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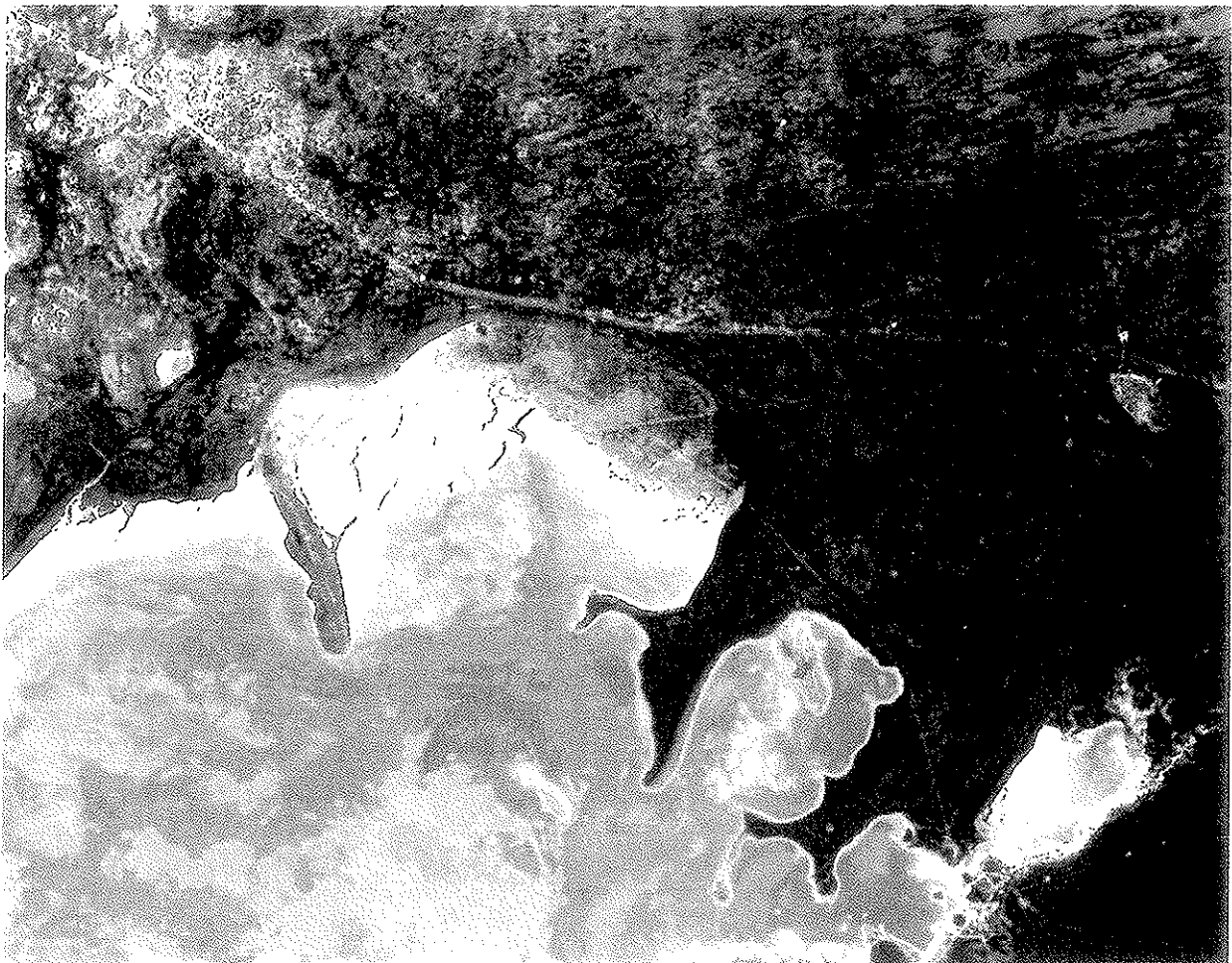
BRITISH GEOLOGICAL SURVEY  
Natural Environment Research Council

TECHNICAL REPORT WD/94/8R  
Hydrogeology Series

Technical Report WD/94/8R

Feasibility Study for Drought Relief Drilling  
in S E Owambo, Namibia

C S Cheney  
[This report was prepared for the Overseas Development Administration]



*Part of the Landsat MSS Image of Etosha Pan*

Bibliographic Reference

Author: C S Cheney, Feasibility Study for Drought Relief Drilling in S E Owambo, Namibia. BGS Report No. WD/94/8R

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## EXECUTIVE SUMMARY

This study has carried out a review of all relevant geological and hydrogeological information for southeastern Owambo around the study area defined in the TOR. General environmental topics in addition to socio-economic factors have also be reviewed in some detail.

Until Independence the study area was very sparsely populated having largely been covered by an exclusion zone used for military training. Since Independence a considerable number of people have moved into the area. Clearance for dryland subsistence farming is spreading with time and will probably, lacking rigid control over land use, eventually cover the entire area. At present the population is dispersed and low density in nature but the area is already heavily overgrazed by migratory cattle herds.

An aquifer of considerable areal extent which contains potable water has been identified as existing beneath the area of interest. The aquifer is in the Kalahari Sequence, position close to the contact between the Andoni and Olukunda formations, sandwiched between saline aquifers above and below. Little is currently known about this relatively thin, confined, low-yielding aquifer or about the effect of faulting upon the aquifer. It has however been subject to limited exploitation for drought relief and it is considered that more extensive use could be made should drought recur in the future, although in view of the possible "fragile" nature of the aquifer caution should be exercised. Limited investigation of the aquifer involving drilling and aquifer testing is recommended as a form of preparedness for future drought conditions.

Development of the much deeper potential Karoo aquifer, although highly speculative, is also considered in the light of a pressing requirement for additional water supplies to input into the southern end of the Owambo pipeline supply. Although most available information shows the aquifer to be saline some indications exist of a possible fresh water aquifer which, if yields are high, may be of use. Further investigation by geophysically logging existing boreholes which penetrate the Karoo is recommended. Exploratory drilling should only follow if the presence of fresher water can be demonstrated.

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## 1. INTRODUCTION

In mid-1992 it was recognised that an area of southern Owambo, centred to the north east of Etosha Pan, was suffering seriously from the effects of prolonged drought. A rapid field investigation was carried out by the Department of Water Affairs, during which the scale of the problem was identified and all possible remedial solutions were considered. It was concluded that the only feasible course of action was to utilise, (at that time unidentified) groundwater resources. A project proposal was drawn up for the drilling of ten boreholes within the affected area, to be sited by the use of geophysics. The suggested boundaries of the project area are included in Figures 1 and 2. A request for drought relief assistance to carry out the drilling project was thereafter submitted to the British High Commission by the Department of Water Affairs via the Ministry of Agriculture, Water and Rural Development.

Doubts were expressed concerning the feasibility of such a project, in terms of general adverse environmental effects as well as the long term viability of the groundwater resource, in respect of both quantity and salinity, as well as the effect which utilisation may have on the artesian boreholes and springs located nearby on the northern fringes of Etosha National Game Park. Following a field visit to the area by Dr C West (Environmental Field Manager) early in 1993, the British Geological Survey (BGS) were requested to provide hydrogeological and related advice on the various issues of concern. After an initial meeting at Overseas Development Administration (ODA), terms of reference for a feasibility study, based on the project document, were drawn up and submitted for approval. The TOR is contained in Appendix 1.

Although the drought ended before a visit to Namibia could be arranged, it was decided that the study should proceed as it would provide an in-depth basis of preparedness for drought which will undoubtedly affect the area in the future. A visit to Namibia to collect relevant data, discuss hydrogeological and environmental aspects of the study area with local experts and visit the study area was arranged for October 1993 to coincide with the end of the winter dry season.

The visit itinerary is contained in Appendix 2.

## 2. PHYSIOGRAPHY

### 2.1 Topography and Drainage

The study area lies within an extremely flat plain extending to the north of Etosha Pan. Elevations rise gently to the north east from about 1100 m AMSL in the south, to a maximum of about 1130 m AMSL in the north east (Figure 2).

Drainage in the centre of the area is, in common with the much more extensive oshana drainage to the west, southward towards Etosha Pan. The upper course of the Amazulau River and its tributaries follow an east north east trend heavily influenced by the orientation of the parallel stabilised dune ridges present in the eastern half of the study area. Pans are found predominantly along the southern and eastern margins of the study area. Drainage courses are commonly poorly defined,





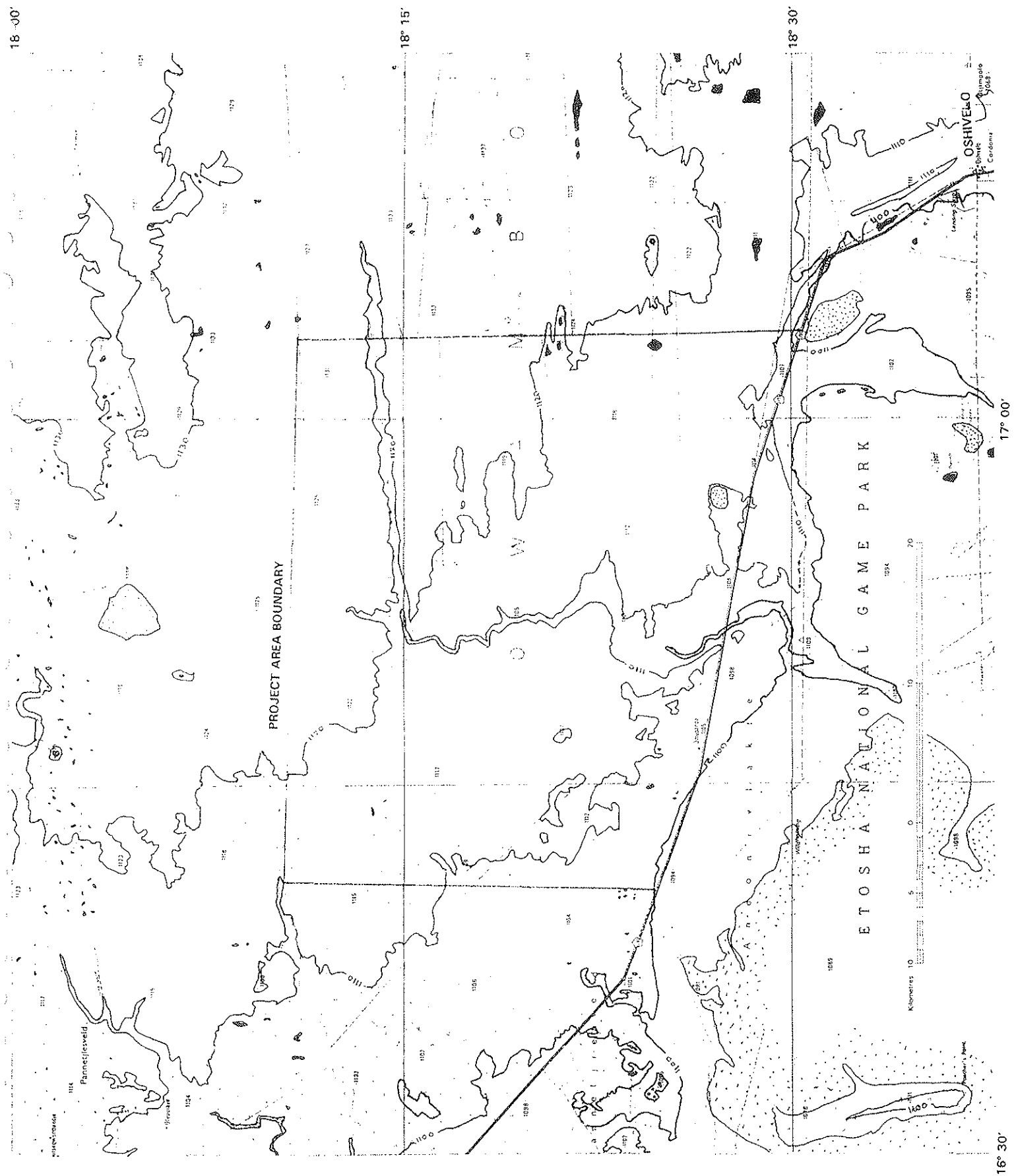


Figure 2 Topography and drainage.

often consisting of a linear depression in the otherwise flat landscape, marked by a line of more dense vegetation and large trees. River flow is distinctly ephemeral and, although marshy areas and pools of standing water may develop on the valley floors during the wet season, flow occurs only infrequently.

