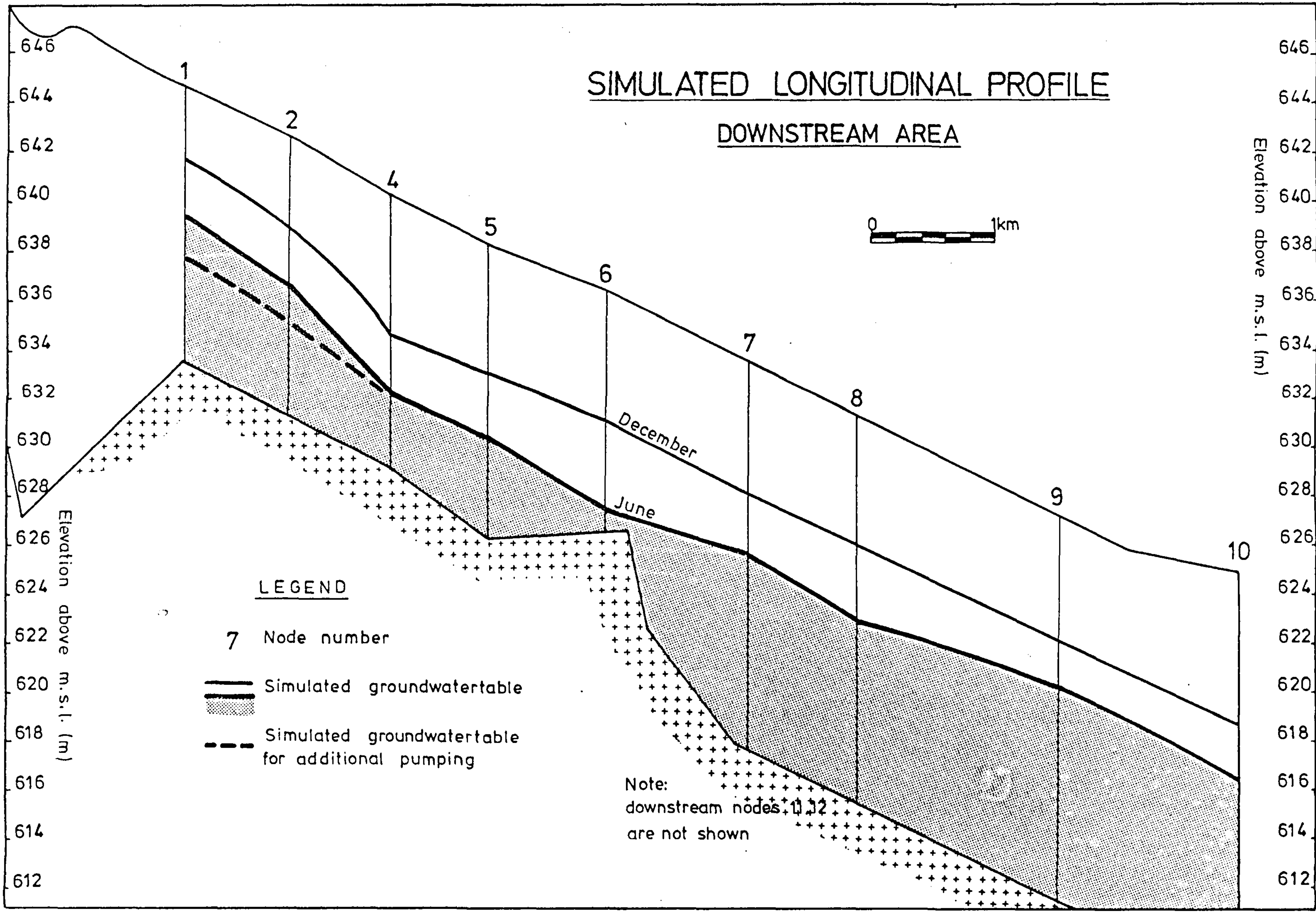
The simulation of the Downstream Area with the model of figure F.11 is not detailed, due to a lack of groundwater level data in this area. The simulation of several development options is therefore not relevant. One computer run was made to assess the effects of pumping 750 000 m³ of groundwater at the location of nodes 1, 2 and 3. Due to the shallow depth of the Basement (max. 12 metres) wells with a mi̇ximum capacity of 400 m³/day (or 20 m³/hour) should be used in this area. The proposed locations of the new wells are indicated in figure F.12.

The drawdown due to the pumping is max. 2 metres in node 1 (see figure F.13).
The variation of the groundwater storage is indicated below.

