national water corporation

NWC

Nyala water resources
WAPS - 2

A summary
of the results
of investigations
in 1983 - 1985

Technical bulletin 86 - 01

06609

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

A Summary of the Results of the WAPS-2
Investigations at Wadi Nyala during
1983-1985

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February 1986

Technical Bulletin no. 86-01
A Publication of the National Water Corporation
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Khartoum
SUDAN

[illegible]S AND RECOMMENDATIONS

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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 climate is hot and dry during most of the year; the wet season lasts for three months, from June to September.
The Wadi Nyala, bisects the town of Nyala and flows intermittently during the wet season.

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 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 from the present 1.9×10^6 m³ to about 4.5×10^6 m³ in years with normal rainfall, if groundwater consumption for agriculture remains unchanged.
The amount of groundwater available 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 14×10^6 m³ in 1984 and 112.4×10^6 m³ in 1985. Flood volumes and flood peaks seem to be increasing because of the deforestation of the catchment.

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 6.0×10^6 m³, and in the area downstream of Jebel Nyala until Bileil, the Downstream Area, it is 18.3×10^6 m³.

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

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 of 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, the "Water Resources Assessment Program in the Sudan", phase 2 (WAPS-2) was executed by the National Water Corporation (NWC), Khartoum, Sudan and TNO Institute of Applied Geoscience (DGV), Delft, The Netherlands.
The project covered a period of three years (January 1983 - December 1985).

The main activities of the WAPS-2 project were:
- Support to the Technical Committee at Kassala, which as follow-up of the WAPS-1 project (1979-1982) focusses on adequate use and management of the water resources in the Gash Basin.
- Execution of water resources studies near Nyala and Geneina, during which NWC-staff was trained.
- The establishment of a database in Khartoum to improve the accessibility of hydro(geo)logical data in Sudan.
- The provision of wells for water supply to three refugee camps in West-Darfur.

The Dutch contribution to the WAPS-2 project amounted to 6 250 000 Dutch Guilders covering the costs of qualified advisors based in Sudan, visiting experts and equipment (a.o. truck with trailer, landrovers, the complete equipment for a mechanical workshop and hydrological, hydrogeological and drilling equipment). The Sudanese budget was estimated at 2 150 000 Sudanese Pounds, covering expenses for a sufficient number of qualified staff, equipment, fuel and office buildings.
In order to improve the access to the technical reports produced by the WAPS-projects, it was envisaged to summarize these in Technical Bulletins.

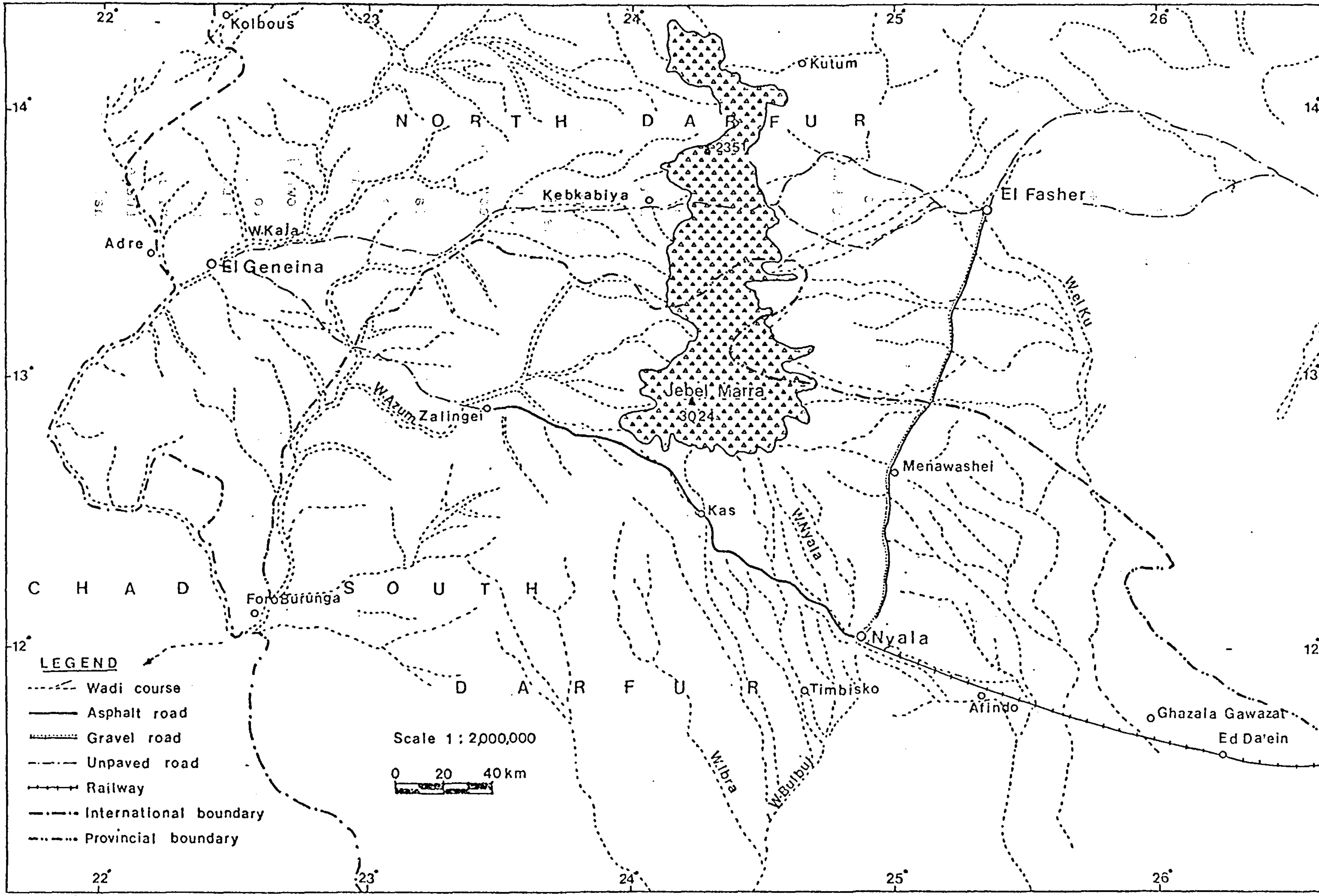
The present Technical Bulletin covers the Nyala Water Resources Study (1983 - 1985), providing a review of the activities, a description of the available water resources and an analysis of the groundwater development potential at Nyala.
The comprehensive account of the Nyala Water Resources Study is published in a Final Report (1985).

1.2 General Setting of Study Area

Nyala, the capital of Southern Darfur Province, is located on the Wadi Nyala at an altitude of 650 m above sealevel. It is connected with Khartoum by railway line, but proper roads do not exist. The direct distance to Khartoum is 900 km, or 1300 km along the railway line.

The area around Nyala is mainly flat and covered by vegetation typical of the semi-arid savannah. At 100 km northwest the Jebel Marra massif is located, a still active volcanic mountain.
The population in the rural area of Darfur is mainly of nomadic origin and consists of many tribes. The nomads cross the area to the north in the wet season and return south in the dry season. The sedentary population is growing due to the influx of people from the drought affected areas in the north, but also due to settling of nomads. Villages are usually located near wadis, where groundwater is found at shallow depth.
The population of the towns and especially Nyala is growing fast because many people are leaving the rural areas in search for jobs. The drought in 1984/1985 has intensified this migration.

A map of Nyala town is shown in figure 2. 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 mainly made of traditional grass huts.



MAP OF CENTRAL DARFUR

Figure 1.

Nyala extends over an area of approximately 8 by 6 km. The number of inhabitants is estimated to be some 205 000 (1985).

Nyala obtains all its water for domestic use from boreholes and wells located in the wadi or on the banks.

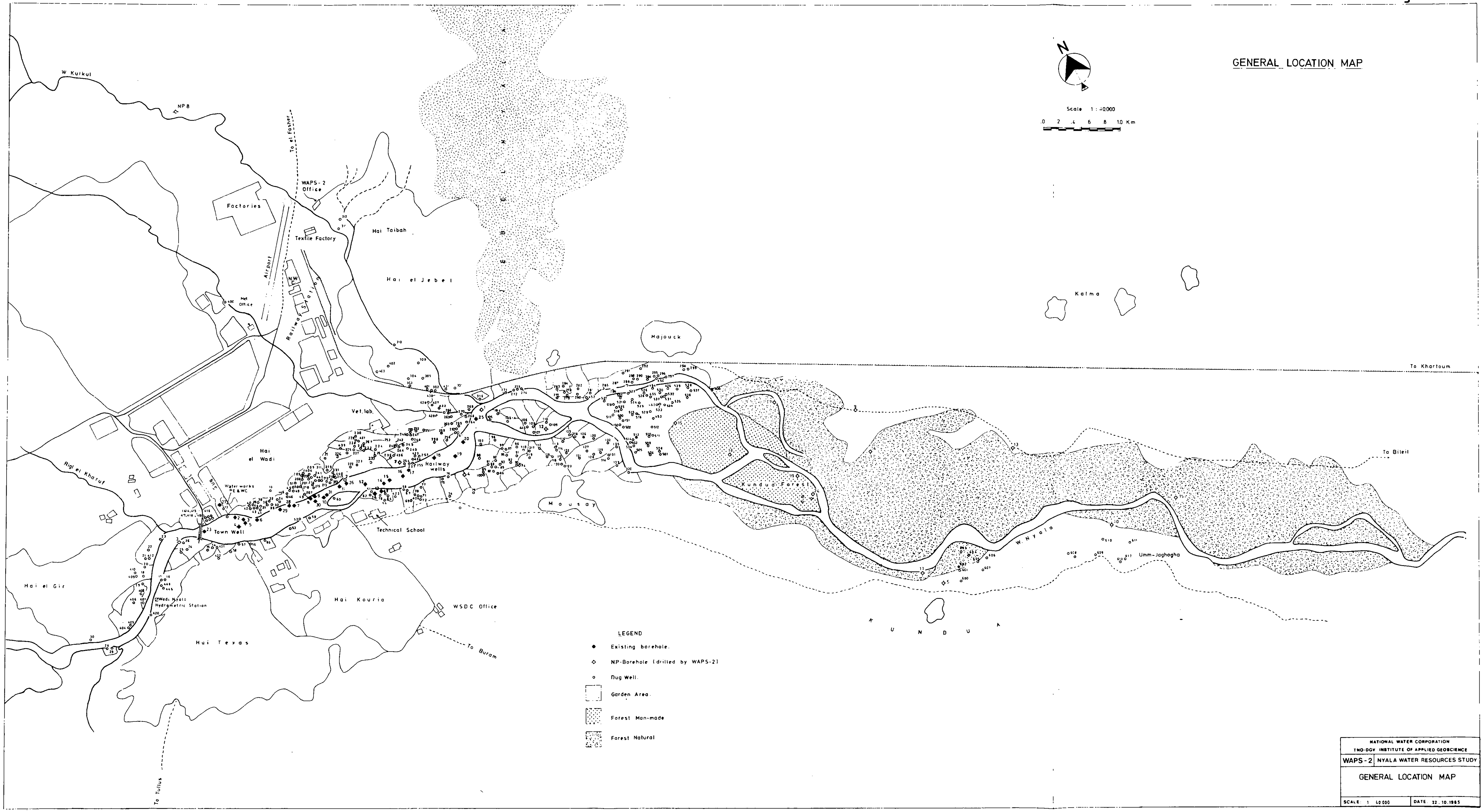
The public water supply run by the Public Electricity and Water Supply Corporation (PEWC) is drawing water from usually eight boreholes. The boreholes (BH 2, BH 3 and BH 4) located at the so-called Town Wells sits, are connected to storage tanks (capacity = 250 m^3) in the yard of the PEWC. The other 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 the boreholes are equipped with electric submersible pumps, but often not all eight are pumping, due to mechanical defects or other causes.