## 2.2 Climate

The area lies within a zone defined as possessing a hot dry steppe climate, according to the Kloppen Classification (van der Merwe, 1983).

### 2.2.1 Rainfall

No rainfall records are available for any location within the study area but long term records are available for Ondangwa (1909-1985) to the north west and Namutoni (1914-1993) to the south. Long term average monthly and annual rainfall for the two locations are provided in Table 1.

In general terms rainfall increases from west to east in this part of Namibia and in consequence it is considered that rainfall in the study area is likely to be most similar to that recorded at Namutoni. The average deviation from annual average rainfall in the area is between 30 and 35%. Over 90% of the total rainfall falls during the summer months between October and March (van der Merwe, 1983).

### 2.2.2 Temperature

Long term temperature data is available for Ondangwa (1944-1985) (Table 2). The highest average temperatures, (exceeding 34°C), were recorded immediately prior to the onset of the rainy season. The lowest temperatures occur during the winter months between May and August; temperatures occasionally fall below zero at night causing frost. As can be seen from Table 2 a considerable diurnal temperature gradient exists over much of the year and is particularly pronounced during the winter months.

### 2.2.3 Humidity

Humidity is greatest during the wet summer season with daily averages commonly exceeding 60%. Humidity declines during the course of the winter dry season to attain a minimum of about 27% in September immediately prior to the onset of the wet season, during which average daily humidity rapidly rises. Within this seasonal pattern, diurnal variations may be considerable; in excess of 30% at times during the wet season and 20% during the dry season.

### 2.2.4 Wind

The prevailing wind direction is from the north east veering predominantly between north and south east. The average velocity is in the range of 3 to 6 m/s (van der Merwe, 1983).

**Table 1. Mean rainfall data (in mm) for Namutoni and Ondangwa**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Namutoni	95.7	106.3	77.3	25.9	2.1	0.7	0.0	0.2	1.6	13.6	43.7	68.5	433.8
Ondangwa	109.3	117.5	91.5	33.9	2.9	0.6	0.1	0.0	2.1	12.7	46.6	76.2	493.4

**Table 2. Temperature data for Ondangwa**

MONTH	TEMPERATURE (°C)		
	Means of:		
	Daily Maximum	Daily Minimum	Max + Min/2
January	31.8	19.3	25.5
February	30.6	18.9	24.7
March	27.5	18.7	23.2
April	30.5	16.7	23.6
May	28.9	11.9	20.4
June	26.5	8.5	17.5
July	26.8	7.8	17.3
August	29.7	9.7	19.7
September	33.3	13.4	23.3
October	34.5	17.2	25.9
November	33.4	18.7	26.1
December	32.8	18.9	25.9
Annual	30.5	15.0	22.7

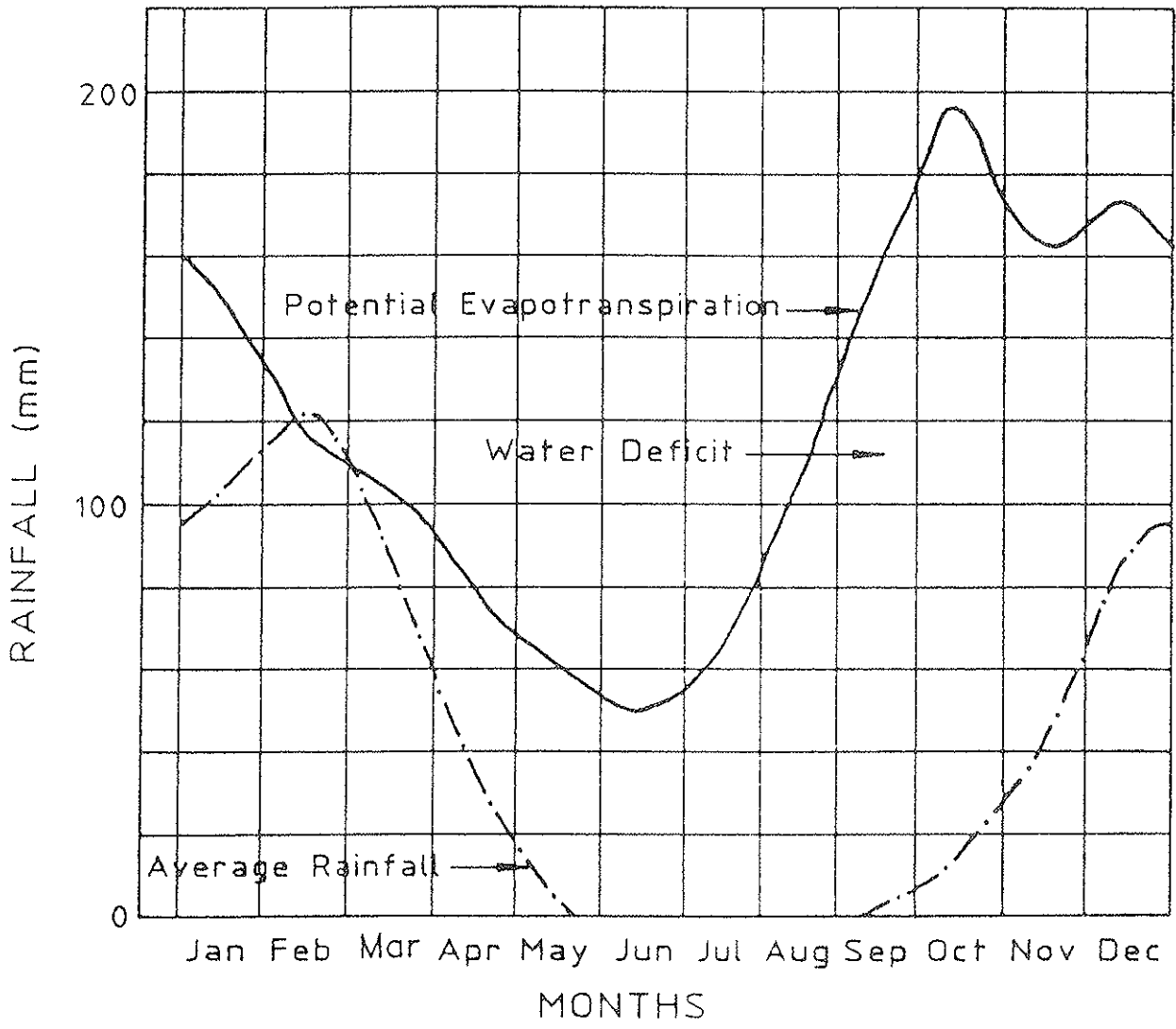


Figure 3 Average rainfall and potential evapotranspiration for Ondangwa. [after Groundwater Consulting Services, 1991]

### 2.2.5 Evapotranspiration

A comparison of potential evapotranspiration and average rainfall for Ondangwa, derived from work carried out by the University of Stellenbosch in 1978 (Ground Water Consultants, 1993) is shown in Figure 3.

The most notable feature of the graph is the very short period (on average) of excess rainfall. A water deficit exists for over eleven months of the year. At first sight this would seem to largely preclude groundwater recharge except in above average rainfall years. The averaging however obscures the intensity of rainfall events. Given the sandy soils and hence rapid infiltration in Owambo, recharge may be more closely related to particularly intense rainfall events. Intense rainfall over a few days would generate a considerable short term excess which could infiltrate and provide groundwater recharge.

## 3. SOCIO-ENVIRONMENTAL

### 3.1 Vegetation

The study area lies within a zone occupied by mixed woodland, the main species being vaalboom and wild seringa with a lesser presence of dolfhout, kiaat and manketti (Department of Water Affairs, 1990). Alternatively van der Merwe (1983) describes the vegetation as consisting of forest savanna and woodlands.

Natural grass cover is moderate but the natural vegetation as a whole has been considerably modified over much of the study area due to the activities of the local population and their livestock, specifically due to overgrazing, bush clearance and the collection of timber for firewood and building. Regeneration of natural vegetation is likely to be very slow due to the often inadequate and unreliable nature of rainfall. More open grass lands are present to the south along the margins of Etosha Pan and in the vicinity of pans within the study area.

### 3.2 Soils

Soils throughout the area are predominantly sandy, being classified as arenosols (van der Merwe, 1983). The sands are generally yellowish in the south, becoming more pale grey to the north and north west. Increased clay contents are likely to be present in the vicinity of pans and along the floors of the ephemeral river valleys.

### 3.3 Demography

#### 3.3.1 Population and Settlement Patterns in Owambo

The study area lies within a much larger area occupied by the Owambo tribal group. The area is occupied by the Ndonga sub-group. The 1991 census provided a population estimate of 615,000, equating to an average population density of 10 persons/km<sup>2</sup> over the entire region. Population is not however evenly distributed and the density may attain 100 persons/km<sup>2</sup> in the central part of the region. Settlement

patterns in Owambo are generally dispersed with few major centres of population located away from the main road traversing the region. Apart from settlements along the line of the main road, where water from a pipeline is available, water supplies have traditionally been obtained from shallow wells dug into a perched fresh or brackish aquifer. In the central part of the region, this has permitted a dispersed settlement pattern, based on a more or less continuous patchwork of cleared areas upon which subsistence dryland farming is carried out. Patches of woodland are only found on areas of higher elevation where presumably soil quality is inferior. Place names frequently apply to an area rather than a particular location although occasionally a few shops and perhaps a school or clinic are found grouped together between the cleared areas. The cleared field areas are defined by bush fences, the materials for which are obtained during the process of clearance. The reserves between the hedges are used for access and are commonly devegetated by livestock.

The study area is rapidly becoming settled in a similar pattern to that which exists to the more populous north and north west. Land tenure is predominantly communal and traditionally headmen would have ruled on the use of available resources including land. It would seem however that this authority has been seriously undermined over a long period of time, leaving little in the way of regulation (Groundwater Consulting Services, 1991). The means by which currently unused land is allocated is unclear and efforts to clarify the situation during a meeting with the Regional Water Committee was not successful.