INITIAL STORAGE DECEMBER				9.5
Infiltration	-	Consumptive use	4.3	
Groundwater inflow	0.1	Domestic use	0.4	
		Groundwater outflow	-	
IN	0.1	OUT	4.7	-4.6
STORAGE JUNE				4.9

LOCATION BOREHOLES DEVELOPMENT DOWNSTREAM AREA





SIMULATED LONGITUDINAL PROFILE
DOWNSTREAM AREA
0
1km
Elevation above m.s.l. (m)
646
644
642
640
638
636
634
632
630
628
626
624
622
620
618
616
614
612
1
2
4
5
6
7
8
9
10
December
June
LEGEND
7 Node number
Simulated groundwatertable
Simulated groundwatertable for additional pumping
Note:
downstream nodes 11,12 are not shown

Figure F.13

APPENDIX G

REVIEW OF TECHNICAL ACTIVITIES WAPS-2 NYALA

AND LIST OF TEAM MEMBERS

APPENDIX G REVIEW OF TECHNICAL ACTIVITIES

G1. Existing Data

In the regional office of the NWC in Nyala the following hydrogeological data were found:

- the 1979 well inventory sheets (some 50 sheets were missing);
- groundwater level measurements of the period October 1979 until April 1982;
- borehole data of 17 out of the total existing 27 bores.

Meteorological data from the Nyala met station from previous years could not be obtained in Nyala, but were available at the Meteorological Department in Khartoum.

G2. Fieldwork WAPS-2

G2.1 Well inventory

The well inventory of 1979 was updated and extended downstream towards Bileil. A total of 346 wells and 31 boreholes were visited and located on the base map. The elevation of each well was determined and a reference point was painted. An estimate of the total annual water abstraction was obtained.

G2.2 Meteorological data

A summary of the meteorological data collected by the Nyala met station was obtained monthly. The project installed 6 rainfall stations in the catchment area and supplied 2 rainrecorders to the NWC hydrometric stations at Timbusku (Wadi Bulbul) and Afindo (Wadi Nyala). Evaporation pans were constructed in the project workshop and installed at the WAPS-2 office and at the Nyala veterinary laboratory.

G2.3 Hydrometric data

The project constructed a hydrometric station on Wadi Nyala at the upstream boundary of the survey area. From the bridge across Wadi Nyala discharge measurements were carried out by current meter. A staff gauge was installed on a pier of the bridge. Crest gauges were installed at the station and at the bridge to record flood peak levels.

G2.4 Geophysical surveys

The project programme included:

- an electro-magnetic survey along profile lines (116.4 km) on selected sites and on locations of vertical electrical soundings;
- an electrical resistivity survey, comprising 120 vertical electrical soundings and horizontal electrical profiling (6.6 km).

A geophysical well logging programme was cancelled due to technical problems with the equipment and because of the doubtful results due to shallow depths and lack of contrasts.

G2.5 Groundwater levels

The water levels in dug wells and boreholes have been observed since February 1982. A maximum total of 150 index wells were visited every month.
Six water level recorders were installed to obtain a continuous record. At the end of the project only two were still operational.

G2.6 Groundwater quality

The project programme included:

- 7 surveys measuring EC, pH and temperature in approximately 50 wells and boreholes with portable EC and pH-meters;

- 4 sampling programmes of water from about 15 wells and boreholes for chemical analysis;
- 1 samping programme of 12 wells and boreholes for chemical analysis by laboratory in Khartoum;
- 4 surveys on bacteriological quality of 22 wells and boreholes used for domestic water supply.

G2.7 Well drilling

The project drilled 19 exploratory boreholes, all of which were completed with 2, 6 or 10 inch PVC casing and screens. Two boreholes were drilled by the NWC under supervision of the WAPS-2 geologist. Drilling samples were collected every metre from each borehole.

G2.8 Aquifer tests

The project carried out 21 pumptests of which 7 were step tests and 14 long duration (max. 3 days) tests. Most of the tests included observations in two piezometers.

G3. Activities at the office

G3.1 Preparation of maps

A base map was made of the survey area between Nyala and Bileil from aerial photography and from observations by the surveyors in the field. The map was updated after new photography became available in 1984. All other maps needed by the project, e.g. well locations, groundwater contours, aquifer geometry etc., were also drafted in the office at Nyala.