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 ten to fifteen open dug wells are used by water vendors, who transport the water from the garden area into the town, in horse-drawn tanks of about 1 m^3 capacity.

Near the town centre and several kilometers 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

Figure 2


GENERAL LOCATION MAP
N
Scale 1 : 40000
0 2 4 6 8 10 Km
W. Kulkul
NP 8
To el Fasher
WAPS-2 Office
Factories
Textile Factory
Hai Taibah
Hai el Jebel
Airport
Railway Station
Met Office
Kalma
Majouck
To Khartoum
Vet. lab.
Hai el Wadi
Railway wells
Rigl el Khatuf
Water works PE & WC
Town Well
Technical School
Mousay
Kundua Forest
To Bileil
W. Nyala
Umm-Jaghogha
Hai el Gir
Wadi Nyala Hydrometric Station
Hai Kouria
WSDC Office
Hai Texas
To Buram
To Tullus
K U N D U A
LEGEND
Existing borehole.
NP-Borehole (drilled by WAPS-2)
Dug Well.
Garden Area.
Forest Man-made
Forest Natural
NATIONAL WATER CORPORATION
TNO-DGV INSTITUTE OF APPLIED GEOSCIENCE
WAPS-2 NYALA WATER RESOURCES STUDY
GENERAL LOCATION MAP
SCALE 1 : 40000
DATE 22.10.1985

potatoes, cucumbers, carrots, ocra, alfalfa, etc. Many of these contain one or more dug wells for irrigation.

The total number of boreholes is 48, including 19 drilled by WAPS-2. The total number of dug wells is 346, if including also those located outside the aquifer area. The number shows that many wells are out of use. Pumping is done by electrical submersible pumps from the boreholes and by diesel driven centrifugal pumps from the dug wells.

2. REVIEW OF TECHNICAL ACTIVITIES

2.1 Previous Investigations and Existing Data

R.B. Salama (1971 - M.Sc. Thesis) carried out a hydrogeological survey in Wadi Nyala in 1968/1969. The fieldwork included groundwater level observations, a geophysical survey (seismic and gravity), pumptests, chemical water analyses and drilling of five exploratory wells. The data and conclusions were not available to the project, only an incomplete handwritten draft version of the thesis was found in the NWC files in Khartoum.

Hunting Technical Services Ltd. and Sir M. MacDonald & Partners (1974) includes an appendix on the Water Resources of Wadi Nyala. This was mainly based on Salama's survey results and data from nine additional boreholes.

Abdul Raziq Mukhtar (1979) carried out an electrical resistivity survey at Nyala. Results were insufficient due to equipment inadequate for the hydrogeological conditions. The well inventory conducted with help of Wad Magboul students comprised about 300 dug wells.
Humphreys & Partners (1983) made a compilation of the available hydrogeological data at Nyala for their study of the Nyala Water Supply and concluded that an extensive hydrogeological study would be necessary before the final design of the Town Water Supply System could be completed.

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 1971 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.

2.2 Fieldwork WAPS-2

2.2.1 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.

2.2.2 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.

2.2.3 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: 41 in 1983, 10 in 1984 and 29 in 1985. 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.

2.2.4 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 doubtfull results due to shallow depths and lack of contrasts.

2.2.5 Groundwater levels

The water levels in dug wells and boreholes have been observed since February 1983. A maximum total of 150 index wells were visited almost every month.

Six water level recorders were installed to obtain a continuous record. At the end of the project only two were still operational.

2.2.6 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 sampling 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.

2.2.7 Well drilling

The project drilled 19 exploratory boreholes, all of which were completed with 2 or 6 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.

2.2.8 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.

2.3. Activities at the office

2.3.1 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 base 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.

2.3.2 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 was stored on cassette tapes.

2.3.3 Analysis of hydrogeological data

The groundwater level data was 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 Summers (1980) for the HP-41C hand calculator. The grainsize distribution of drilling samples was determined in the office by mechanical analysis.

2.3.4 Analysis of water samples

The chemical analysis of water samples was 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.

2.3.5 Groundwater model

Two groundwater models were prepared for the Town Area and for the Downstream Area, which were run on the HP-85 deskcomputer.

2.3.6 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.

2.4. 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 the aspects of:

- (geo)hydrology : planning, execution and interpretation of field investigations, processing and evaluation of data, water balance study, groundwater modelling etc.;
- geophysics : planning, execution and interpretation of geophysical measurements;

- drilling : execution of drilling and well completion;
- reporting : writing of reports and preparation of maps and figures;
- technical maintenance: the use and maintenance of equipment and vehicles.

3. CLIMATE AND HYDROLOGY

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.

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 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 southwesterly 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.

Table 1 Monthly Averages of Mean, Maximum and Minimum Daily Temperatures in °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

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.

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.
It therefore seems prudent to take into account only rainfall data pertaining to the period since 1971, in planning for future water resources development.

3.2 Rainfall

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 northeast to southwest with local higher quantities around the Jebel Marra massif.

The catchment of Wadi Nyala is situated in the transient zone of low to intermediate annual rainfall amounts, the annual mean at Nyala being 366.2 mm (period 1971 - 1985).

The recorded rainfall at the project rainfall stations in the catchment area shows 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.

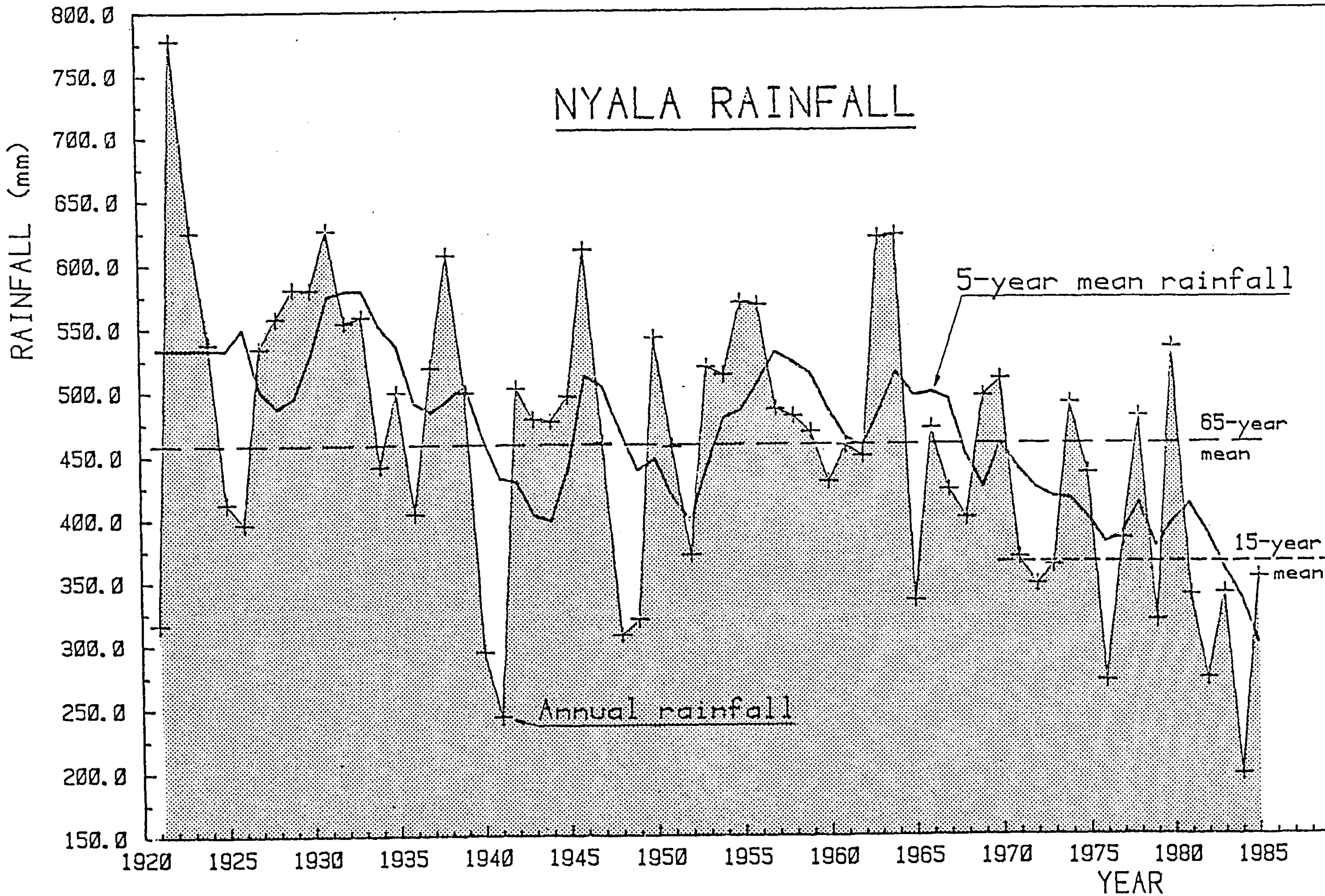
The rainy season generally lasts from May to October, but is concentrated between the end of June and the middle of September. The wettest months are July and August with 61% of the total annual rainfall (1921 - 1985).

Table 2 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

The annual rainfall has been fluctuating between 197.3 and 778 mm at Nyala during the 65 year observation period. (The minimum annual rainfall at the WAPS-2 office was 154.2 mm).
Figure 3 shows the five 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 comprises ten of the fifteen 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.



FIVE YEAR MOVING MEAN RAINFALL NYALA.

Figure 3

The monthly and annual totals of rainfall are composed of a limited number of storm events of short duration. At Nyala the number of raindays was never more than 33 during the project period (see table 3). The rainfall duration was on average only 1.3 hours per day.

In 1983 52% of the total rainfall was produced in only 4 days during a total time of 12.9 hours.
The number of raindays did not vary much during 1983 - 1985. It seems that the low annual rainfall is caused more by an absence of large events than by a smaller number of rainfall events.

The short duration of the rainfall shows that high rainfall intensities occur. The maximum amount of rainfall measured during one hour was 63.6 mm on July 24, 1983 at Nyala. These high rainfall intensities produce large flood peaks in the wadis.

Table 3 Rainfall Data Nyala 1983 - 1985

	1983	1984	1985
Total Rainfall	322.6	154.3	350.6
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

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 generally 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 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.

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 water 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 evapotranspiration was determined seperately for the Town Area and the Downstream Area, as for both areas a water balance was established (section 6.3).

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).

The total annual waterloss by evapotranspiration from the wadi alluvial aquifer was estimated at 2.30 x 10^6 m³ for the Town Area and 12.22 x 10^6 m³ for the Downstream Area.