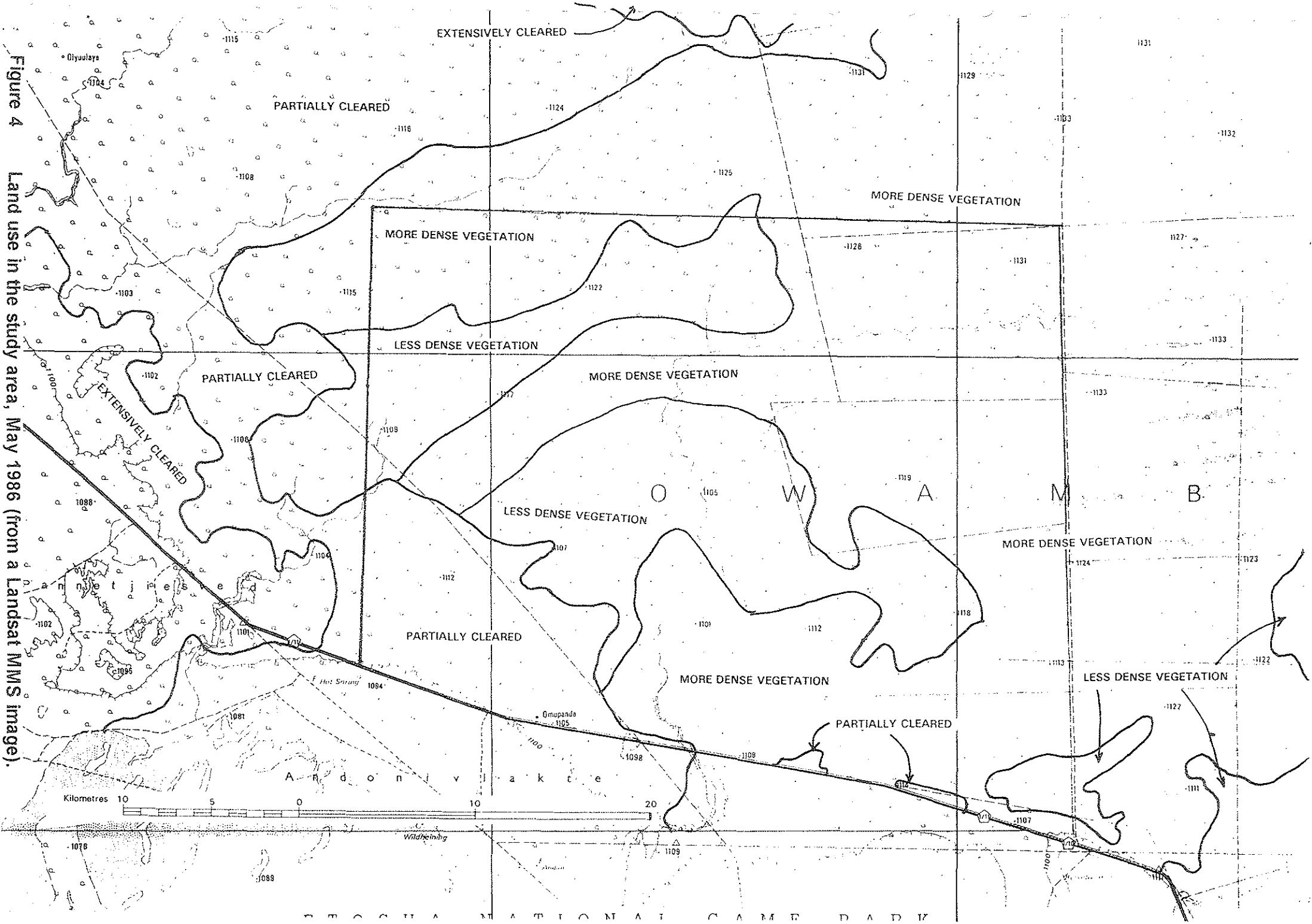
Cattle are apparently kept in the densely populated areas but only during the wet season when grazing and water are available. They are then moved south eastward into the study area before moving northward into Angola when grazing and availability of water deteriorates. The only livestock observed close to settlements at the end of the dry season were goats, donkeys and possibly sheep.

### 3.3.2 Population and Settlement Patterns in the Study Area

In the vicinity of the study area the population density is considerably less than that over much of Owambo. Population density is thought to range from 6-24 persons/km<sup>2</sup> in the vicinity of the main road bordering the southern edge of the area but falling to only 0-5 persons/km<sup>2</sup> over the remainder of the area (Department of Water Affairs, 1990). There are no discernible centres of population within the area, the settlement pattern being highly dispersed. The King Kauluma resettlement camp is located immediately outside the south eastern corner of the area of interest. The camp houses people who have returned to the area since Independence but the total population is not known.

Land use, with specific regard to the degree of land clearance and vegetation thinning, is shown in Figure 4. The distribution was taken from a Landsat MSS image for 10 May 1986. The image unmistakably shows major clearance inroads into the study area from the more densely populated areas to the north and north west, where the natural vegetation has already almost entirely been cleared. The extent of the areas extensively cleared, partially cleared and thinned have undoubtedly expanded considerably since May 1986 but unfortunately a comparable more recent image was

Figure 4 Land use in the study area, May 1986 (from a Landsat MMS image).



not available at the time of writing. Although the image is far too large to be included as part of this report, a much reduced copy of the relevant section of the image has been included on the front cover.

From the presence of ongoing land clearance, observed from the air in October 1993, within the area it would appear that the overall population density is increasing with time due to inward migration from more densely populated areas and "returnees". The original project proposal document reports a population between two and three thousand people to be living in the area which, if the study block is considered to have an area of about 1200 km<sup>2</sup>, is well within the figure which may be expected from the population density quoted above. There were also reported to be "several thousand" head of cattle present in the study area.

The study area is rapidly becoming settled in a similar pattern to that which already exists in the more populous areas to the north and north west. Settlement is spreading predominantly from the north east but also along the line of the main road and along lines of access within the area, such as cut lines and tracks. The area was protected from earlier settlement partially by a lack of access and a considerable section of the area comprised an exclusion zone, used for military training, prior to Independence. In addition the shallow perched aquifer, commonly used elsewhere as the traditional source of water, does not appear to be generally present in the area as will be discussed further in Section 5.1.1. Despite this major limitation it would seem that population pressure combined with the demand for land from "returnees" moving back into the area since Independence, is driving the present expansion of settlement into the area.

The visit to the study area showed that it was extensively overgrazed presumably earlier in the dry season since no herds of cattle were visible. The extensively cleared and partially cleared areas were undoubtedly more extensive than was the case in 1983 and some clearance (apparently recent) was seen to have commenced in previously untouched areas. Some older "hedges" around cleared areas had been replaced by wire fences thereby straightening an original irregular outline and in one location wire fencing had been erected in preference to the bush hedge around an area in which clearance was in progress. A longer straight section of wire fence was observed at one location but appeared to be incomplete and not associated with ongoing clearance. It is entirely possible that further work is intended but the final purpose was unclear.

From observation, the pattern of land clearance within the study area is likely, in the absence of regulation, to continue to spread and may, ultimately, cover the entire area to produce a dispersed community dependent on dryland subsistence farming. Under such circumstances cattle will only be able to graze within the area for very limited periods during the wet season, as is currently the case to the north west. Those areas which have not been cleared for farming will in any case be devegetated by the felling of trees for firewood and the rapacious appetite of goats and sheep.



### **3.4 Water Supply**

#### **3.4.1 Supply in the Owambo Region**

Prior to Independence the responsibility for the establishment, operation and maintenance of water supply infrastructure was divided between the Regional Administration for Owambo and the Department of Water Affairs (DWA). DWA was responsible for the bulk water supply primarily to major centres of population in the region whilst the Regional Administration was responsible for the reticulation of the bulk supply within communities and establishment and maintenance of potable rural water supplies by the use of ephemeral surface water, cisterns, wells and boreholes. A full and highly detailed Regional Master Water Plan for the Owambo Region was completed by the DWA in 1990 but having been prepared predominantly prior to Independence, deals mostly with bulk supplies with only relatively minor consideration of rural water supplies.

At Independence responsibility for rural water supply shifted to the Department of Rural Development and resulted in the re-organisation of the various regional rural water supply sections. More recently responsibility has been transferred to DWA who are, in consequence, in the process of revising the Master Plan to take account of rural water supply.

The current and proposed extensions to the bulk water supply network is shown in Figure 5. The source of supply for the network is located at Calueque upstream of Ruakana on the Cunene River. The headworks are in fact reportedly capable of supplying considerably more water than currently abstracted but the pipeline a short distance into Namibia is incapable of carrying more than the current 1.5 m<sup>3</sup>/sec. Upgrading the pipeline to carry increased quantities of water will be extremely expensive. The construction of a new purification works at Oshakate will, (when complete), ensure an adequate supply for the existing network and planned extensions for the next 15 to 20 years. There are however often difficulties in maintaining an adequate quantity of supply at the outer limits of the system especially during the dry season due to excessive water use and wastage at stock watering points, in addition to occasional intentional breaking of the pipeline to provide "unofficial" stock watering points.

It may be noted from Figure 5 that the pipeline runs south eastward adjacent to the main road but terminates about midway along the southern boundary of the study area, some 60 km short of Oshivelo. There was a tentative proposal to extend the pipeline to Oshivelo to allow the input of groundwater from this location to ease supply difficulties over the southern section of the existing network. This did not however prove feasible since yields and water levels at Oshivelo seem to be declining thereby removing the anticipated water surplus.

#### **3.4.2 Water Supply in the Study Area**

Settlements along the main road already have reasonable access to a potable water from the southernmost end of the pipeline. King Kauluma resettlement camp located



at the south eastern corner of the area is supplied with potable groundwater from recently completed boreholes (Bittner, 1993).

Areas adjacent to the main road between the end of the pipeline and Oshivelo are more sparsely populated as is the majority of the study area. A few wells exist within the area allowing access to shallow groundwater of dubious or brackish quality. The majority of the population undoubtedly have to carry potable water from the nearest source of supply; (Oshivelo, the pipeline or perhaps one of the villages to the north of the area). Ten boreholes were drilled within the area and those with acceptable water quality equipped with handpumps under the Drought Relief Programme in 1992. Two boreholes were equipped with diesel-powered pumps and a further four with handpumps. At least one of the latter provides water of such salinity that it may not even be suitable for stock watering. The current condition of these sources is not known.

Prior to drilling, other solutions to the water shortage had been considered. A branch pipeline was considered inappropriate due to the highly dispersed nature of settlement and consequent lack of a terminal point (a school or clinic). In addition there were already problems in providing an adequate supply to the southern end of the pipeline without creating additional demand. A temporary tanker service was also considered inappropriate due to dispersed nature of settlement, bad roads and distance from the water source which would make such a supply impossible to maintain. It was therefore concluded that groundwater utilisation was the only feasible alternative, although no particular source was identified at that time.

No further work has been done within the area to improve water supplies since the end of the drought since the salinity of the traditional water sources had presumably decreased in response to recharge. The problem of increasing salinity of traditional sources will undoubtedly recur whenever the area is again subject to drought conditions but the consequent problems of finding an alternative supply will have much increased due to the steadily increasing population living in the area. It is therefore deemed highly advisable that a feasible preparedness strategy be drawn up to cope with such an eventuality whenever it occurs. As will be detailed in later sections, in the light of additional information gained during and since the Drought Programme drilling programme, groundwater utilisation is likely to prove the only viable solution.

#### **4. GEOLOGY**

The geology of the Owambo basin, within which the area of interest is located, has been described in considerable detail by Miller (1990) in a Namibia Geological Survey unpublished report. There follows a brief description of the stratigraphy of the Kalahari Beds and the upper section of the bedrock, namely the Cretaceous Nanzi Formation, Karoo Group and Mulden Group. Due to the considerable thickness of Kalahari Beds in the general vicinity of the study area, bedrock stratigraphy is only known from a few very deep boreholes. Strata known to be present at greater depth in the basin will not be discussed in this report as they are unlikely to be feasible drilling targets in terms of groundwater resources. The general stratigraphy is shown in Table 3.