G3.2 Analysis of geophysical data

The data from the electro-magnetic and electrical resistivity surveys was plotted and interpreted in the office at Nyala with the aid of an HP-85 printer/plotter deskcomputer. All data were stored on cassette tapes.

G3.3 Analysis of hydrogeological data

The groundwater level data were analysed, after preparation of hydrographs of selected wells, and of groundwater contour and groundwater fluctuation maps. The pumptests were analysed with curve-matching methods (Theis, Boulton); the step tests were analysed using a method derived by Birsoy and Summer (1980) for the HP-41C hand calculator. The grainsize distribution of drilling samples was determined in the office by mechanical analysis.

G3.4 Analysis of water samples

The chemical analysis of water samples were carried out in the office at Nyala using a Hach DR-EL/4 field laboratory. The high room temperatures (above 30°C) may have affected the accuracy. The bacteriological water quality was determined using Millipore coli-count samplers and a small incubator. The results were verified in the Nyala veterinary laboratory using the plate count method.

G3.5 Groundwater model

Two groundwater models were prepared for the Town Area and for the Downstream Area, which were run on the HP-85 deskcomputer.

G3.6 Analysis of hydro-meteorological data

The charts from the rainfall recorders were analysed for total rainfall, rainfall duration, rainfall intensity etc. The meteorological data from the Nyala met station was used to estimate evapotranspiration rates, which were compared with the observations from the evaporation pans. The surface water level and discharge data were used to prepare the stage-discharge relation of the Wadi Nyala runoff at Mekkah Bridge. Daily discharge volumes were calculated.

G4. Training of Staff

The WAPS-2 project staff, composed of NWC-employees transferred from Khartoum or from the regional office at Nyala and of personnel employed locally, were trained in aspects of:

- (geo)hydrology : regarding planning execution and interpretation of field investigations, processing and evaluation of data, water balance study, groundwater modelling etc.;
- geophysics : regarding planning, execution and interpretation of geophysical measurements;
- drilling : regarding execution of drilling and well completion;
- reporting : regarding writing of reports and preparation of maps and figures;
- technical maintenance: regarding the use and maintenance of equipment and vehicles.

TEAM MEMBERS WAPS-2 NYALA, 1983-1985 — Table G.1

	Sudanese Team	
	Management	
1	Mohamed Kheir Salih	Co-Manager WAPS-2
	Hydro (Geo)logical & Geophysical Team	
	Yahia Ahmed Adam	Geophysicist
**	Abdullah Mohamed Kheir	Hydrogeologist
	El Wasila Ahmed Mohamed	Hydrogeologist
	Osman Mahgoub el Hassan	Hydrogeologist
2**	El Tayib el Sadig	Geologist
	Hamdam Mastore Ibrahim	Geologist
**/*	Nagib Ismail Abdallah	Civil Engineer
**/*	Adam Mohamed Suleiman	Civil Engineer
*/3	Abdel Gafar Mohamed Abdella	Groundwater Technician
*	Mohamed Adam Ginaya	Groundwater Technician
	Mohamed Salih Abdel Hadi	Groundwater Technician
3/*	Ibrahim Basherry	Groundwater Technician
	Khalifa Mohamed el Hassan	Electronic Engineer
	Mohamed Abdallah Salih	Assistant Electronic Engineer
	Mohamed Ahmed Aoud Elkarim	Technical Assistant
	Omer Adam Bruma	Technical Assistant
*	El Sadig Abdalla Adam	Technical Assistant
	Ahmed Adam Mohamed	Technical Assistant
	Mohamed Suleiman	Technical Assistant
	Idris Mohamed Beshir	Technical Assistant
	Salah Ahmed Adam	Technical Assistant
	Mohamed Mohamedein	Technical Assistant
	El Taib Mohamed Idris	Labourer
	Sabah El Kheir	Labourer
	Sneen Omer	Labourer
	Survey Team	
	Radi Abu el Kheir	Chief Surveyor
	El Thom el Sheikh el Noor	Surveyor, Draughtsman
	Osman Mohamed Idris	Surveyor, Draughtsman
	Adam Said Fadul	Draughtsman
3	Mohamed Abdel Hafiz	Draughtsman
	Ahmed Abdallah Doudain	Chainman
	El Douma Adam Ali	Chainman
	Abdel Moneim Adam	Labourer
	Mohamed Ahmed Nasser	Labourer
	Mechanical Team	
*	Mahmoud Mohamed Shareif	Chief Mechanic
	Osman Ali Ezerg	Chief Mechanic
	Mohamed Abdallah Mohamed	Assistant Mechanic
	Abdel Gadir Marzoug	Assistant Mechanic
	Fadel Fadella	Assistant Mechanic
	Adam Abdul Rahman	Assistant Mechanic
	Aboud Mohamed Abdel Gabar	Assistant Mechanic
	Isag Mohamdien	Assistant Mechanic
	Yahia Ali Abdallah	Steel Worker
	Ali Idris	Labourer
	Khalid Abdel Rahman	Labourer
*	Ibrahim Mohamed Hamid	Labourer