Table 4 Actual Evapotranspiration (AE) Estimate for the Alluvial Aquifer

	TOWN AREA			DOWNSTREAM AREA		
	Area (km²)	AE (mm)	Volume (10^6 m³)	Area (km²)	AE (mm)	Volume (10^6 m³)
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

3.4 Surface Water Runoff

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 water levels in the wadi were recorded continuously with a water level 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 water level for each flood from which the maximum discharge was determined using the slope-area calculation method.

The total daily discharges of 1983, 1984 and 1985 are presented in table 5. The maximum daily discharge was 16.8×10^6 m^3 in September 1985. The maximum 24 hours discharge was 31×10^6 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. 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 5 Wadi Nyala Discharge Data 1983 - 1985

	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 Sept	28 Sept	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 to 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 localized storms produce high peaks of short duration (see figure 4). Sometimes floods occur without rainfall being observed at Nyala.

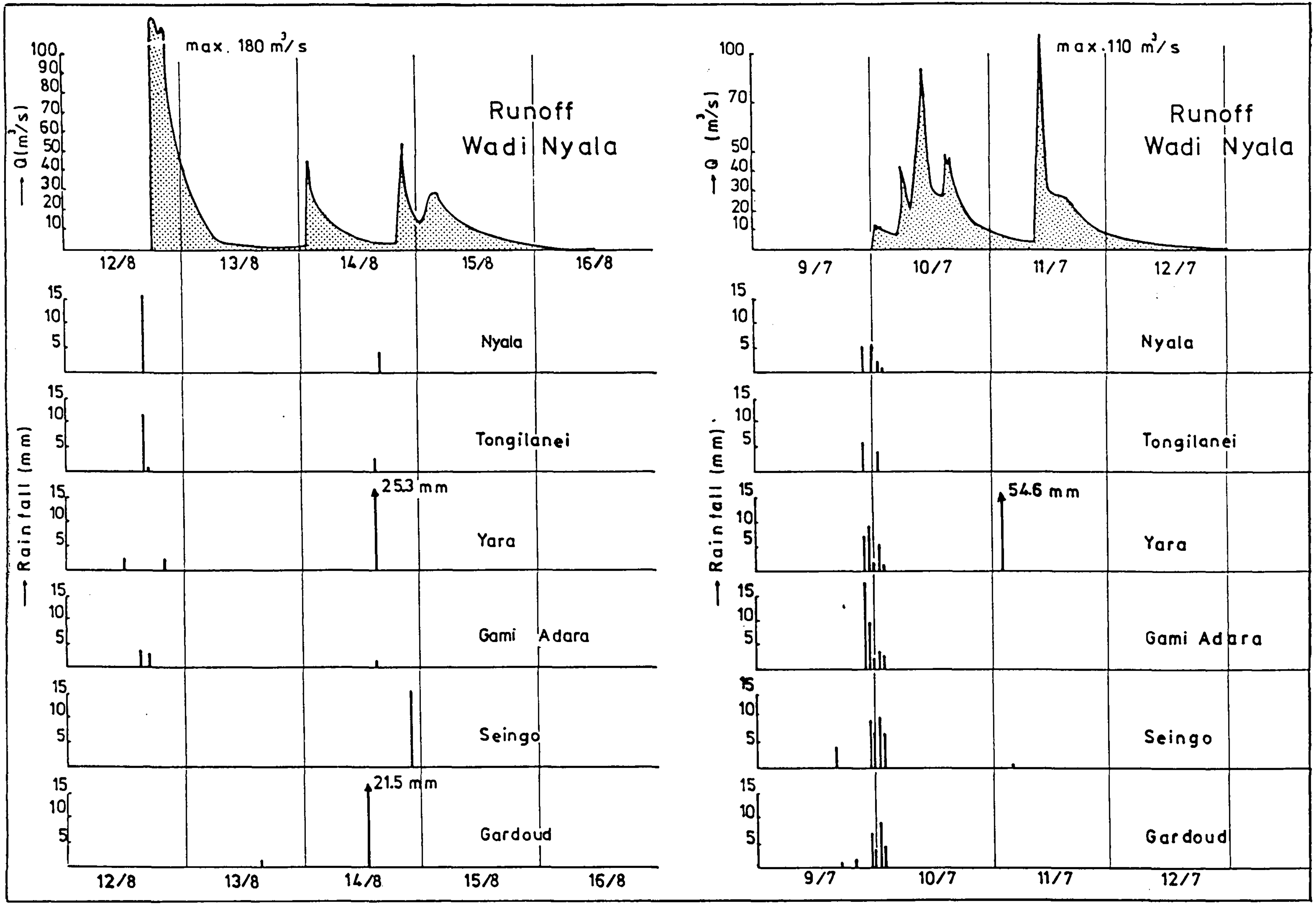


Figure 4

TWO RUNOFF EVENTS WADI NYALA 1983

The percentage of the rainfall which reaches Nyala as Wadi Nyala surface runoff varies (see table 6). The annual percentage increases with a larger catchment rainfall. The monthly percentage reaches its maximum in July, August and September. The growth of the vegetation during the rainy season seems not to have much effect.

The Wadi Nyala discharge is sufficient to recharge the groundwater in the alluvial aquifer if the catchment rainfall is more than about 250 mm.

Table 6 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

4. THE AQUIFER OF WADI NYALA

The Wadi Nyala basin is situated on the Basement Complex, which extends from the tertiary volcanic rocks of the Jebel Marra massif in the northwest to the sandstone of the Baggara Basin 70 to 100 km to the southeast of Nyala. The Basement Complex consists mainly of Pre-Cambrian metamorphic rocks (gneisses, schists). The Basement is cut by quartz dykes, which form jagged ridges, the dominant features of the landscape.

The drainage pattern in the Basement Area is dendritic with a high density. On a large scale the drainage appears to be structurally controlled, with long narrow catchments (wadis to the west of Wadi Nyala) trending to the south-southeast. The Wadi Nyala has the same orientation upstream of Nyala, but then changes to east-southeastern direction, following what seems to be a major linear structure.

The Basement Complex rocks contain no groundwater except small quantities in weathered zones or in fractures. Only in recent times water has been produced from a few deep boreholes elsewhere in Darfur. The main source of groundwater in the area are traditionally the alluvial sediments in the wadis.

The alluvial sediments are of shallow thickness in the upstream part of the wadi, where rocks form the wadi banks. Further downstream the thicknesses increase and the wadi is flanked by silty terraces. The sediments consist in this part mainly of coarse sands, but become more variable downstream with an increase in clay content.
Finally the wadi reaches its floodplain, where the sedimentation is by relatively slow-moving water. Here the alluvium is fine grained, with narrow sandy strips close to the wadi channels.

The Wadi Nyala reaches at Nyala the point where the rocky banks disappear and the width of the alluvium increases from 200 to

900 metres. The thickness of the alluvial deposits reaches its maximum depth at Nyala: about 20 metres.
A few kilometres downstream the depth of the alluvium is about 12 metres, which is much the same in the residual soils and sheet wash on either side of the wadi. The width of the alluvial deposits reaches here more than 1.5 km.

The composition of the alluvium is heterogeneous due to the braided character of the wadi system. Boreholes show that the wadi alluvium is variable both laterally and vertically and that it contains thick beds of clays, silts and sands in close proximity. Also gravels and boulders are found interspersed with the sediments.
To distinguish between permeable and less permeable parts of the alluvial sediments a classification was made. This classification was mainly based on a qualitative analyses of the electromagnetic geophysical measurements.
The distribution of the alluvium types inside the Wadi Nyala aquifer area is shown in figure 5.

- S (sandy)
  This type mainly contains sand and gravel layers; only thin clay or clayey intercalations may occur; high permeabilies can be expected.

- 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 thicknesses. 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 intercalations may be present, this type should not be considered as productive.

Figure 5


ALLUVIAL AQUIFER MAP
LEGEND
Aquifer boundary
Contour line depth to Basement complex (in meters)
S Sandy alluvium (Type S)
CS Clayey/Sandy alluvium (Type CS)
C Clayey alluvium (Type C)
Fault
Line of cross-section shown in figure 6.2
VES Location with calculated depth to Basement complex (in m)
Existing borehole
WAPS-2 borehole with depth to Basement complex (in m)
Dug well
scale 1 : 40000
0 0.5 1 Km
JEBEL NYALA
Hai el Jebel
Hai el Wadi
Hai el Gir
Hai Kouria
Hai Texas
Majouck v.
Mousay villages
Kundua Forest
Kundua v.
Kalma
Outcrops
NATIONAL WATER CORPORATION
TNO-DGV INSTITUTE OF APPLIED GEOSCIENCE
WAPS-2 NYALA WATER RESOURCES STUDY
ALLUVIAL AQUIFER MAP
SCALE 1 : 40000
DATE: 26.4.1985

The lateral extent of the alluvial aquifer was determined within the boundaries of the S and CS areas. The thickness of the alluvial aquifer could not be determined accurately from the geophysical measurements, but is known from the large number of boreholes in the area.

Table 7 Pumping Test Analysis Results

Well number	Transmissivity (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 groundwater in the alluvial aquifer is unconfined, the water-table forming the upper boundary of the aquifer.
The hydraulic parameters of the quifer are the permeability k and the specific yield S, which were determined from pumptests. The pumptests did not show differences in values of k and S between the wells located in the Town Area and those in the Downstream Area.
However, the simulation of the aquifer with the groundwater model and also the water balance analysis indicated that generally the S-values are lower in the Downstream Area.

Table 8 Hydraulic Parameters of the Alluvial Aquifer

	Permeability (m/day)	Specific yield (%)
TOWN AREA		
Sandy Aquifer	50	20
Clayey/Sandy Aquifer	20	10
DOWNSTREAM AREA		
Sandy Aquifer	50	16
Clayey/Sandy Aquifer	20	8

5. GROUNDWATER QUALITY

The groundwater from the Wadi Nyala alluvial aquifer is used intensively for domestic purposes and to a lesser extent for agricultural purposes. The chemical quality of the groundwater does not impose any limitations. The concentrations of dissolved chemical constituents are very moderate.
The groundwater is generally of the calcium-carbonate type. The hardness varies from moderate to sometimes very hard.

The electrical conductivity (EC) of the groundwater varies between 250 and 700 µS/cm (see figure 6), the lower values being found in and near the wadi. The groundwater is slightly alkaline, the pH is on average about 7.4. The temperature of the groundwater is about 26°C.

The location of the aquifer inside the town renders the groundwater 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 aminals. The aquifer in the wadi is not covered by any less permeable layers and therefore, if water is available, diluted contaminants quickly reach the groundwater.

The main danger of pollution is caused by:
- 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 of the boreholes and dug wells used for drinking water supply;
- the trucks entering the wadi to quarry sand.

The water for domestic use is supplied by the PEWC from boreholes in the wadi. The majority of the people, however, rely on supply from water vendors who take their water from dug wells located on the banks of the wadi. Of the dug wells which are used for this purpose, 16 were tested on their total coliform bacteria content. All of these were found to be bacteriologically contaminated.