**Table 3. Geology and Stratigraphy (after Groundwater Consulting Services 1992; Miller, 1990)**

Group/ Sequence	Formation	Description	Surface Distribution	Comments	Maximum Thickness (m)
KALAHARI	Andoni	White sand, light green clayey sand, green clay and calcrete	Seen occasionally in road borrow pits and river banks	Seen in numerous boreholes and wells	274
	Olukonda	Medium grained red sand and clay	Borehole intersection only	Seen in many boreholes	120
	Beiseb	Reddish sandstone, argillaceous	Borehole intersection only	Seen in several boreholes	35
-	Nanzi	Red semi-consolidated sandstone, clayey shale	Borehole intersection only	Identified in several drilling programmes	135
KAROO	Prince Albert equivalent	Carbonaceous shale, sandstone, siltstone and low grade coal	Borehole intersection only	Identified in several drilling programmes	221
	Dwyka	Tillite, shale, limestone, etc	Borehole intersection only	Identified in Coal Commission boreholes	158
MULDEN	Owambo	Black, grey and vari-coloured shales with siltstones and sandstones	Borehole intersection only	Identified in Coal Commission boreholes	2600
	Tschudi	Grey sandstones, siltstones and shales	Borehole intersection only	Identified in Coal Commission boreholes	1800

#### **4.1 Mulden Group**

The Mulden Group consists of the lower Tschudi Formation overlain by the Owambo Formation. The Tschudi Formation which may attain a maximum thickness of 1800 m consists of grey sandstones, siltstones and shales with minor conglomerates. The overlying Owambo Formation is only known from boreholes and may attain a total thickness up to 2600 m. The lower horizons consist of grey siltstones with lesser thicknesses of sandstones and shales, only distinguishable from the underlying Tschudi strata by geophysical logs. The grey shales are succeeded by black shales which in turn are overlain by green and grey shales, siltstones, sandstones and vari-coloured shales. The upper horizons contain considerable thicknesses of dolomite, sandstones with shales and siltstones. The uppermost 100 m consists of grey dolomites.

#### **4.2 Karoo Sequence**

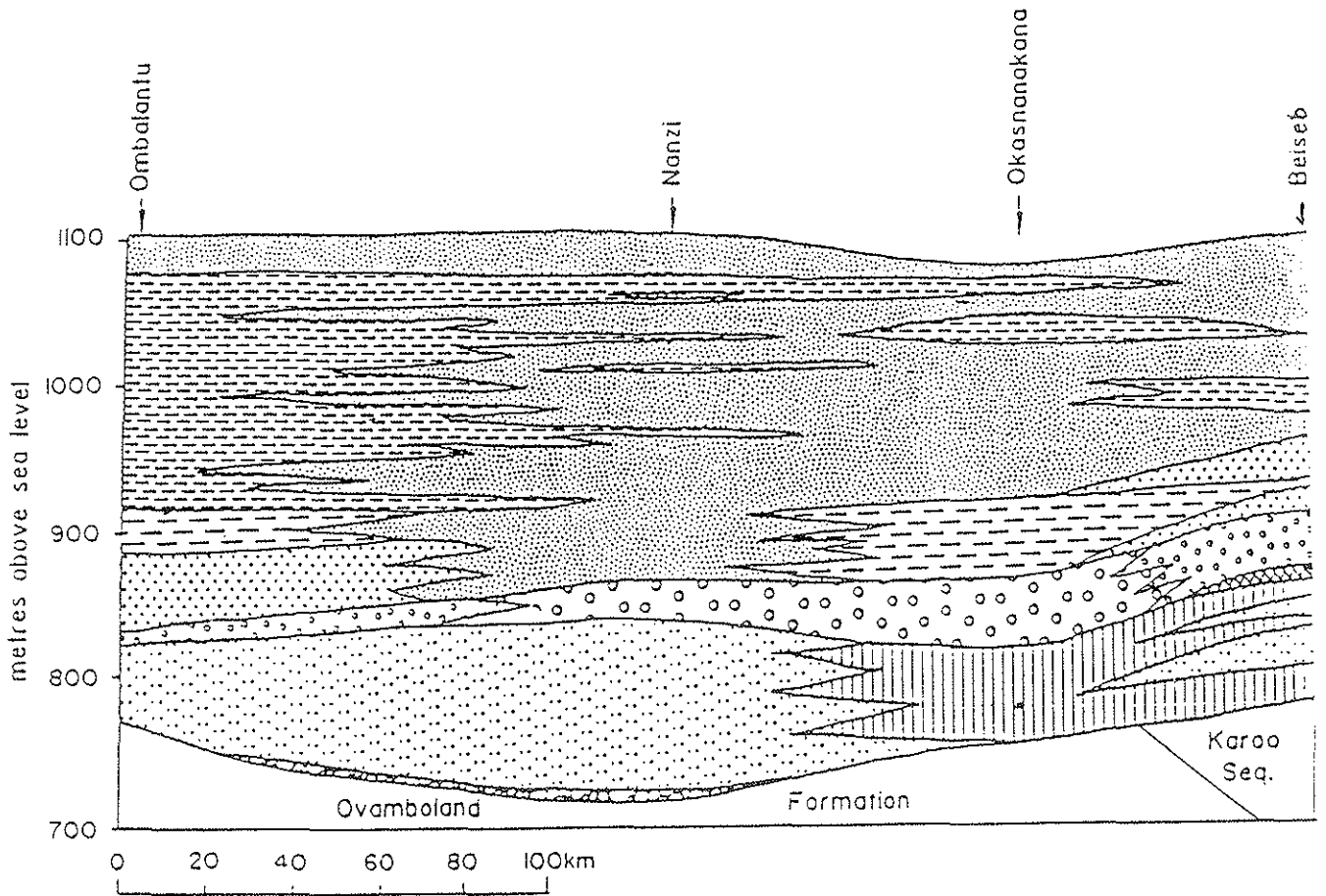
The Dwyka Formation at the base of the sequence consists predominantly of tillites, with thin interbedded shales, dolomitic siltstones, limestones and sandstones. The Dwyka is overlain by strata referred to by Miller (1990) as "equivalent of the Prince Albert Formation" which consists predominantly of black carbonaceous shales in the lower section and alternating dark shales and light to greenish grey fine-grained silty and argillaceous sandstones. The same strata are referred to as the Upper Dwyka Shales by Hugo (1969). The upper part of the sequence consisting of basalts (Etendeka Formation) and aeolian sandstones (Etjo Formation) are not present in the central part of the Owambo basin. The maximum thicknesses attained by the Dwyka and Prince Albert "equivalent"; both of Lower Permian age, are 158 and 221 m respectively.

#### **4.3 Nanzi Formation**











The Nanzi Formation consists of a succession of red well-bedded, semi-consolidated sandstones and clayey shales, which have in the past been classified as part of the Karoo Sequence by Hugo (1969). Miller (1990) was however of the opinion that these strata were neither typically Karoo or Kalahari and suggested that they may be Cretaceous in age.

#### **4.4 Kalahari Sequence**

The Kalahari Sequence ranges in age from Tertiary to Recent and may be divided into three distinct parts; Andoni, Olukonda and Beiseb Formations (Table 3). The inter-relationship and variable nature of the Formations across the Owambo basin as envisioned by Miller (1990) is shown in Figure 6. The eastern part of the section between Okosnanakana and Beiseb is of particular relevance being located immediately to the south of the area of specific interest. The locations of boreholes which penetrate the complete thickness of the Kalahari Sequence is shown in Figure 7.



LEGEND

-  Light green to white calcareous sand, clayey sand, calcrete and dolcrete nodules in places
-  Light green clay, sandy clay, limestone lenses
-  Red clay, sandy clay
-  Red sand, clayey sand
-  Light green to white gritty, conglomeratic sand, locally clayey
-  Red gritty, conglomeratic sand, locally clayey
-  Red semiconsolidated sandstone, calcareous
-  Red slumped shale, with angular sandstone fragments
-  Red shale or clay, sandy in places, local sandstone and limestone lenses
-  Red conglomerate, calcareous, clayey

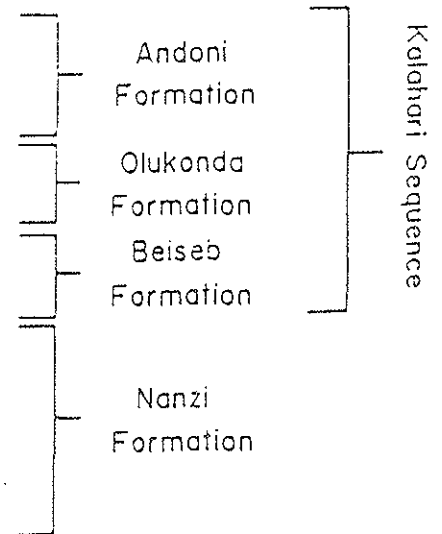
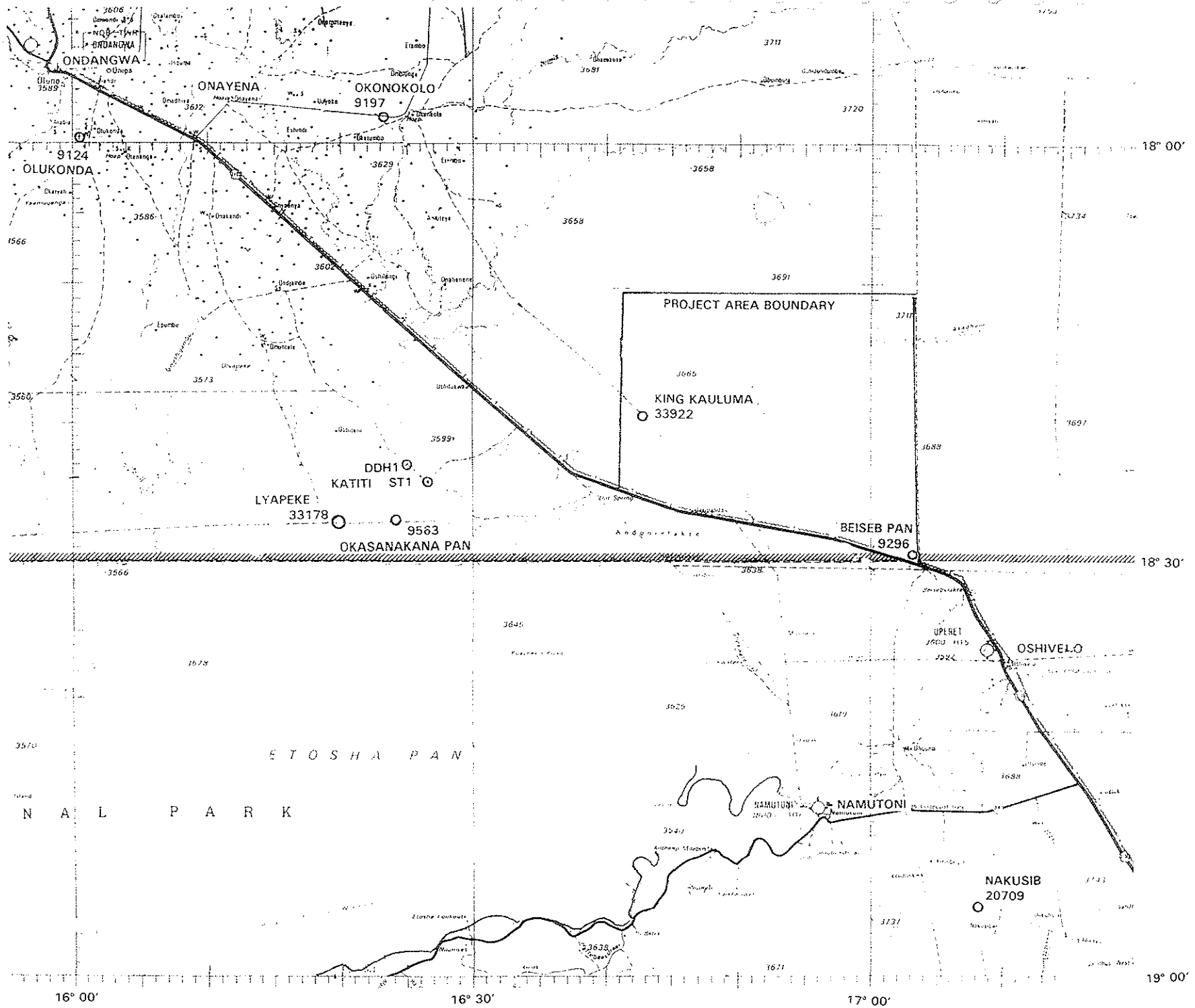


Figure 6 Diagrammatic cross-section of the Kalahari Sequence in the Owambo Basin. [after Miller, 1990]

Figure 7 Locations of boreholes which penetrate the base of the Kalahari Sequence.