Table G.1 continued

	Name	Position
	Administration	
	Kamil Ibrahim Sid Ahmed	Administrative Officer
1	Ali Abdel Hafiz	Administrative Officer
	Ali Mohamed Ali Fatouh	Chief Accountant
	El Tegani Abdel Karim	Store Keeper
	Bedour Yousif Ismail	Typist
	Atima Eisa Hamid	Typist
	Mohamed El Sadig Sahid	Store Keeper
	Adam Mohamed Abdalla	Clerk
	Drilling Team	
	Abdallah El Tayeb Gorashi	Driller Engineer
	Mohamed Abdel Rahman Lutfy	Driller Foreman
*	Osman Ahmed Ibrahim	Driver/Mechanic
	Faulo Peter	Driller Assistant
	Ibrahim Ahmed Mohamed	Driller Labourer
	Faysal Ali Adam	Driller Labourer
	Mahmoud Abdallah El Safi	Driller Labourer
	Daoud Ali Adam	Labourer
	Abdalla Ali Yousif	Labourer
	Drivers	
	Mohamed Adam Mabrouk	
	Bakheit Ahmed Gadid	
*	El Tagini Ahmed Fadella	
	Khalid Abker Abdel Rahman	
	El Rasheed Yacoub	
	El Douma Adam Abdallah	
	Abdel Halim Mahagoub	
*	Ahmed el Tahir	
*	Berima Omer Ahmed	
	Haram Adam Abdallah	
	Bushara Berima Hager	
	Bahar Hassan Khalil	
	Ibrahim Abdallah El Safi	
	Watchmen	
	Ali Abu	
	Ibrahim Hillo	
	Aboud Ibrahim Abu Sekeim	
	Ismail Abaker Abdallah	
	Khatir Isag	
	El Hag Bushara	
	Hussein Abdel Rasool	
	Adam Sharif el Din	
	Hassan Nagmous	
	Ibrahim Ahmed Mohamed Ali	
	Dutch Team	
1	Jan-Anne Boswinkel	Co-Manager WAPS-2,
	Wim van der Linden	Geohydrologist
	Ko van Kuijk	Geophysicist
	Nol Kootstra	Technical Supervisor

Key

* Left the Project in Nyala
** On Course during part of the project
1 Partly in Nyala only
2 Geological Advisor, NWC Darfur Region
3 Transferred to Technical Committee, Kassala

APPENDIX H

<u>NYALA WATER RESOURCES DEVELOPMENT</u>

<u>AND UTILIZATION ACT</u>

APPENDIX H

NYALA WATER RESOURCES DEVELOPMENT AND UTILIZATION ACT

A SUGGESTION

In 1984, the Regional People Council of the Eastern Region passed a water act to control and manage the water resources of the Kassala Gash Basin. As suggestion for an act for the Nyala Water Resources hereunder the Kassala Gash Basin act is given. Although some items are already adapted, this act needs further amendments and additions to suit the local conditions at Nyala.

NAME OF THE ACT AND ITS APPLICATION

Art. 1 This Act is called ' The Nyala Water Resources Development and Utilization' Act, 1985 and it is applicable once it is passed by the Council regional authorities which are spelt out in Articles 3 and 4.

Art. 2 Accoording to this Act or otherwise stated:

Council :means Nyala Water Resources Development and Utilization Council, established according to Article 3 of this Act.

Government :means Regional Government of the Darfur Region.

Area :means Wadi Nyala

Water :means groundwater and surface water.

Government Units :means all governmental institutions from either Central or Regional Government.

Committee :means the Technical Committee, established according to Article 9 of this Act.

Well :means hand-dug well, not screened.

Borehole :means a drilled well with screens.

Groundwater specialist :means graduated hydrogeologist with at least 5 years experience, to be appointed as Head of the Technical Committee by the National Water Corporation in consultation with the Council.

COUNCIL ESTABLISHMENT

Art.3 According to this Act a Council should be established called the Nyala Water Resources Development and Utilization Council.