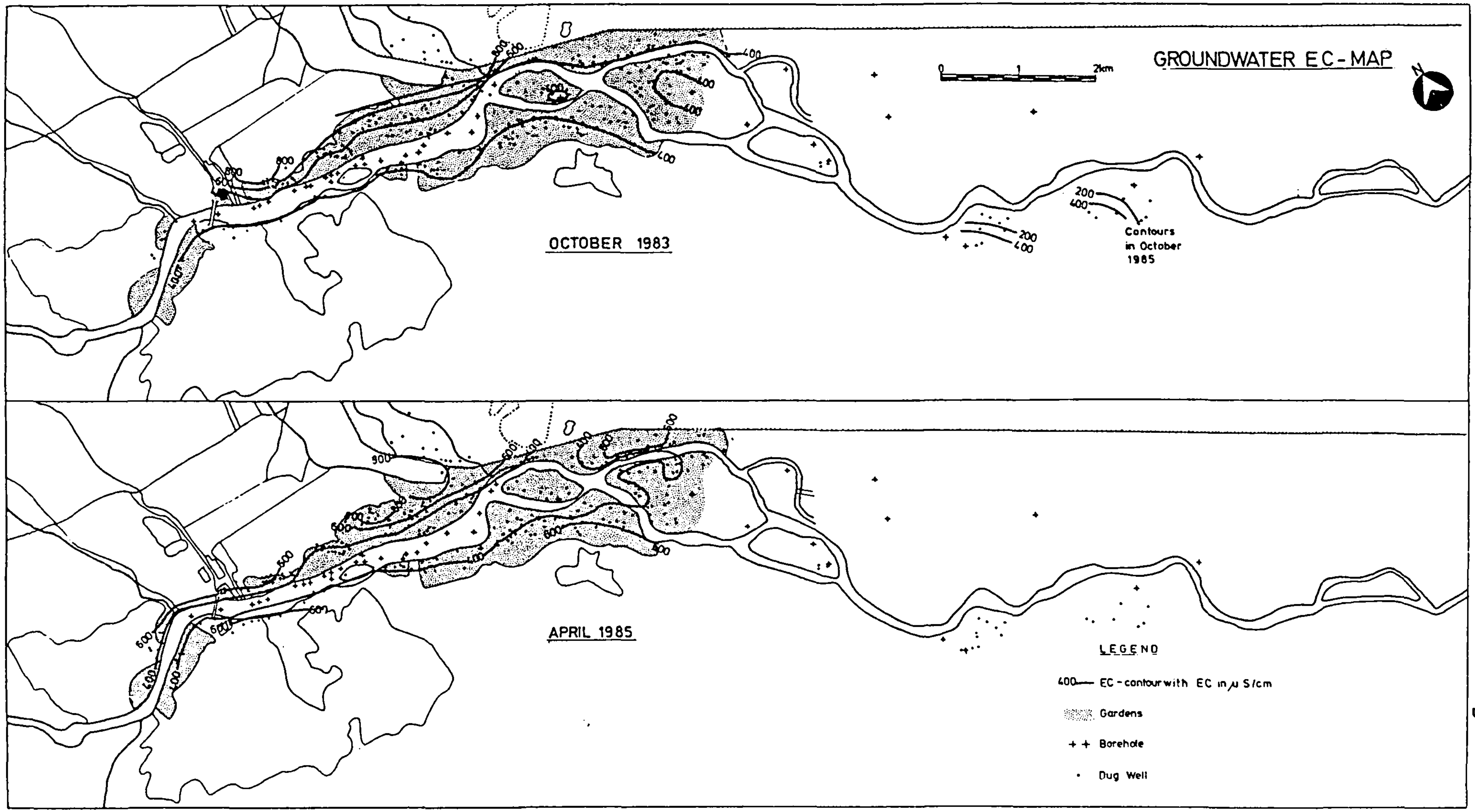

GROUNDWATER EC-MAP
0
1
2km
OCTOBER 1983
Contours
in October
1985
APRIL 1985
LEGEND
400 EC-contour with EC in μ S/cm
Gardens
+ + Borehole
· Dug Well

Figure 6

Table 9 Results Chemical Analyses Groundwater Wadi Nyala

Well number	PEWC	BH 2	BH 15	19	59	269	Wadi Nyala Runoff	
Date of sampling	1981 May	1983 Oct	1983 Oct	1983 Oct	1983 Oct	1983 Oct	1983 Sep	
Conductivity	295	-	210	-	-	-	8.6	µS/cm
pH	7.4	7.1	7.1	7.2	7.6	7.8	8.2	
TDS	210	120	120	230	250	680	-	mg/l
Total Hardness	138	90	90	165	210	330	88	mg/l
Total Alkalinity	145	80	100	140	240	440	75	mg/l
Excess Alkalinity	-	Nil	10	Nil	30	120	-	mg/l
Calcium (Ca)	44	30	30	60	70	70	12	mg/l
Magnesium (Mg)	7	5	5	5	10	35	14	mg/l
Sodium (Na)	12	10	5	10	10	70	-	mg/l
Potassium (K)	5	5	2	5	5	5	-	mg/l
Total Cations	3.40	2.47	2.18	3.96	4.90	9.79	-	mg/l
Chloride (Cl)	4	20	25	25	15	30	9	mg/l
Sulphate (SO_4)	5	-	55	80	55	65	3	mg/l
Nitrate (NO_3)	18	Nil	Nil	Nil	Nil	Nil	-	mg/l
Nitrite (NO_2)	Nil	0.04	Nil	Nil	Nil	0.01	-	mg/l
Fluoride (F)	0.19	0.50	0.50	0.50	0.80	0.80	-	mg/l
Total Anions	3.40	4.14	3.85	5.15	6.35	11.00	-	mg/l
Ammonia (N)	Nil	Nil	Nil	Nil	Nil	Nil	-	mg/l
Albuminoid-Nitr.	0.07	Nil	Nil	Nil	Nil	Nil	-	mg/l
Arsenic (As)	-	Nil	Nil	Nil	Nil	Nil	-	mg/l
Lead (Pb)	Nil	Nil	Nil	Nil	Nil	Nil	-	mg/l
Iron (Fe)	Nil	Nil	Nil	Nil	Nil	Nil	Nil	mg/l
SAR	0.4	0.2	0.6	0.3	2.1	1.7	-	

Table 10 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
BH 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: -ve = negative, no coliform bateria present

+ve = positive, but count of bacteria not possible

\- = not tested.

1984 Nov tests by water analysis laboratory El Fasher, all other tests by WAPS-2

The boreholes in the wadi used by the PEWC did not show contamination from bacteries. However, they are not protected, the casing being open on the top and often pipefittings are leaking near the borehole. So there always is a risk of contamination.

The PEWC well no. 1 and BH 2 at the Town Wells site are both vulnerable to pollution, as they are located near the suq. At present BH 2 still seems reliable, but well no. 1 was closed in 1984 as its water showed a high bacterial count. The well was put back in production in 1985, after the removal of the suq from the wadi.

To ensure a safe water supply for domestic use, preventive measures should be taken to remove the sources of pollution. Also it is advisable to add chlorine to the water supplied by the PEWC, to kill the bacteria which may be present in the pumped water. Regular checks on the water quality should be made in the PEWC office at Nyala, something which is not done at present.

6. GROUNDWATER QUANTITY

6.1 Introduction

The groundwater storage of the alluvial aquifer was investigated in the two parts of the study area (see figure 2):

- Town Area, extending between the hydrometric station and Jebel Nyala.
- Downstream Area, extending from the Jebel Nyala to the boundary of the study area at Bileil.

The aquifer area was considered to coincide with the sandy and clayey/sandy part of the alluvium (see figure 5). Groundwater flow between the aquifer and the clayey part of the alluvium or between the aquifer and the underlying basement was assumed to be negligible.

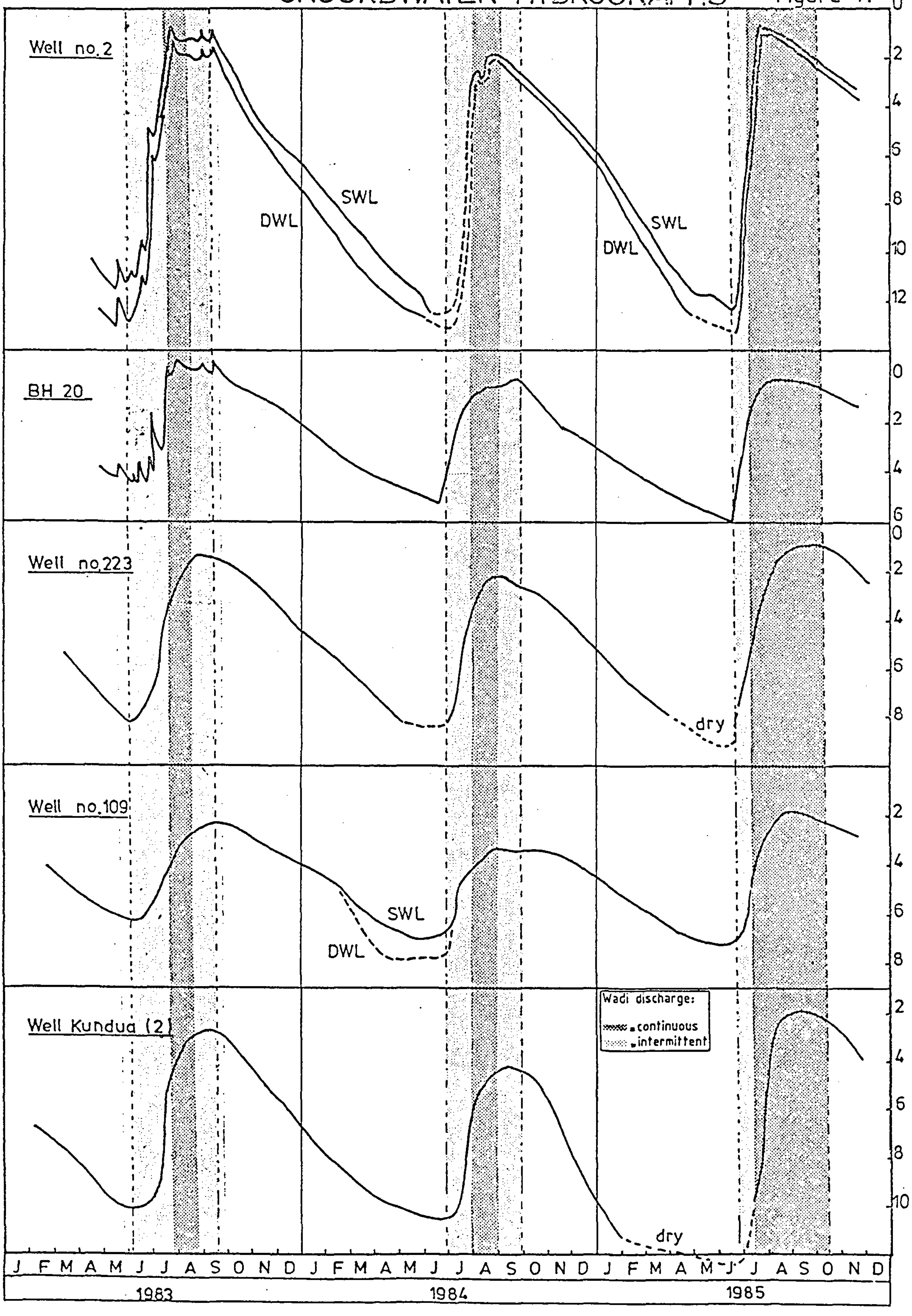
6.2 Groundwater Recharge

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. 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 posses a good permeability and infiltration of surface water takes place immediately. In the banks the recovery of the groundwater levels shows a delay of about one month (see figure 7).