#### 4.4.1 The Beiseb Formation

The formation consists of a matrix of fine to medium grained argillaceous sandstone, with clasts of sandstone, mudstone and grey and black chert up to 12 cm in diameter. The sandstone may be calcareous or dolomitic and may be very hard where well-cemented by calcrete or silcrete. The coloration is generally reddish but a predominance of light green to white was noted in the Nanzi and Okosnanakana boreholes.

#### 4.4.2 The Olukonda Formation

The Formation is described by Miller (1990) as consisting of a friable, poorly consolidated reddish brown, poorly sorted massive sand and sandstone up to 120 m thick. Dark red clay may be present towards the top of the Formation. The Formation has a limited distribution within the Owambo Basin as a whole, but appears to be present beneath the whole of the study area and to the northwest where it has frequently been penetrated beneath the overlying Andoni Formation. Boreholes drilled within the study area and to the north west commonly do not penetrate the Olukonda to any great depth and generally record the strata as consisting of clays and sandy clays, sometimes with minor sands or sandstones. Only one borehole (33922) penetrated the complete thickness of the Olukonda which was 85 m thick and underlain by about 40 m of probable Beiseb Formation. The two formations at this locality have a very similar stratigraphy and to some extent colouring and a precise boundary between the two is difficult to define.

#### 4.4.3 The Andoni Formation

The Andoni Formation occurs throughout the Owambo Basin and has been penetrated by numerous boreholes and wells in the vicinity of and within the study area. The majority of these boreholes are too shallow to penetrate the base of the formation. The Formation consists of interbedded white medium grained sand, light greenish clayey sand and green clay.

In the Oshivelo area (Hoad, 1992) and at King Kauluma it has been noted that a clay horizon of significant thickness overlies calcretised sands at the bottom of the formation. Similar stratigraphic conditions have also been found in several boreholes drilled through the base of the Andoni within the study area. This feature is of considerable importance when considering the hydrogeology of the area as well be discussed further in Section 5.1.3. In boreholes penetrating the base of the Andoni at Onayena some distance to the north of the study area (Figure 7), a very hard well-cemented sandstone about 7 m thick was encountered overlying a thin sand (about 1 m) at the base of the Andoni. Similar conditions were found at Okankolo some distance to the east but the borehole was terminated in the softer water-bearing horizon without penetration of the Olukonda which is thought to be immediately below.

#### 4.4.4 Recent Deposits

A veneer of Recent deposits exists over most of the study area, consisting predominantly of reworked Andoni deposits and are therefore effectively



indistinguishable from them. In the east of the area Recent deposits consist of red brown aeolian sands in the form of parallel linear stabilised dunes orientated in an east-west direction.

#### **4.5 Etosha Pan**

Etosha is by far the largest of the numerous pans which occur in the Owambo Basin, covering some 7,000 km<sup>2</sup>. Historically the pan would have been very much larger than at present and would probably have ranked as sixth or seventh largest lake in the world. The size of the lake shrank in stages as the amount of water entering the basin diminished, due to headwater capture of the rivers supplying the area, notably the Cunene which now drains to the Atlantic. Climatic changes may also have reduced the quantities of water entering the system via the remaining rivers.

As the pan lies to the south of the immediate area of interest its origins and formation will not be discussed at length here. The matter is discussed in detail by Marsh and Seely (1992), Groundwater Consulting Services (1992) and Miller (1990). It should however be noted that the study area was almost certainly affected by a relatively recent higher pan level at an elevation of 1120-1130 m AMSL to which the current salinity of shallow groundwater is attributed. This subject will be discussed in more detail in Section 5.1.2.

#### **4.6 Lineaments and Faults**

Interpretation of the Landsat MSS image showed consistent patterns of linear features throughout the whole image. The lineations were most clear in the south and west where outcrop occurs and become less marked to the north where Kalahari strata are present. Two main lineament pairs were detectable; ENE/NNW and NE/NW. Some variations are seen in places especially in the area of interest where NNE trends are also observed. The correspondence of these linear trends with pan margins particularly Etosha Pan suggest that many lineations are faults cutting the Kalahari Sequence. A similar analysis carried out by GCS (1991) also concluded that the lineations were the surface expression of faults. There has been little comment regarding the precise effect of these faults particularly the relative displacement of the Kalahari strata. Borehole data over much of the area is far too sparse and the lithology of the Kalahari Sequence too variable for stratigraphy thus obtained to provide substantial assistance. The Kalahari has however undoubtedly been affected by faulting which caused displacement of strata across fault lines. Fault lines can be shown to be associated with springs along the margin of Etosha Pan and may act as conduits for saline and possibly fresh water (GCS, 1992). Fault bounded blocks may act as isolated aquifer sections, cut off from any source of recharge.

Bedrock may also be affected by the same faults but given the sparsity of borehole data this is impossible to assess. Hugo (1969), using a combination of seismic profiling and other geophysical data, together with deep borehole data determined that a major bedrock fault coincided with longitude 16°15' east. This fault constituted the western boundary of a downfaulted trough about 50 miles wide. The southern margin of the downfaulted block is also a fault, coinciding approximately with latitude 18°30' south. The trough is tilted, decreasing in depth in a northerly direction, probably

disappearing to the north of borehole 9179 at Okonkolo. Karoo strata is present beneath the Kalahari Sequence and Nanzi formation within the bounds of the trough but apparently absent both to the east and west of the trough where the Owambo Formation directly underlies the Kalahari Sequence and Nanzi Formation.

## **5. HYDROGEOLOGY**

The following hydrogeological description will be oriented towards the study area but will, of necessity, draw on extensive information obtained from drilling and testing programmes in adjacent areas. A number of aquifers are present beneath the area. The aquifers are predominantly saline but some relatively fresh water also exists. Most information is available for the relatively shallow aquifers and for clarity the various aquifer horizons will be discussed by order of depth from surface.

### **5.1 The Andoni Formation**

The Andoni Formation constitutes a widespread shallow aquifer over much of the Owambo region. A detailed study carried out on this aquifer in central Owambo by GCS (1991) found that there were two relatively shallow aquifers present, referred to as the "discontinuous perched aquifer" (DPA) and the "main shallow aquifer" (MSA). In addition recent work appears to show the widespread presence of a further aquifer positioned at or close to the base of the Andoni Formation.

#### **5.1.1 The Discontinuous Perched Aquifer**

This aquifer provides the main traditional source of water for the rural population of central Owambo. As the name suggests the aquifer is perched above the MSA possibly by a harder better cemented sand or clay horizon or may simply consist of a fresh water lens lying above but in contact with the MSA. These perched aquifers are not laterally extensive and are only capable of providing small quantities of water over limited periods. Shallow hand dug wells are usually used to obtain water from this aquifer which are sustained by annual recharge events. Wells frequently dry or become progressively more saline as the dry season progresses. The water from this source is highly susceptible to contamination and water quality often changes dramatically over very short distances. GCS (1991) concluded that the DPA exists predominantly in central Owambo but was not generally present in eastern Owambo. The possibility does however remain that shallow relatively fresh perched aquifers may occur within the study area wherever local recharge is capable of sustaining them, possibly in the vicinity of pans and associated with river valleys.

#### **5.1.2 The Main Shallow Aquifer**

This aquifer has been penetrated by many boreholes and innumerable wells throughout the Owambo region; although, until very recently, none were located within the area of interest. Boreholes penetrating the Andoni formation had however been drilled at a number of adjacent locations (such as King Kauluma camp, along the line of the main road and margin of Etosha Pan to the south), although little information existed to the north and east. Few of these boreholes provided detailed geological

information. Fortunately a number of boreholes were drilled within and to the northwest and east of the study area during 1993 as part of the Drought Relief Programme which did provide detailed geological logs.

Aquifer conditions vary markedly across the region. The aquifer is multi-layered but most wells and shallow boreholes only penetrate the uppermost water table section of the aquifer, which commonly lies between a few metres and 20 meters of ground surface. Deeper boreholes have shown that confined conditions exist at depth within the Formation. Sand, gravel or broken calcretised horizons act as aquifer horizons confined by well cemented or clay horizons. It is probable that many of these horizons vary laterally and may, in many cases, only constitute a very localised feature. The possibility also exists that block faulting affecting the Kalahari sequence may completely isolate sections of the confined aquifer creating locally anomalous conditions. More extensive confined sections of the aquifer do however exist, for example on the northern margin of Etosha Pan where the degree of confinement causes overflowing artesian conditions. A number of springs are also present along the northern margin of the pan, apparently associated with faults which may penetrate these deeper confined aquifers. Lower salinity springs, used by wildlife, are likely to be associated with a local perched fresh water aquifer although some contribution from the deeper saline aquifer may be present.

Regional groundwater gradients decline from the north towards Etosha Pan (GCS, 1991) although the presence of a multi-layer aquifer system and localised perched aquifers makes the detailed picture more confused, with local highs and lows superimposed on the regional trend. Although comparatively little information is available, the groundwater table would also appear to decline from the east towards Etosha Pan.

Water quality of the Main Shallow Aquifer over the whole of central Owambo is invariably saline and non-potable. Total dissolved solids in the centre of the basin exceed 20,000 mg/l but decline to the northeast and east, falling to below 5000 mg/l and becoming potable in the extreme northeast and east of the region (Figure 8). The transition zone over the range 2000 to 5000 mg/l occurs over a surprisingly narrow zone, the upper limit of this range having been taken by GCS (1993) to be the maximum salinity at which groundwater was usable. Figure 8 shows the study area to be located close to this transition zone which lies to the northeast and east. The position of the transition zone was noted by GCS (1991) to correspond remarkably closely to the 1120 to 1130 m contour interval. It was therefore postulated that the shoreline of the maximum stand of the protolake Etosha may have occupied this position and that the increased salinity to the west is a result of evaporation processes during the reduction of the protolake to its present maximum shoreline. This theory, with few exceptions, is in keeping with the steadily increasing salinity towards the centre of the basin. Boreholes drilled at higher elevations to the east and northeast almost invariably encountered potable groundwater.