This Council is a legal body with the authority of signature.

Art.4 4.1 The Council should consist of the following persons:

1. Director General for Water, Darfur Region - Chairman;
2. Manager of the provincial NWC office at Nyala - Vice Chairman;
3. Head of the Committee - Secretary;
4. Director-General for Economics & Finance, Darfur Region - Member;
5. Head of Services Committee Regional Assembly - Member;
6. Representative of the farmers unions - Member;
7. Director Town Water Supply Nyala - Member;

In addition, the Regional Government can appoint members as representatives of each of the following government sectors:

8. Agriculture.
9. Public Health.
10. Irrigation.

4.2 The groundwater specialist should be the Secretary of the Council.

Art.5 Resolutions are passed in the Council by absolute majority.

Art.6 If votes are equally divided, the chairman's vote is decisive.

COUNCIL DUTIES

Art.7 The council should bear and carry out the following responsibilities and tasks respectively:

7.1 To formulate short and long term plans for the development of the area.

To execute the water policy and coordinate the different studies and programmes of the governmental units and private enterprises to ensure an optimal exploitation of the groundwater in the area.

7.2 To set priorities for exploitation of the groundwater in the area.

7.3 To issue licenses concerning the drilling of boreholes, the construction of wells, the permissible discharge for each well and the licenses for the pumps.

7.4 To issue provisional licenses for groundwater abstraction for only limited periods (5 years is suggested). This could be transferred into permanent licences only when:

i) It has been proved that the abstraction of water is not in contradiction with the plans mentioned in Art.no. 7.1,or

ii) When no damage to the already-existing licensed abstraction has taken place.

7.5 To supervise the necessary research and studies for the Government and for the Council. To formulate regulations and set penalties in order to protect the water resources from illegal exploitation, pollution and bad usage.

7.6 To secure the necessary financial means to support the Technical Committee, established according to Art. 9 of this Act, and to check the accounts submitted by the Committee.

DIRECTIONS OF REGIONAL GOVERNOR

Art.8 The Regional Governor may issue general directions for the Council to be executed only within its field of specilization.

THE TECHNICAL COMMITTEE ESTABLISHMENT

Art.9 9.1 A Technical Committee should be established by NWC in consultation with the Regional Council. Head of the Technical Committee should be the groundwater specialist.

9.2 The members of this Committee should be qualified and experienced.

9.3 The committee should be under the supervision of the national Water Corporation which should supply the Committee with qualified personnel and equipment.

9.4 Under delegation of the Council, the Committee bears and carries out the following responsibilities and tasks respectively:

9.4.1 Executing the regulations set according to Art. 13 of this Act. To continue with the collection of time dependent data (recharge, evapotranspiration, runoff, groundwater abstractions, groundwater levels, groundwater fluctuations) and with the collection and analyses of water samples in areas where pollution has been demonstrated, or where it is likely to develop.

9.4.2 Yearly set-up of a water balance in order to maintain the safe yield criteria and avoid overdraft situations.

9.4.3 Carrying out, when necessary, additional hydrogeological and geophysical studies.

9.4.4 Registration of all existing boreholes and wells and updating the existing information.

9.4.5 Advising the Council in:

i) Selection of location of new wells and boreholes.

ii) Well design.

iii) Permissible discharge for each well and maximum pump capacity.

iv) All other conditions mentioned in the license to be issued by the Council as mentioned in article 7.3

9.4.6 Offering technical advice for the governmental units and private enterprises regarding water and water related matters, according to the regulations put in this Act.

9.4.7 Submission of annual budgets to the Council for approval and checking.

FINANCE

Art.10 The budget of the Council is from all of the following sources;

a. Budget allocated by the Regional and Central Governments.
b. Water license fees.
c. Any aids or loans.
d. Any other sources.

ACCOUNTANCY

Art.11 The Council should keep proper and detailed accountancy concerning its budget.

AUDIT

Art.12 12.1 The accounts of the Council should be examined by the General Auditor.

12.2 The audit of the accounts should be completed within three months after the end of each financial year. A copy of the General Auditor's report should be submitted to the Regional Governor.

COUNCIL REGULATIONS

Art.13 13.1 The Council in consultation with the Technical Committee should formulate the following regulations:

a. Regulations for the discharge of wells and boreholes.
b. Regulations for the licenses of newly drilled boreholes or dug wells and regulations for licenses to increase the rate of discharge from existing wells together with the necessary fees.
c. Regulations of penalties.