GROUNDWATER HYDROGRAPHS Figure 7.



In normal years full recovery is reached in the banks. Only in dry years, such as 1984 - and also 1983 but to a lesser extent - the groundwater levels in the banks do not recover fully. In 1984 the groundwater levels were generally one metre below the levels of 1985.

6.3 Groundwater Discharge

6.3.1 Introduction

The loss of groundwater is caused by the following elements of discharge:

- evapotranspiration;
- pumping from wells and boreholes:
- 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 outflow across the boundary between the Town Area and the Downstream Area is calculated at only 210 000 m^3/ year.

6.3.2 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, minus the evapotranspiration from the (net) rainfall on the area and is presented in table 11.

6.3.3 Discharge from wells and boreholes

The present groundwater consumption from wells and boreholes includes:

- the pumping for the town water supply by the PEWC from eight boreholes all located in the wadi;
- the pumping by private water vendors from dug wells located on the banks in the gardens;
- the pumping by farmers from 192 dug wells for irrigation of the gardens;
- the abstraction of water from stock wells (temporary wells in the wadi) for domestic purposes and livestock watering.

The PEWC uses at present eight boreholes, all located inside the wadi. The total pump discharge is not known, because only the boreholes at the Town Wells site are metered (at the pumphouse).

Table 11 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 other boreholes are not metered and are directly connected to the distribution net. 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.

The discharge from dug wells was obtained from the well inventory data. The water is used for irrigation and domestic consumption (table 13).

Table 12 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

Table 13 Estimate of Discharge from Dug Wells

	Irrigation (m^3)	Domestic (m^3)	Total (m^3)
Town Area	1 100 000	340 000	1 440 000
Downstream Area	1 000 000	25 000	1 025 000
Total Aquifer Area	2 100 000	365 000	2 465 000
Total All Wells*	2 839 000	447 000	3 286 000

* Including wells located outside aquifer area.

Shallow seasonall wells ("stock wells") are located inside the wadi, from which water is taken by bucket for domestic use and livestock watering. The total annual abstraction was estimated at 40 000 m^3.

LONGITUDINAL PROFILE TOWN AREA

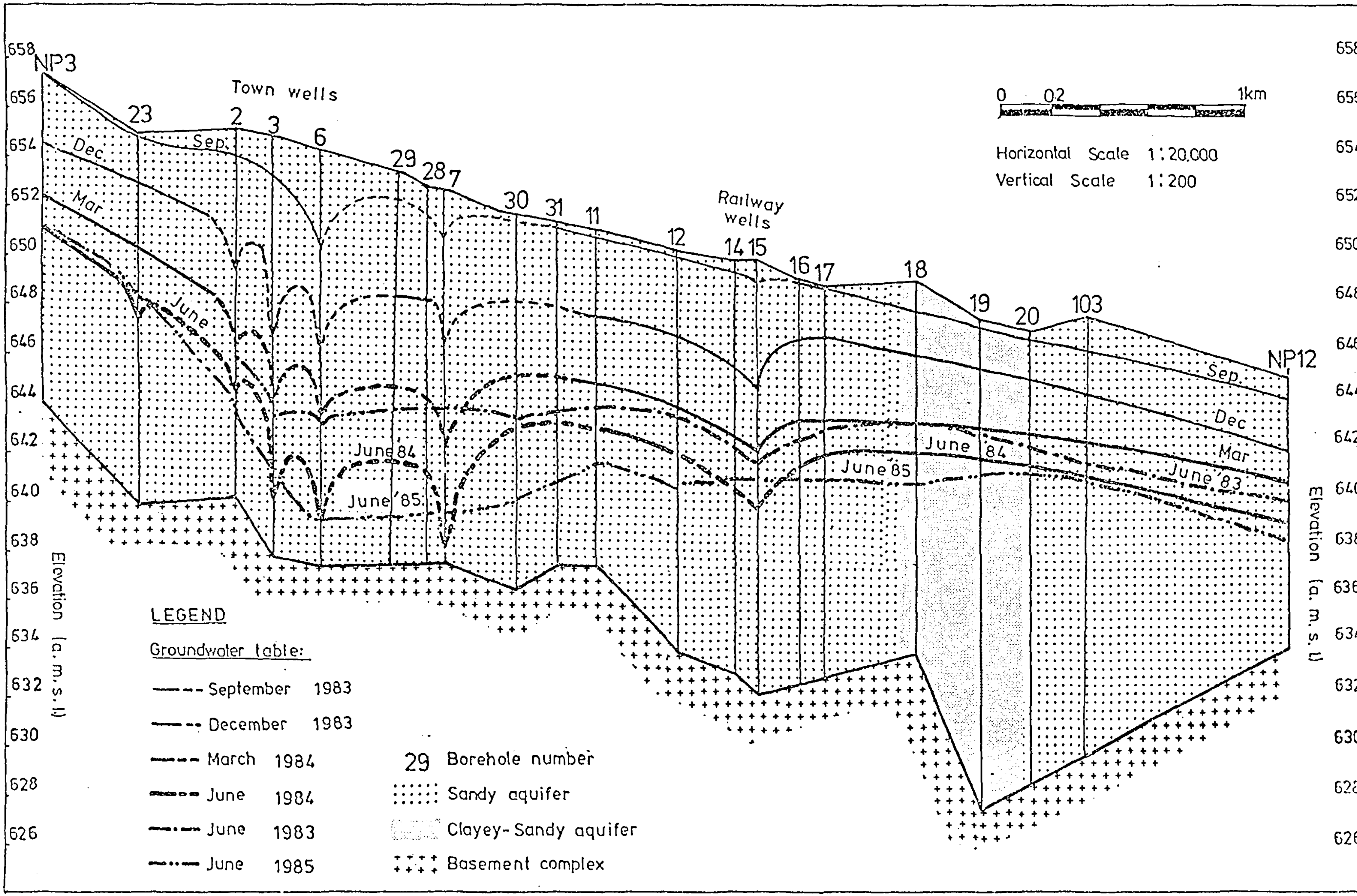


Figure 8.

6.4 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 aquifer was subdivided schematically in two parts, sandy aquifer and clayey/ sandy aquifer, as described in chapter 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 total groundwater storage capacity for the aquifer in the Town Area and the Downstream Area is presented in table 14. 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.

Table 14 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

Figure 9

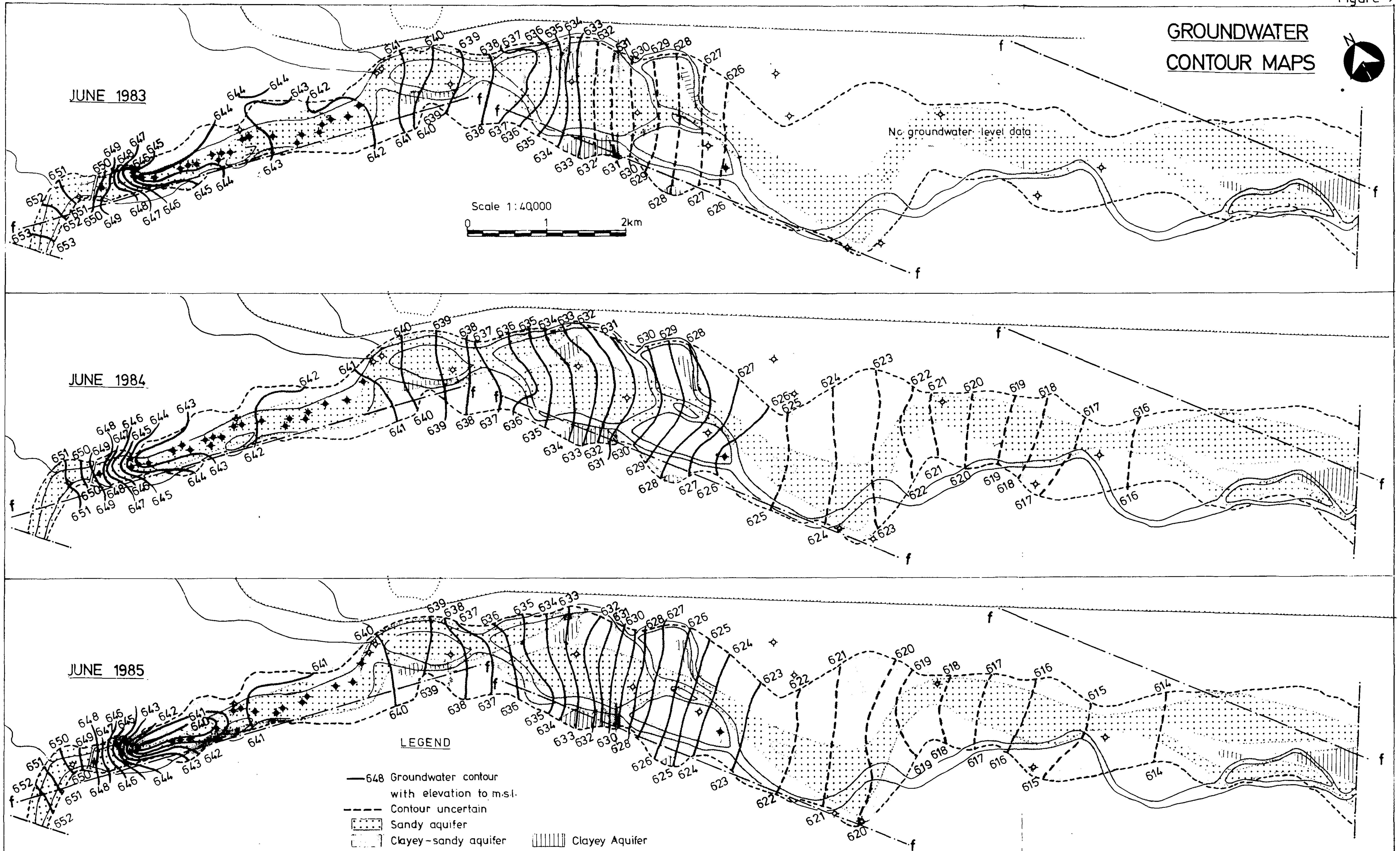

GROUNDWATER
CONTOUR MAPS
N
JUNE 1983
JUNE 1984
JUNE 1985
No groundwater level data
Scale 1:40,000
0
1
2km
LEGEND
648 Groundwater contour with elevation to m.s.l.
Contour uncertain
Sandy aquifer
Clayey-sandy aquifer
Clayey Aquifer