Borehole yields obtained from the MSA are only rarely quoted because few boreholes are likely to have been adequately tested in view of the high salinity of the groundwater. Yields are however rather variable ranging up to about 5 l/sec, although

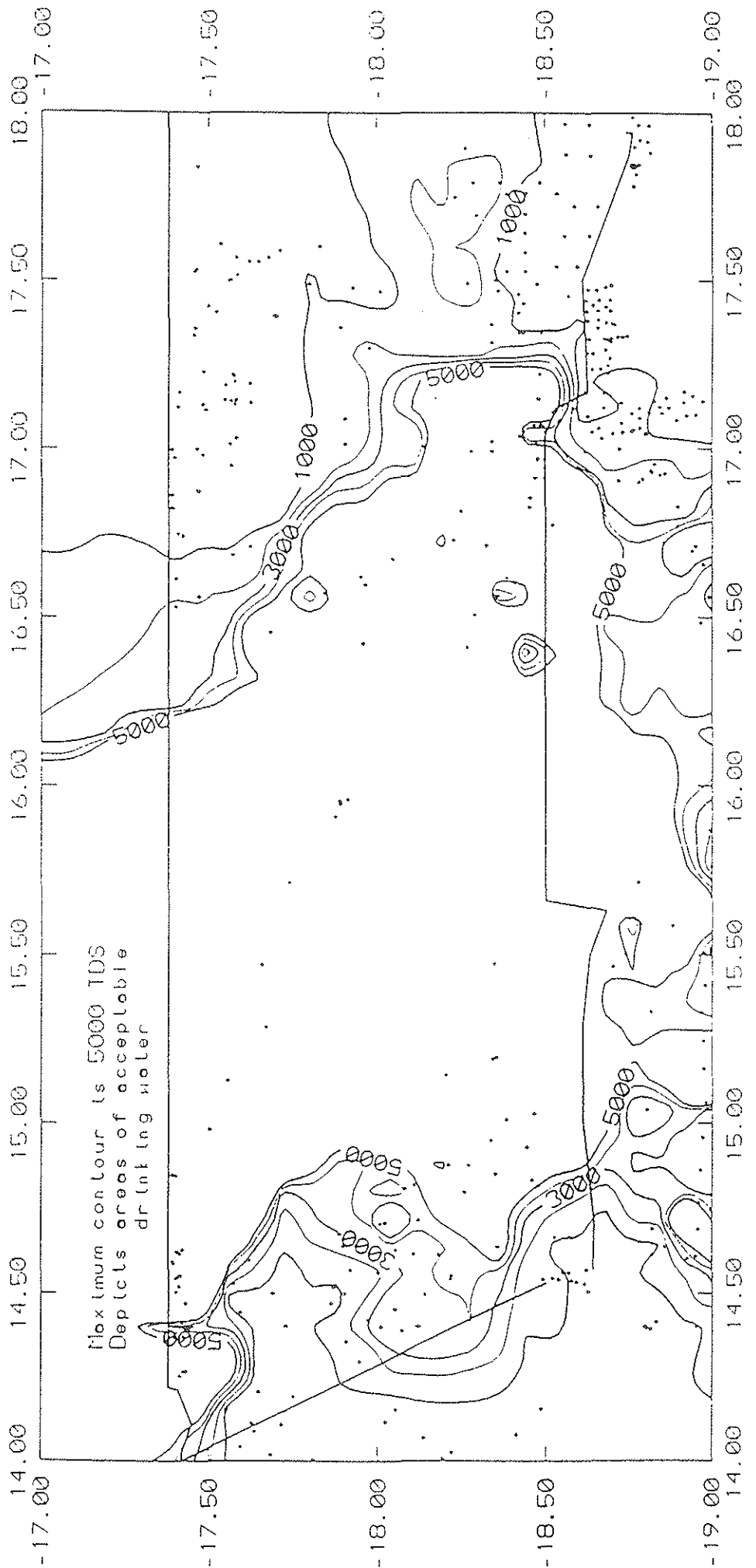


Figure 8 Water quality of the Andoni main shallow aquifer in Owambo. [after Groundwater Consulting Services, 1993]

the maximum yield recorded for recently drilled boreholes penetrating the Andoni within the study area was 2 l/sec.

### 5.1.3 The Basal Aquifer

The presence of an additional aquifer, containing relatively fresh water, associated with the base of the Andoni formation was first recorded by Hoad (1992). The aquifer was shown to exist in the Oshivelo area where it consisted of a brecciated calcretised erosion surface, overlain by a green coloured laminated clay of variable thickness (which forms the aquiclude). The aquifer has a remarkably planar form which dips to the northwest of Oshivelo with both the aquifer and aquiclude thickening northward and westward to a maximum of 11 and 12 m respectively. It was not however possible to identify the outcrop area (and hence recharge zone) of the aquifer but extrapolation indicated that it would be located some 10 km to the southeast of Oshivelo and borehole 21625. Contours of the upper surface of the aquifer are shown on Figure 9, those to the south of the main road being after Hoad (1992), with those to the north of the main road being tentatively constructed from information obtained from boreholes penetrating the base of the Andoni Formation, although in many cases no aquifer was recorded as being present at that position.

At King Kauluma to the northwest of Oshivelo an additional level of fresh water aquifer, positioned some distance above the base of the Andoni Formation, was encountered during recent drilling (Bittner, 1993). Previously two shallower boreholes drilled nearby (22538 and 22716), had only obtained brackish water from the MSA. A diagrammatic representation of the various lithologies and positions of aquifer horizons found at King Kauluma is shown in Figure 10. The lowest water strike of this aquifer lies at an elevation of 1010 m; well above the predicted position of the basal aquifer. The diagram also shows a deeper calcretised semi-consolidated horizons straddling the Andoni/Olukunda Formation interface. The upper surface elevation of this horizons would however be in keeping with the planar surface of the basal aquifer, although no water strike was recorded at that depth. The boreholes were drilled using mud flush techniques, and the only indication of water strikes was gained by regular monitoring of conductivity. It is therefore feasible that if the lower section of the borehole contained water of similar quality to the higher aquifer, then a water strike could be overlooked. It is therefore possible that some contribution to total borehole yield may be coming from this basal horizon. Yields of about 3 l/sec have been obtained at King Kauluma. A much higher yield of 15 l/sec was recorded for borehole 32617, located to the northeast King Kauluma although there may be a substantial contribution from shallower aquifer horizons.

Very few of the older boreholes located outside the general vicinity of Oshivelo penetrate the base of the Andoni Formation. There are however occasional clues to the presence of a basal aquifer which may contain relatively fresh water. Three brine investigation boreholes (10275, 10276 and 10391, Figure 9) were originally thought to have penetrated almost to the base of the Kalahari Sequence having terminated in a basal conglomerate overlain by dolerite and sandy clay. In hindsight it seems more likely that the boreholes only penetrated to the base of the Andoni formation and that the basal conglomerate may in fact be a semi-consolidated calcretised horizon. Borehole 10276 is recorded (Hugo, 1970) as having penetrated an artesian aquifer in



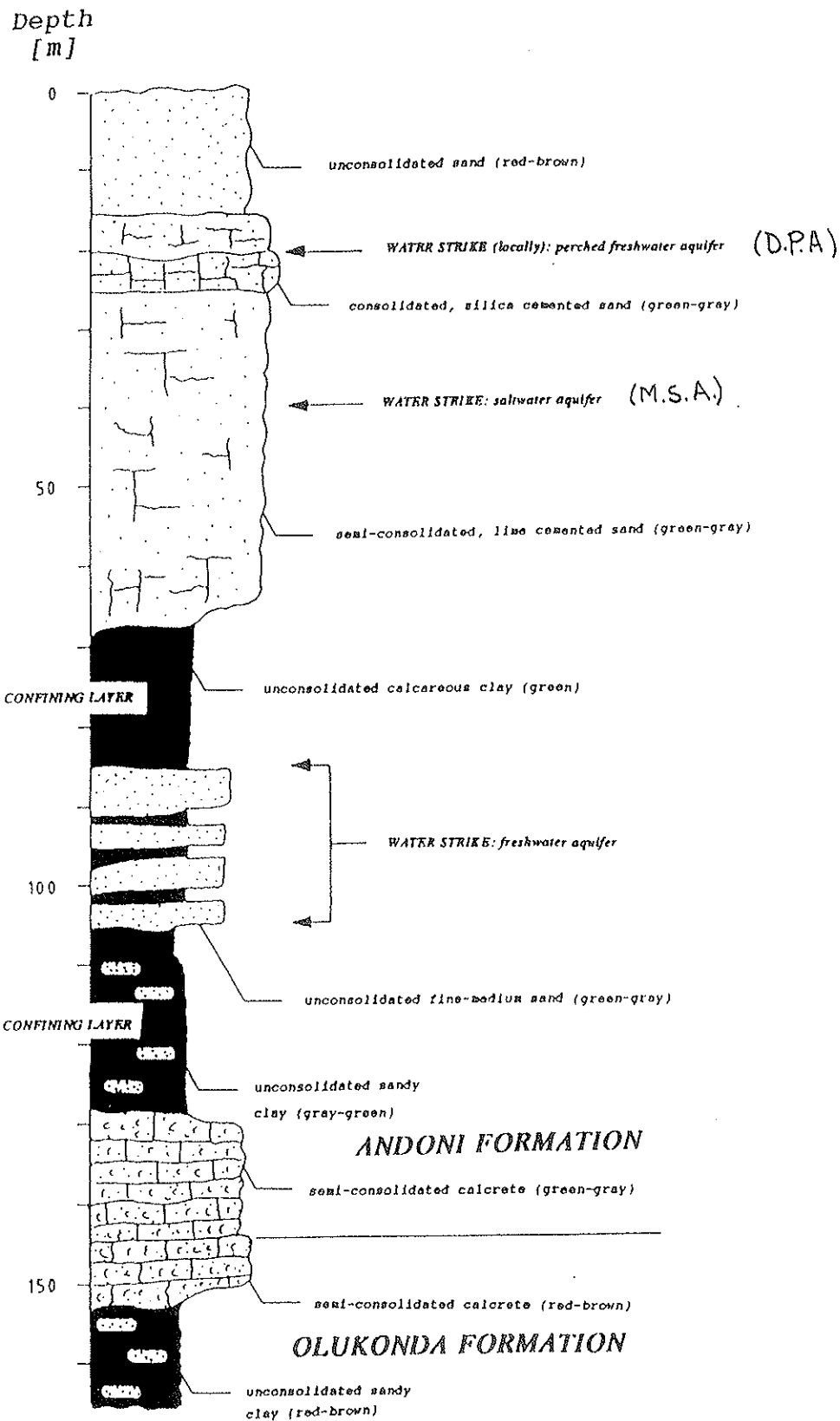


Figure 10 Generalised lithology and aquifer positions at King Kauluma. [after Bittner, 1993]

the "basal conglomerate" which although saline was of a markedly lower salinity (TDS 12,381 ppm) than the saline artesian aquifer encountered above (TDS 112,000 ppm). Considering that the sample assumed to have originated from the lower aquifer is almost certainly a mixed sample from both artesian aquifers, then the lower aquifer may have been considerably less saline than indicated by the analysis, and may even have been relatively fresh. Similar reductions in salinity were also recorded with increasing depth in the other two investigation boreholes, again indicating the possible presence of less saline water towards the base of the Andoni.

Recent drilling within the area of interest has again shown the presence of lower salinity water in boreholes which penetrate the base of the Andoni Formation and some distance into the underlying Olukonda Formation, although there is only rarely any record of a water strike at the interface. Screens are sometimes set above and below the interface between the Formations but more commonly in the underlying Olukonda. Recorded yields range up to 3 l/sec.

Also of interest is an investigation borehole (33178) located at Lyapeki, some 25 km to the west of the study area, completed in October 1992 (Figure 9). The borehole penetrated the whole of the Kalahari Sequence and terminated in the underlying Nanzi Formation. Disappointingly all recorded water strikes were within the Andoni with the lower two at 194 and 242 m being artesian. All waters encountered were saline to strongly saline. Difficulties were encountered in monitoring water quality due to the high salinity of the drilling water and the use of high viscosity mud to control artesian pressure may have sealed aquifers in the lower part of the borehole. It however seems likely that any ingress of low salinity waters would have been detected whilst the presence of predominantly clay deposits both above and below the Andoni/Olukonda contact suggests that no basal aquifer exists at this location.

The most recent drilling operations which penetrated the base of the Andoni Formation were specifically aimed at investigating the presence of a fresh water aquifer at that position. Boreholes drilled at Okankolo and Onayena (Figure 9) were both successful in obtaining a usable quantity of potable water from the base of the Andoni beneath a shallower saline aquifer, although in both cases the thickness of the aquifer horizons was very limited. At Okankolo a confined saline aquifer was encountered between 142 and 150 m whilst the fresh aquifer lay between 235 and 240 m. The aquifer consisted of a grey white slightly calcretised sand overlain by a confining, hard, well cemented (silcrete and calcrete) horizon. The underlying Olukonda was not penetrated but was thought to be a few metres below the base of the borehole. At Onayena the first water strike was at 152 m and although initially of reasonable quality rapidly became saline. A hard, well cemented band (calcrete and silcrete) was then encountered between 248 and 255 m before penetrating only a 1 m thickness of aquifer below. The Olukonda was encountered beneath but the borehole did not penetrate more than a few metres due to rapidly increasing salinity. It was anticipated that a yield of about 5 l/sec may be obtainable from this borehole.

It is apparent that an areally extensive aquifer, containing relatively fresh water is present at or near the contact between the Andoni and Olukonda Formations. This aquifer is likely to underlie the whole of the area of interest but available information is sparse.



## 5.2 The Olukonda Formation

Groundwater within the Formation has generally been reported as confined and saline although, recent evidence, although limited, suggests that relatively fresh water may be found in the uppermost horizons of the Formation but only in the most northern part of the study area.

## 5.3 The Beiseb Formation

The lithology and widespread occurrence of the Beiseb Formation makes it ideally suited to form an aquifer beneath the study area. This possibility has been investigated by a small number of boreholes but in all cases only saline water was obtained.

## 5.4 The Karoo Sequence

The study area is underlain by a downfaulted trough, beneath the Kalahari Sequence, containing Karoo Sequence rocks (4.6) first described by Hugo (1969). The strata directly underlying the Kalahari Sequence are those referred to by Miller (1990) as the "equivalent of the Prince Albert Formation" (4.2). Much of the information regarding bedrock geology in the vicinity comes from only three boreholes drilled at the margins of the fault bounded trough, of which two of the boreholes (9197 and 9563) lie well outside the study area whilst the third (9296) is located close to the southeastern corner of the area of interest (Figure 7). All three of these boreholes penetrated through the Karoo, which consisted of the Prince Albert "equivalent" and Dwyka, before penetrating the Mulden Group; (although the Dwyka was absent in borehole 9197, due to shallowing of the trough in a northerly direction). The strata mentioned above were referred to as Upper Dwyka Shales, Dwyka Tillite and Owamboland Formation respectively by Hugo (1969). These boreholes along with a number of others located elsewhere in Owambo were drilled to provide information on the presence of exploitable coals, freshwater aquifers, the quality and quantity of brines and exploitable clay deposits. Little of the information available for the boreholes is however directly relevant to the hydrogeology of the bedrock strata. Hugo commented that no water suitable for human consumption was found in any of the investigation boreholes and also that the salinity of the brines increased with increasing borehole depth. There seems however to have been no effort made to obtain water samples specifically from the Karoo strata. In consequence it is more likely that the samples constitute a mixed sample of waters originating from the Mulden, Karoo and overlying Kalahari. Analyses of water samples from borehole 9563 and an older deep artesian borehole (ST1) were provided by Hugo (1970) as part of an investigation into the brines in the Etosha area. Total dissolved solids were in excess of 40,000 mg/l, considerably in excess of levels commonly observed for samples obtained from the Kalahari Sequence. In addition, Hugo states that total dissolved solids of brines occurring in the Kalahari and Karoo are generally about the same as sea water (32,000-38,000 ppm), whereas brines from the Mulden Formation (Owamboland Formation) are more than double that of sea water in places and quotes a level of 90,000 ppm for borehole 9563. Unfortunately no information was provided on the size of potential yields which could be expected from possible bedrock aquifers.

More recently one further borehole (33922) located close to the western edge of the study area penetrated the Karoo underlying 348 m of Kalahari strata. The borehole was originally drilled to obtain water from the Kalahari strata but later deepened to investigate the possibility of obtaining potable supplies from the underlying Karoo. The borehole penetrated a total of 52 m of Karoo consisting of 42 m of varicoloured mudstones with coal layers overlying 10 m of mudstones and grey sandstones in which a water strike was tentatively recorded. Since the borehole was not originally designed to penetrate to such a great depth modifications to boreholes construction were made to attempt to seal out the saline waters contained in the Kalahari Sequence. It is by no means certain if this was in fact successful. Firstly butt-welded steel casing was employed which commonly leaks at the joints and it would appear that cement grouting of the borehole annulus was by gravity rather than displacement or pressure grouting. In consequence it is probable that the grout has not provided a complete seal and that the casing is likely to leak. Water samples are therefore likely to constitute a mixture of saline Kalahari water and water from the Karoo. Drilling mud conductivity was monitored closely during drilling and did show some improvement, accompanied by reduced mud viscosity, towards the bottom of the borehole possibly indicating the presence of less saline groundwater in the Karoo. No assessment of possible yield from the Karoo aquifer was obtained or for that matter, a final rest water level.

Vague information was also received regarding a recently completed exploratory borehole drilled some 10 km to the south of Oshigambo, (which is itself 20 km to the northeast of Ondangwa), by Oriental Petroleum Investment (OPIC). It was rumoured that this borehole encountered fresh water in Karoo strata at the bottom of the borehole but confirmation was not obtainable.

Despite persistent rumours of a bedrock fresh water aquifer none has as yet been proven. Drilling techniques and construction employed for these deep boreholes do in fact militate against such an aquifer being detected, as only mixed water samples originating from several aquifer horizons (mostly saline) can be collected, whilst high mud viscosity and back pressure to control artesian conditions prevent the detection of changes in water level and water strikes. The general lack of water level data prevents the determination of possible flow directions. The question is only likely to be resolved with the drilling of a borehole which is properly cased and grouted through the entire thickness of the Kalahari Sequence into the upper section of the Karoo before penetrating deeper. It is only by this means that water samples originating solely from the Karoo may be obtained.

## **6. THE FEASIBILITY OF DROUGHT RELIEF DRILLING**

### **6.1 Water Demand**

The scope of the study has permitted a review of probable water requirements and potential shortages, both in terms of drought relief and of more general future demand.

The first requirement is for a potable water supply for widely scattered rural communities when their traditional sources of water dry up or become saline at times

of drought. The dimensions of this problem can only increase as the population density grows with time due to inward migration (3.3.2). The highly dispersed nature of settlement makes the utilisation of groundwater resources, (if available), the only viable alternative (3.4.2). The positioning and number of water points would need to be controlled by local variations in population density. The relatively low demand could be met from small diameter boreholes equipped with handpumps or low yielding powered pumps.

The second sector to be considered is the more densely inhabited areas located along the southern fringe of the study area and to the northwest, currently supplied by piped supplies. It is often difficult to provide an adequate supply to areas close to the end of the pipeline especially at times of drought, when demand is at a maximum throughout the area supplied by the system. As discussed in 3.4.1, the Department of Water Affairs had hoped to supplement the supply at the southern end of the pipeline, by extending the pipeline to Oshivelo to make use of the groundwater resource at that location. The apparent decline in the anticipated water surplus in that area has more recently removed this alternative. There is no other economically viable source of water which could be used to supplement the piped scheme. If a large scale potable source of groundwater could be found to feed into the southern end of the pipeline this would ensure the availability of adequate supplies during periods of drought, in addition to providing improved flexibility for the overall management of the pipeline supply. It should however be stressed that such a groundwater source would have to be both large capacity and of potable quality.

## **6.2 Potential Aquifers**

### **6.2.1 The Kalahari Sequence**

As discussed in detail in 5.1.3 the only viable Kalahari Sequence aquifer known to be present beneath the study area is located at the base of the Andoni Formation, perhaps extending into the upper part of the underlying Olukonda formation particularly in the north. The aquifer is relatively thin, ranging from perhaps only a few metres to about 20 m in thickness. The overlying confining horizon also appears to vary markedly in both composition and thickness being generally clayey and up to 50 m thick over much of the study area but being composed of a well cemented horizon only a few metres thick to the northwest and around Okankolo and Onayena. The presence of this aquifer has only been detected fairly recently and its overall aquifer properties and general characteristics are only poorly known; particularly with respect to the effects of faulting. Borehole yields are not high, only infrequently exceeding 5 l/sec and although water quality is not particularly good it is generally potable. In the absence of any viable alternative such a resource is well suited for development for use by scattered low density rural communities.

The resource could however prove to be somewhat fragile. Although the aquifer horizon may appear to be remarkably planar and dipping gently to the northwest the effects of faulting within the Kalahari Sequence is completely unknown. It is possible that faults may act as conduits for the flow of both fresh and saline waters but may also isolate blocks of the aquifer from sources of recharge. In addition the aquifer has a limited thickness, the zone of recharge is likely to be remote and it is overlain and

underlain by saline aquifer horizons. The aquifer should therefore be developed with great care in order to prevent overexploitation, which could rapidly induce saline intrusion from adjacent aquifers or by the depletion of storage causing declining yields. The effect of exploitation on the aquifer should be monitored closely in order to prevent adverse effects and wherever possible only handpumps should be installed in boreholes rather than higher yielding motorised pumps to reduce the possibility of overpumping.

At present there are no urgent requirements for additional water supplies within the area as a result of the ending of the period of drought. Drought will however undoubtedly recur in the area at some time in the future. It is deemed advisable to prepare for that eventuality by drilling a number of investigation boreholes to better define the position of the fresh water aquifer beneath the study area. With this information in hand, any future drought relief drilling will be much more effective, as the depth at which casing (to seal off saline horizons) should be set would be known, as would the maximum depth to which boreholes should be drilled (in order to preclude the penetration of deeper saline aquifers). Similarly it would also be advisable to further investigate the apparent presence of fresh water in the upper part of the Olukonda Formation near the northern margin of the study area.

#### 6.2.2 The Karoo

From the rather sparse information available it would appear that, despite persistent rumours of fresh water, groundwater in the Karoo is generally saline. There remains however tentative evidence which suggests that fresh water may be present. It has not been possible to definitely detect the presence of fresh water due to the difficulties imposed by drilling techniques employed and borehole construction, which has not allowed a water sample to be obtained solely from the bedrock.

Any attempt to obtain potable water from the Karoo or any underlying strata can only be described as speculative. In view of the great drilling depths involved (350-400 m) combined with the difficulty of drilling and sealing out the thick sequence of overlying Kalahari strata and hence high cost, it cannot be considered feasible that this potential source could be used for a drought relief supply. The upper section of the Karoo (the Prince Albert "equivalent") which includes sandstone horizons presents a better prospect for aquifer development than the finer grained well cemented Dwyka Tillites below. On a more long term basis however there is merit in further investigating the possible resource. As stated in 6.1 there is a considerable need of a large scale water supply for input to the southern end of the supply pipeline. If such an augmentation of the piped supply were to prove possible it would greatly improve water supplies during periods of drought over a very large part of the Owambo region. The Kalahari strata are patently unable to provide such a supply and in consequence the only possible remaining alternative is the Karoo. The underlying Mulden formation although consisting of lithologies suitable for the development of aquifers lies at a depth of over 600 m and is therefore highly unlikely to be an economically feasible target, especially since the indications are that groundwater is likely to be highly saline.