Figure 10

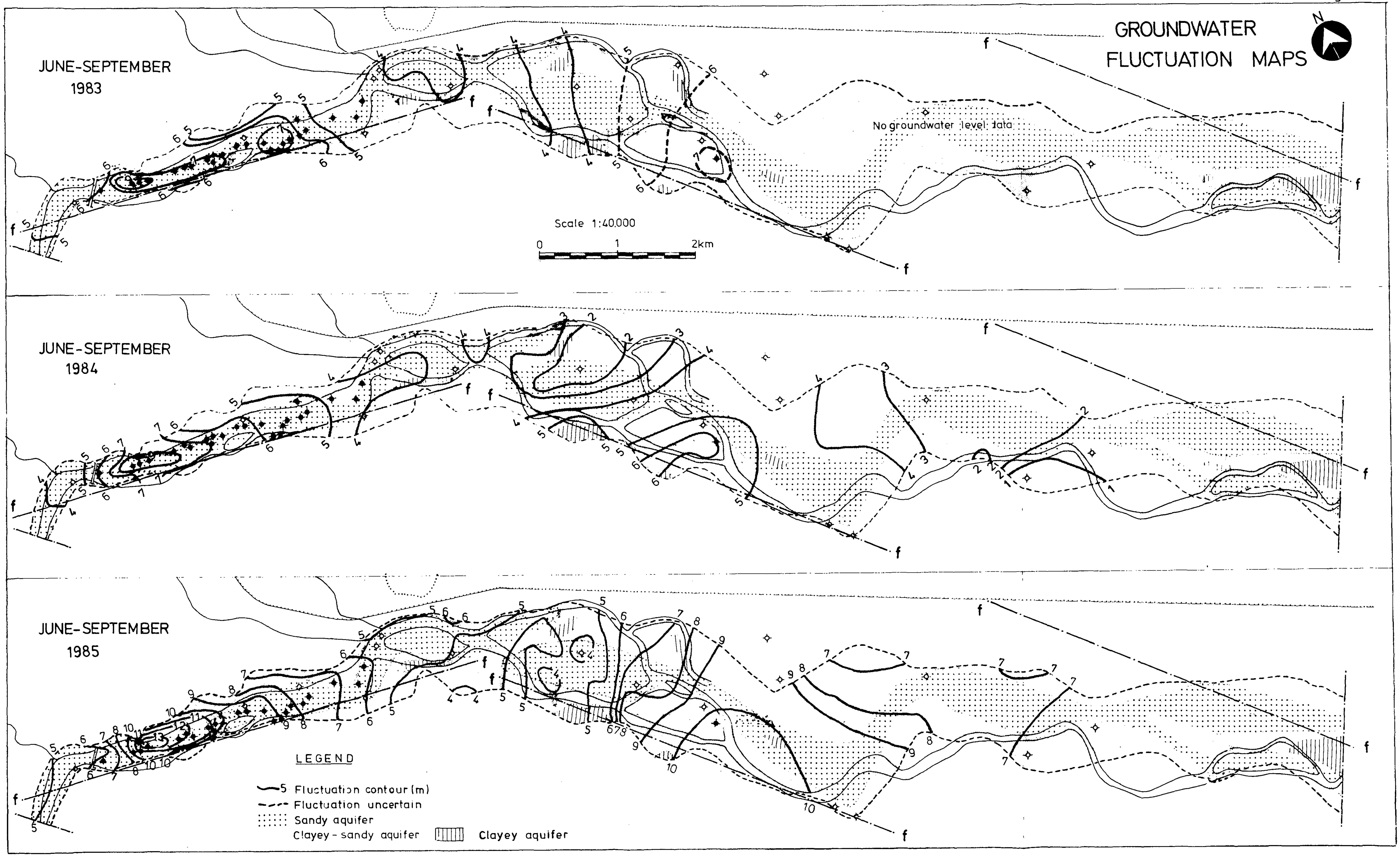
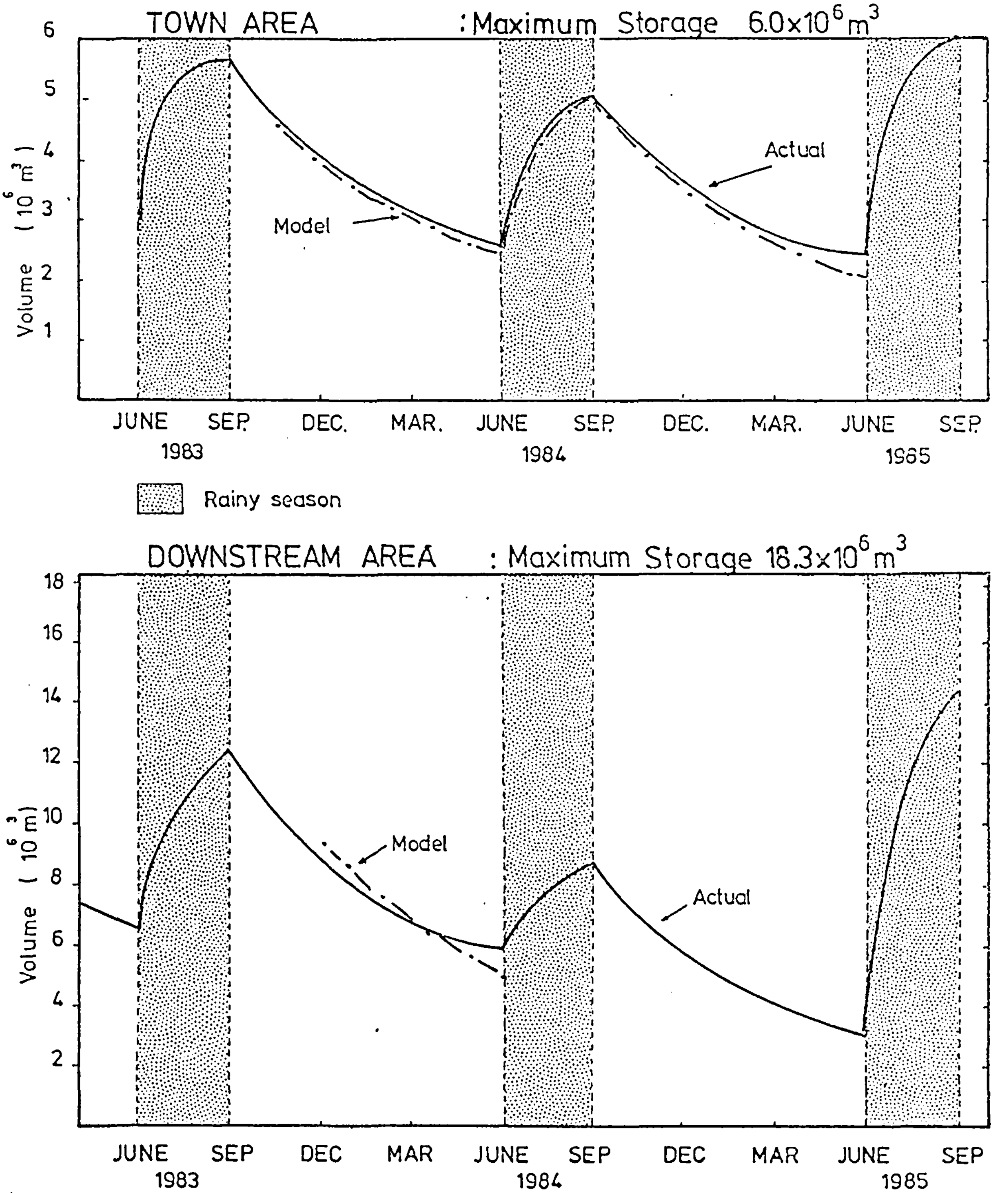

GROUNDWATER FLUCTUATION MAPS
N
JUNE-SEPTEMBER 1983
No groundwater level data
Scale 1:40,000
0 1 2km
JUNE-SEPTEMBER 1984
JUNE-SEPTEMBER 1985
LEGEND
5 Fluctuation contour (m)
Fluctuation uncertain
Sandy aquifer
Clayey-sandy aquifer
Clayey aquifer

Figure 11 Variation of Groundwater Storage in 1983 - 1985



The groundwater storage fluctuation during the wet season in the years 1983, 1984 and 1985 was determined from the groundwater fluctuation map (figure 10). This fluctuation equals the total recharge to the groundwater minus the groundwater consumption during this period. The variation of the aquifer storage in the years 1983 - 1985 is presented in figure 11.

6.5 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 mean 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.

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, see table 12). 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.

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.

Table 15 Water Balance of Wadi Nyala Aquifer

	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.

The events in the years 1983 until 1985 have shown the repercussions of low rainfall:

- 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.

At present there is no appropriate control by the authorities on the use of the small water resources, e.g. by limiting the irrigated areas or by fixing the groundwater volume available for the PEWC town water supply. The increase in population of Nyala and the presently lower rainfall require, however, that measures are being taken to protect the quantity and quality of the water resources at Nyala. It is recommended to implement such measures through the establishment of a water management policy, which is described in chapter 10.

7. WATER DEMAND

7.1 Domestic Demand

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 x 10^6 m^3 and 2.0 x 10^6 m^3 (table 12), 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 x 10^6 m^3 (table 13), 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 water consumption for domestic and industrial purposes 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 x 10^6 m^3 for 1981, they estimated the total water demand in 1995 at 6.4 x 10^6 m^3 (table 16).

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.

Table 16 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

7.2 Agricultural Demand

The present water consumption by irrigation was estimated in the Town Area at 0.95 x 10^6 m^3 and in the Downstream Area at 0.87 x 10^6 m^3 (see table 15).

In the Town Area an increase 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 controlled to avoid an inefficient use of groundwater for irrigation. This process should be controlled by the Administration. However, water levels are low in dry years, resulting in small saturated thicknesses and hence low well water production rates. The choice of the crop types should take this into account.

8. GROUNDWATER MODEL

8.1 General

A simulation of the alluvial aquifer was carried out, using a groundwater model developed for the project's HP-85 microcomputer by TNO-DGV Institute of Applied Geoscience (Schoute and Swenker, 1984). The model is a finite difference polygonal one aquifer layer model. A description of the model is provided in the Nyala Water Resources Study, Final Report (WAPS-2, 1985).

The objectives to use a groundwater model were:

- 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.

Two models were designed, covering:

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

The lay-out of the models is shown in figure 12.

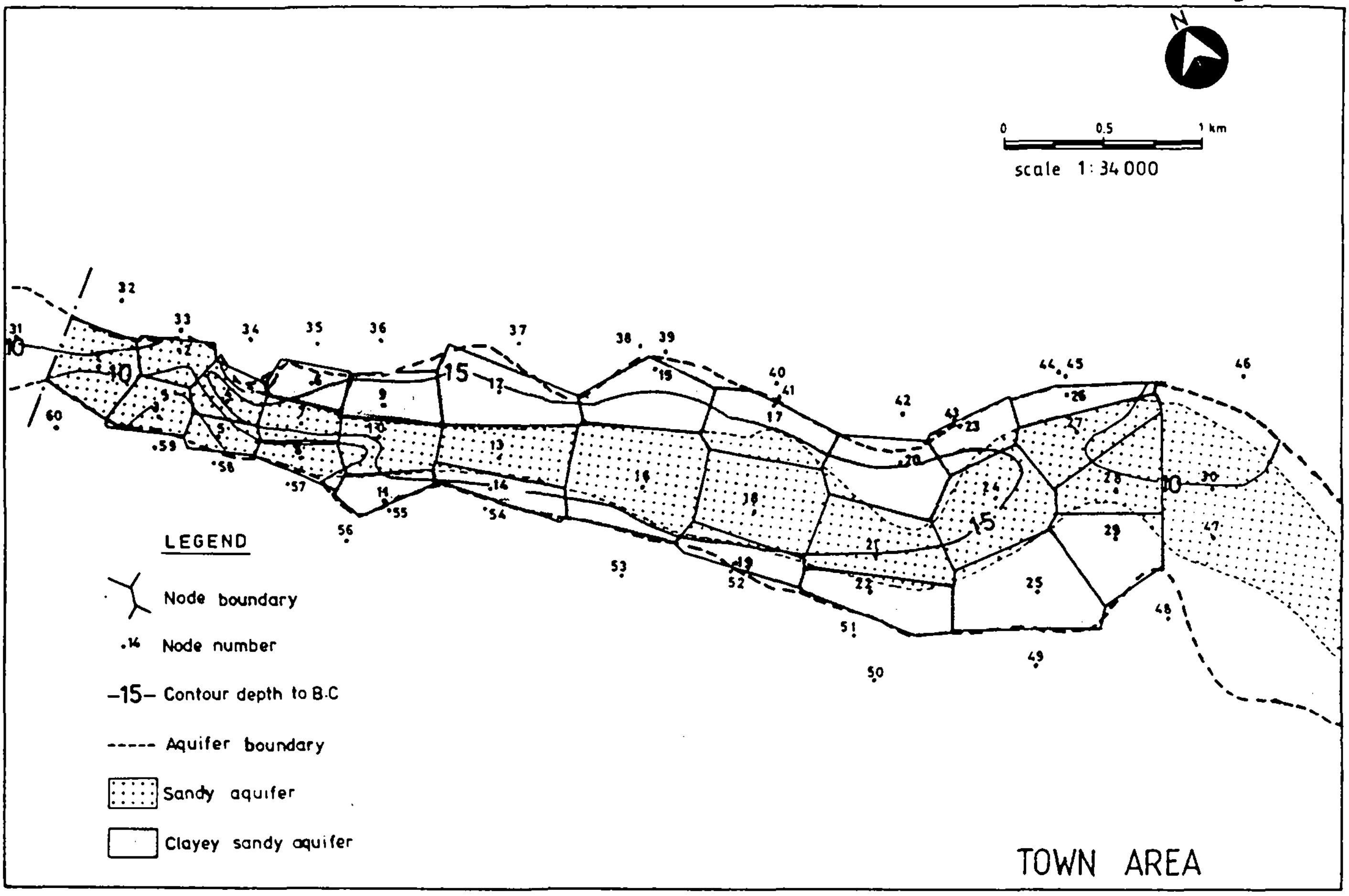
After calibration of the models, development runs were made to analyse the effect on the groundwater levels and groundwater storage of increased pumping for the town water supply.

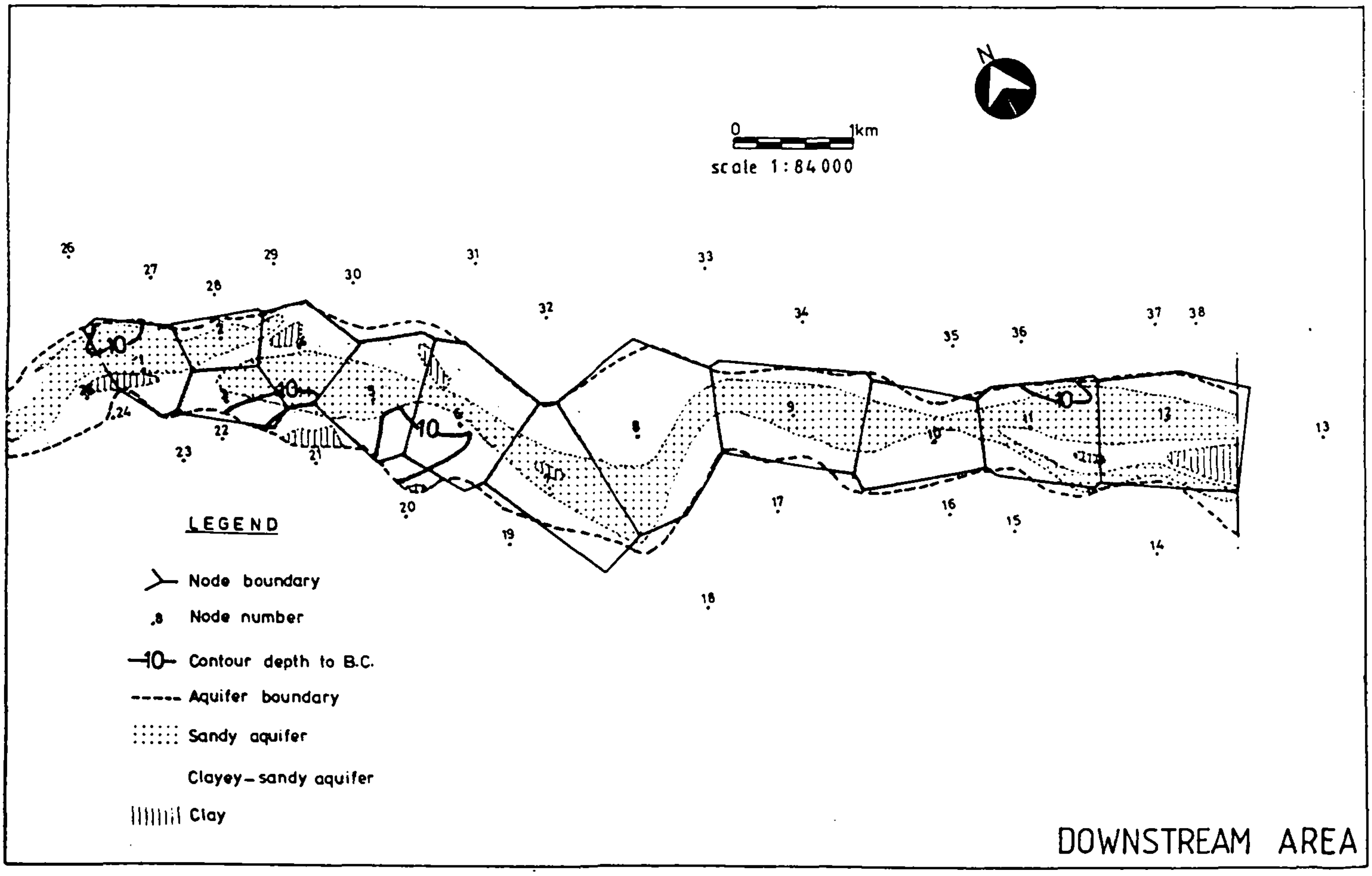
8.2 Town Area Model

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.

GROUNDWATER MODELS

Figure 12





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 volume of each of these discharge/recharge components was estimated based on calculations included in the Nyala Water Resources Study, Final 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 rainy season months. This simulates the quick recovery of the groundwater table in the wadi, within one month after surface runoff has started.

The possibility of increasing the groundwater abstraction for the town water supply was analysed with the groundwater model. Six development options were designed, increasing the pump capacity stepwise from the 1984-level of 1.4×10^6 m^3 to maximum 4.0×10^6 m^3/year.

The abstraction of the groundwater was assumed to take place from:

- the presently pumped wells BH 2, BH 3, BH 6, BH 7, BH 14, BH 15 and BH 30;
- the presently not used wells BH 23 and BH 31 (BH 23 might have to be replaced by a new well at the same location);
- an additional 11 new wells.

The possible locations of the new wells are indicated in figure 13. The six development options each require an increasing number of wells (see table 17). The maximum pump capacity from

GROUNDWATER DEVELOPMENT IN TOWN AREA- LOCATION OF NEW BOREHOLES.

Figure 13

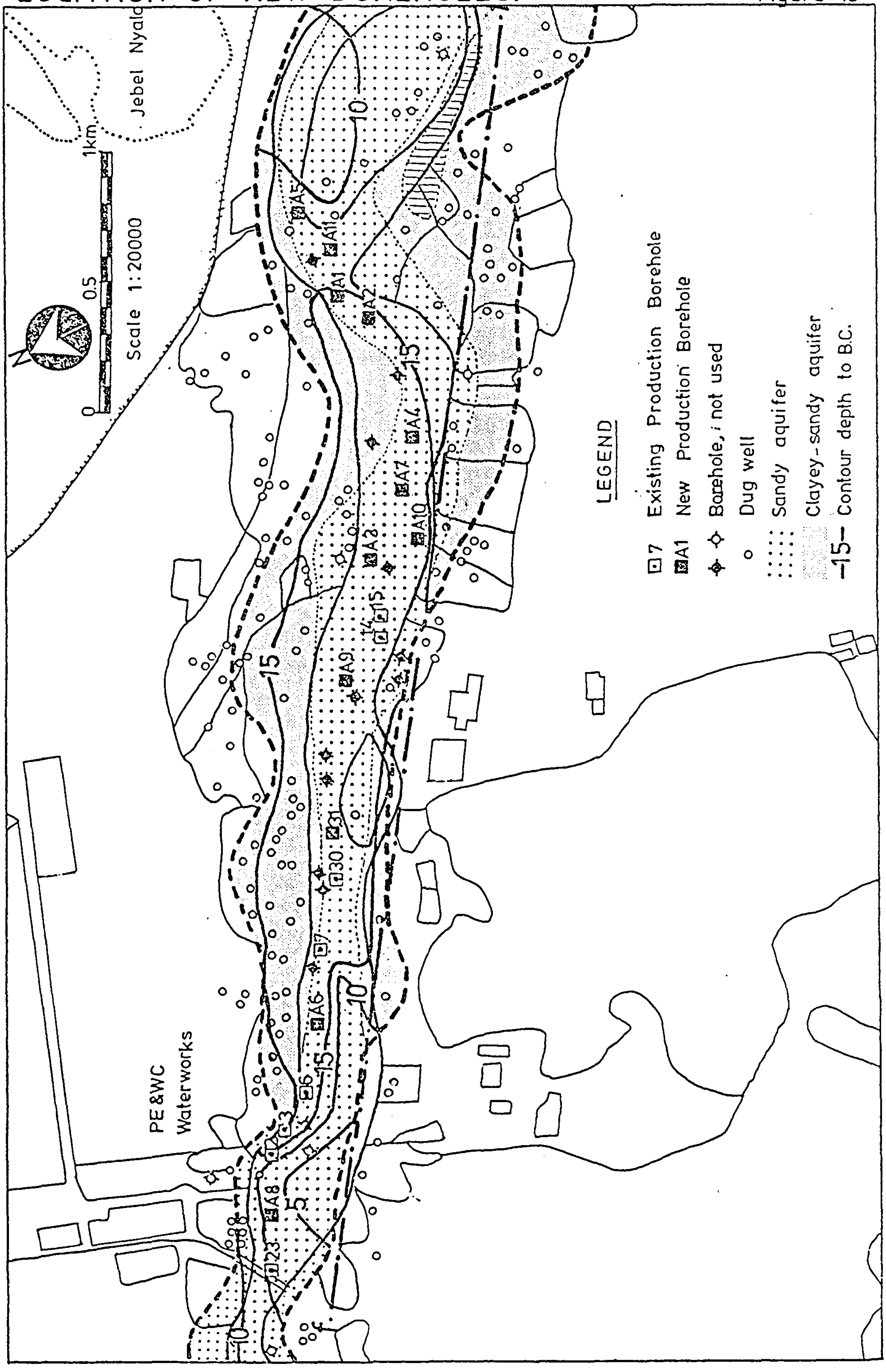


Table 17 Description of Town Area Development Options

- **Option 1**
  The existing boreholes are pumped to their full capacity
  450 m³/day: BH 23 (or new), BH 3
  725 m³/day: BH 2, BH 6, BH 7, BH 30, BH 14 and BH 15
  The concentration of wells at the Town Wells site causes excessive drawdowns, and pumping has to be interrupted regularly after April.

- **Option 2**
  Two new boreholes are added and pumping from the existing boreholes is reduced.
  400 m³/day: BH 23, BH 2, BH 3 and A 1
  625 m³/day: BH 6, BH 7, BH 30, BH 14, BH 15 and A 2
  The drawdowns are acceptable and even after a dry year pumping does not have to be interrupted.

- **Option 3**
  Five new boreholes
  400 m³/day: BH 23, BH 2, BH 3, A 1 and A 5
  475 m³/day: A 3
  625 m³/day: BH 6, BH 7, BH 30, BH 14, BH 15, A 2 and A 4
  Efficient use of the groundwater resources; after a dry year pumping does not need to be interrupted.

- **Option 4**
  Six new boreholes
  400 m³/day: BH 23, BH 2, BH 3, A1 and A 6
  500 m³/day: BH 30 and A 3
  625 m³/day: BH 6, BH 7, BH 31, BH 14, BH 15, A 2, A 4 and A 5
  After a dry year pumping has to be interrupted at the Town Wells due to excessive drawdowns; reduction in pump yield, however, is small.

- **Option 5**
  Ten new boreholes
  300 m³/day: A 10
  400 m³/day: BH 23, BH 2, BH 3, A 1, A 7, A 8 and A 9
  500 m³/day: BH 30, BH 14 and A 3
  625 m³/day: BH 6, BH 7, BH 31, BH 15, A 2, A 4, A 5 and A 6
  The drawdown in the Town Wells area leads to a reduction in total pump yield after a dry year.

- **Option 6**
  Eleven new boreholes
  400 m³/day: BH 23, BH 2, BH 3, A 1 and A 8
  500 m³/day: BH 30, A 3 and A 10
  625 m³/day: BH 6, BH 7, BH 31, BH 14, BH 15, A 2, A 4, A 5, A 6, A 7, A 9 and A 11
  In a year with average rainfall the total pump yield can be achieved but after a dry year the water supply to the town is expected to be severely disrupted from April until June.

one borehole was determinded at 30 to 35 m³/hour, providing a total daily production of 625 m³ for on average 20 hours pumping per day.
Other groundwater requirements (for irrigation etc.) were kept unchanged from the present situation.
The simulation of the development options was run for 20 months, comprising the conditions of an average year and of a dry year. A summary of the results is provided in table 17. A short description of the development options is given in table 18.

A discussion of the results of the simulation of the development options is included in chapter 9.

Table 18 Summary of Simulation Results, Town Area

Development Option	Required Exploitation Rate (10^6 m³/ year)	Number of Wells		Average year	Dry year	Minimum
		Old	New	Actual Exploitation Rate (10^6 m³)	Actual Exploitation Rate (10^6 m³)	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.

8.3 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 km². 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. The simulated period was therefore restricted 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.

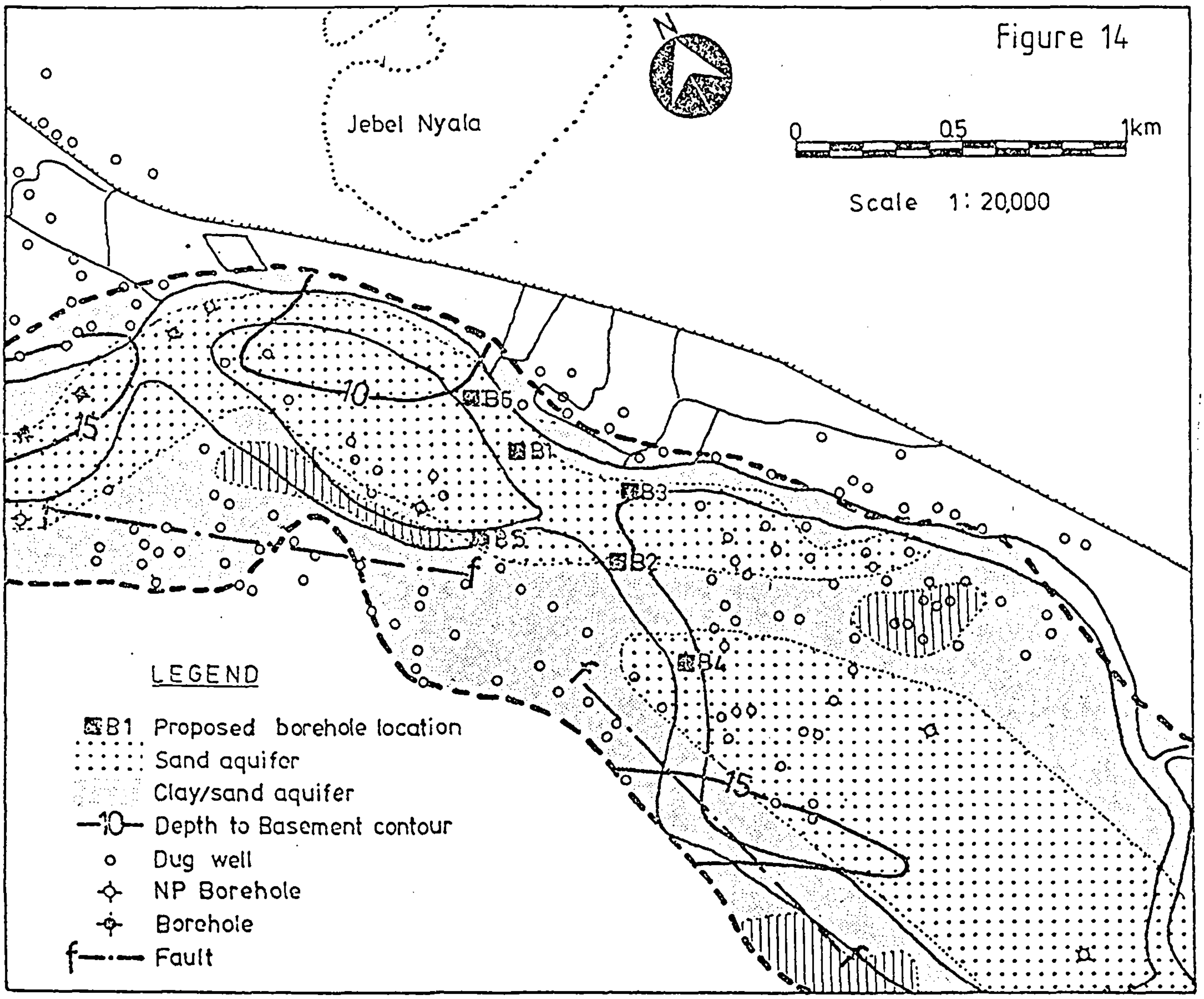
The pumptests in the area did not show a significant difference in results with those in the Town Area. However, from water balance analysis it appeared that a lower estimate of S should be used (see chapter 4):

- 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 by introducing an additional annual abstraction of 750 000 m³, was simulated with the model. To achieve this quantity six boreholes with an average capacity of 20 m³/hour will be necessary (see figure 14). Also after a dry year the same quantity may be abstracted.

A proper calibration of the Downstream Area model could not be carried out. The simulation of several different development options was therefore not relevant.

GROUNDWATER DEVELOPMENT IN DOWNSTREAM AREA-LOCATION OF NEW BOREHOLES.



9. FUTURE GROUNDWATER DEVELOPMENT

9.1 Available Resources Town Area

The simulation of the development options shows that any increase in groundwater exploitation in the Town Area should be planned in the downstream part of this area. The area of the Town Wells contains almost its maximum number of wells.

A maximum production of 4.0×10^6 m^3 for domestic use 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 is 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. The infiltration required at maximum development of the Town Area aquifer is 5.5×10^6 m^3 (see option 6). This is a minimum, because it creates the dry year conditions as simulated. For average conditions an infiltration of about 6.2×10^6 m^3 is required. Considering the large flood volumes observed in 1983 and 1984, this infiltration will probably be achieved. However, in the event of a dry year the infiltration might be insufficient for full replenishment of the aquifer.

The drawdown caused by the increased pumping from deep boreholes in the wadi, will effect 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 (2.5×10^6 m^3 pump capacity) will entail an extra drawdown of about 2 metres in the garden area. Under full development (4.0×10^6 m^3 pump capacity) the extra drawdown can be about 4.5 metres. 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.

9.2 Available Resources Downstream Area

The Downstream Area does not contain large resources for the town water supply of Nyala. At present it seems possible only to pump an additional 750 000 m^3 in the area upstream of Kundua forest.
Further downstream in the aquifer the saturated thickness is too small, especially after a dry year. This is due to the large groundwater losses by the consumptive use of the forest, but possibly also by groundwater flow into fractures in the underlying Basement.*

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 town water supply.
However, the resources could be used for increased agricultural development.

* 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 than some exploitable water may be stored in this zone. However, the quantification of this water was not possible, because the drilling facilities of the project did not allow this to be verified.

9.3 Groundwater Development Potential

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.

Small groundwater resources exist in areas outside Nyala (upstream at Romalia and east of Jebel Nyala at Buldanga). But it is not feasible to use water from these areas 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 for irrigation 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 the number of boreholes has been increased only in recent years. 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: 25 to 50 m^3/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.

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 19, for a total groundwater production of 2.0 to 4.0 x 10^6 m^3/year.

The pump yield from one borehole should not exceed 30 to 35 m^3/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.
- 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. 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 metres.
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

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 can be considered as the process that guides the equilibrium between water demand, natural water resources by means of technical and administrative measures (legislation, fees, etc.).
Water management is required because of the limited groundwater resources and the lack of alternatives. Pollution (waterborne diseases) and overuse of water (dry wells, loss of investments) are considered to be serious risks.
For both quantity (efficient use) and quality (protection) the (ground)water system should be carefully monitored and actions may be required. The realization of these actions may be done by policy makers (e.g. Regional Water Authorities) and technical advisors (Technical Committee) through legal provisions (Water Act).

The establishment of such authorities should be considered as a logical continuation of water resources assessment studies, as future and possible fuller development of the water resources requires an increased management of these resources.
The authorities should be technically advised by a Technical Committee, whose members should be qualified and experienced groundwater specialists.

A legal basis is required for an executive water management body with authorative 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, as well as the financial aspects involved. An example of a Water Act (adapted from the Kassala Gash Basin) is given in annex 3.

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

In order to provide the Regional Water Authority with the required information for a sound water management, 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.

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ANNEX 1 NYALA RAINFALL DATA

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	93.3	----	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

ANNEX 2

BOREHOLE INVENTORY SUMMARY - WADI NYALA

Borehole No. Nyala	Borehole No. NWC Kht	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
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

ANNEX 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	

ANNEX 3

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.