As an initial step the matter may be resolved by geophysically logging borehole 33922. This borehole is at present capped and has not been disturbed since completion in April 1993. If groundwater quality variations exist over the screened or lower open sections of the borehole, stratification is likely to have developed in the intervening period. Temperature/conductivity logging should detect such variations and identify the position of any relatively fresh horizons. It may also be possible to identify leaks of more saline waters through casing joints or the base of the plain casing using the temperature/conductivity logs in concert with caliper and gamma logs. It is thought that adequate basic logging equipment is available within the Department of Water Affairs. It may also be possible to locate and log deep boreholes ST1 and 9563 which were both reported by Hugo to be open and artesian in 1969, although their current status is unknown. In view of the high costs involved, further investigations should only proceed if definite indications of the presence of fresh water can be obtained from borehole logging.

If a fresh water aquifer can be identified, it would then be necessary to drill an exploratory borehole constructed to completely exclude saline water originating from the Kalahari Sequence. Previous attempts at achieving this by a mixture of displacement and gravity grouting methods was not successful. It is therefore recommended that a string of screw jointed steel casing be employed, set to at least 10 m below the top of the Karoo (or deeper depending on the nature of the strata). Total drilling depth is likely to be of the order of 500 m. The borehole annulus should be pressure grouted. There is little option given the nature of the Kalahari Sequence but to drill using mud. The drilling technique is widely used in Namibia but the great depth involved is likely to be close to or exceed the capacity of most if not all locally available drilling rigs. In addition pressure grouting equipment is not available in Namibia but can be hired in South Africa. It is therefore probable that drilling and grouting equipment together with properly experienced operators would need to be imported, probably from South Africa. Assuming the initial borehole is successful in proving the presence of an aquifer containing potable water and of adequate potential yield, then a second larger diameter production borehole would need to be drilled adjacent to the exploratory borehole in order to carry out an aquifer test. Site selection could only be carried out following a re-assessment of all borehole and geophysical data available (including some currently held as confidential by the Geological Survey) and would therefore need to be the subject of a separate study.

### **6.3 Environmental Factors**

As stated in 3.3.2 the study area is currently only sparsely settled having previously been largely covered by an exclusion zone used for military training. Population densities are likely to steadily increase in the future, in concert with increasing bush clearance for dryland subsistence farming. Serious inroads are already being made into the area from the northwest. This pattern of settlement is likely to continue and is likely, in the absence of rigid land use control, to lead eventually to clearance of virtually the whole area. The provision of permanent potable water supplies is likely to accelerate the pace of clearance and settlement which in itself will further increase demand for potable water supplies.

It is considered that springs utilised by wildlife along the northern margin of Etosha Pan are unlikely to be affected by exploitation of the basal Andoni aquifer as their water supply is likely to originate from shallower horizons within the Andoni. The artesian boreholes are similarly unlikely to be affected. Even if some degree of interconnection were to exist, the very low abstraction rates involved are not likely to adversely affect either the springs or artesian boreholes.

## 7. CONCLUSIONS AND RECOMMENDATIONS

This study has included a review of all relevant geological and hydrogeological information for the region around the study area as defined by the TOR. Socio-economic factors and a range of environmental topics have also been reviewed in some detail.

A widespread aquifer containing potable groundwater has been identified as existing beneath the area of interest. Located in the Kalahari Sequence close to the contact between the Andoni and Olukunda Formations, the aquifer is both overlain and underlain by numerous saline aquifers also contained within the Kalahari Sequence. From available information the aquifer appears to form a remarkably planar surface dipping towards the northwest. Although not of prime quality, groundwaters from this aquifer are generally potable. Yields are generally low, ranging up to about 5 l/sec.

The aquifer has already been utilised for drought relief supplies but only to a very limited extent. In the absence of any other viable water supply option, it is considered feasible to utilise the available resource more extensively in the future when drought again affects the area. As the population of the area is currently growing and settlement patterns are changing it is appropriate that specific borehole sites should be decided in response to conditions at the time of any future drought, rather than as part of this study.

It should however be noted that relatively little is known about the resource in the study area, especially with regard to the effect of faulting. The resource should therefore be regarded as "fragile" and development should only proceed with great care, in order to prevent overexploitation which could lead to saline intrusion and declining yields. To this end it would be desirable that a limited investigation be carried out as a form of drought relief preparedness, to better define the position and characteristics of the aquifer. It is therefore recommended that:

- (i) Three investigation boreholes be drilled, targeted at investigating the basal Andoni aquifer. In view of the limited thickness of the aquifer and need to completely exclude overlying saline aquifers, drilling should be carried out by personnel of proven experience of drilling in similar conditions. All phases of the investigation should be overseen and closely monitored by hydrogeological consultants.
- (ii) The boreholes should be positioned in the north centre, southwest and southeastern sectors of the study area to maximise the spread of information.

- (iii) The boreholes should be geophysically logged and aquifer tested.

Information obtained would better define the position and extent of the aquifer, thereby providing much improved target definition for any future drought relief drilling programme, speeding the provision of completed successful water sources and reducing overall costs, whilst simultaneously reducing the risks involved with overexploitation. The cost of such an investigation is not expected to exceed £40,000.

Environmental effects resulting from development of the aquifer for drought relief purposes are not thought to be significant. It is thought that, lacking control, land clearance will continue to expand across the area and this would be accelerated by the provision of permanent potable water supplies. Springs used by wildlife along the northern margins of Etosha Pan are unlikely to be affected, as they are almost certainly supplied by groundwater originating from more shallow aquifers. In any case abstraction from low yielding boreholes using handpumps is not likely to be significant in terms of the overall resource.

The possibility of utilising the much deeper potential Karoo aquifer is regarded as distinctly speculative. Although much of the limited information is indicative of only saline groundwater being present, there are nevertheless tantalising indicators that fresh water may be present. In view of the depth to this potential aquifer, it would not be suitable for utilisation in any fast response drought relief programme. If however a high yielding potable resource could be found, then it would be of immeasurable benefit in ensuring water supplies, particularly during times of drought, to a very large section of the population served by the pipeline system throughout central and southern Owambo. Development of such an option would be very expensive and only appropriate to bulk water supplies. Initially steps should be taken to resolve the question as to the existence of fresh water in the Karoo. It is therefore recommended that:

- (i) Borehole 33922 be geophysically logged preferably using equipment (if suitable) already in the possession of the Department of Water Affairs. Given the construction of the borehole, temperature/conductivity logging in conjunction with caliper and gamma logging could resolve the matter.
- (ii) The present condition of previously open and artesian boreholes ST1 and 9563 should be determined and, if still open, be geophysically logged in the same manner as borehole 33922. Their much greater depth may preclude logging of the lower section of the borehole but a considerable part of the Karoo could be covered.
- (iii) If the presence of fresh water in the Karoo can be demonstrated then logging should be followed up by the drilling of an exploratory borehole and possibly if this is successful, a production borehole to allow full scale aquifer testing (6.2.2). Such drilling should be carried out by fully experienced personnel and closely monitored by a hydrogeologist. The cost of an exploration borehole may be of the order of £40,000 whilst additional works involved in drilling and testing a production borehole would more than double that figure.

## REFERENCES

- Bittner A (1993). Memorandum on drilling and test pumping of fresh water yielding boreholes in the subartesian Kalahari aquifer at King Kauluma. Unpublished report, File No. 12/4/2/18 Geohydrology Division, Department of Water Affairs, Republic of Namibia.
- Department of Water Affairs (1990). Regional master water plan for the Owambo region. Report No. 13/1/6/9, Department of Water Affairs, Ministry of Agriculture, Water and Rural Development, Republic of Namibia.
- Gavine P & Stuart-Williams V (1993). Desk study of the area east of central Owambo between 17°30' - 18°30' and approximately 16°-17°. Unpublished report, Groundwater Consulting Services, Windhoek, Republic of Namibia.
- Groundwater Consulting Services (1993). Owambo drought relief report: Volume 1: Report, Appendix A and Volume 2. Unpublished report prepared for Department of Water Affairs by Groundwater Consulting Services, Windhoek, Republic of Namibia.
- Groundwater Consulting Services (1992). Central Owambo - geological history, basin evolution and groundwater reserves and resources. Unpublished report prepared for the Swedish International Development Agency (SIDA) by Groundwater Consulting Services, Windhoek, Republic of Namibia.
- Groundwater Consulting Services (1992). Drought relief programme, south east Owambo. Report on geophysical investigation for drilling target selection. Unpublished report for Department of Water Affairs by Groundwater Consulting Services, Windhoek, Republic of Namibia.
- Groundwater Consulting Services (1992). Evaluation of the drought situation in eastern Owambo. Unpublished report, Groundwater Consulting Services, Windhoek, Republic of Namibia.
- Groundwater Consulting Services (1991). Final Report - Phase 1, Groundwater investigations, eastern Owambo. Volume 1 - report and Volume 2 - appendices. Unpublished report No. 2710/4/G2 prepared for Department of Water Affairs by Groundwater Consulting Services, Windhoek, Republic of Namibia.
- Hoad N (1993). An overview of groundwater investigations in the Tsumeb and Oshwelo areas. Report No. 2700/4/G2, Geohydrology Division, Department of Water Affairs, Republic of Namibia.
- Hoad N (1992). Resource assessment and development potential of contrasting aquifers in central northern Namibia. Unpublished MSc project report, University College, London.



- Hugo P J (1969). Report on the cored drilling programme in Owamboland. Economic Geology Series Open File Report EGO80, Namibia Geological Survey, Republic of Namibia.
- Hugo P J (1969). Stratigraphic test boreholes: Owamboland. Economic Geology Series Open File Report EGO81, Namibia Geological Survey, Republic of Namibia.
- Hugo P J (1970). Results of boreholes drilled for brine in the Kalahari Beds, Southern Owamboland. Economic Geology Series Open File Report EGO72, Namibia Geological Survey, Republic of Namibia.
- Miller R McG (1990). The Owambo basin of northern Namibia. Unpublished report, Namibia Geological Survey, Republic of Namibia.
- Miller R McG & Schalk K E L (1980). The geological map of South West Africa/Namibia. Namibia Geological survey, Republic of Namibia.
- van der Merwe J H (ed) (1983). National atlas of South West Africa. National Book Printers, Goodwood, Cape, RSA.

**Table 3. Geology and Stratigraphy (after Groundwater Consulting Services 1992; Miller, 1990)**

Group/ Sequence	Formation	Description	Surface Distribution	Comments	Maximum Thickness (m)
KALAHARI	Andoni	White sand, light green clayey sand, green clay and calcrete	Seen occasionally in road borrow pits and river banks	Seen in numerous boreholes and wells	274
	Olukonda	Medium grained red sand and clay	Borehole intersection only	Seen in many boreholes	120
	Beiseb	Reddish sandstone, argillaceous	Borehole intersection only	Seen in several boreholes	35
-	Nanzi	Red semi-consolidated sandstone, clayey shale	Borehole intersection only	Identified in several drilling programmes	135
KAROO	Prince Albert equivalent	Carbonaceous shale, sandstone, siltstone and low grade coal	Borehole intersection only	Identified in several drilling programmes	221
	Dwyka	Tillite, shale, limestone, etc	Borehole intersection only	Identified in Coal Commission boreholes	158
MULDEN	Owambo	Black, grey and varicoloured shales with siltstones and sandstones	Borehole intersection only	Identified in Coal Commission boreholes	2600
	Tschudi	Grey sandstones, siltstones and shales	Borehole intersection only	identified in Coal Commission boreholes	1800

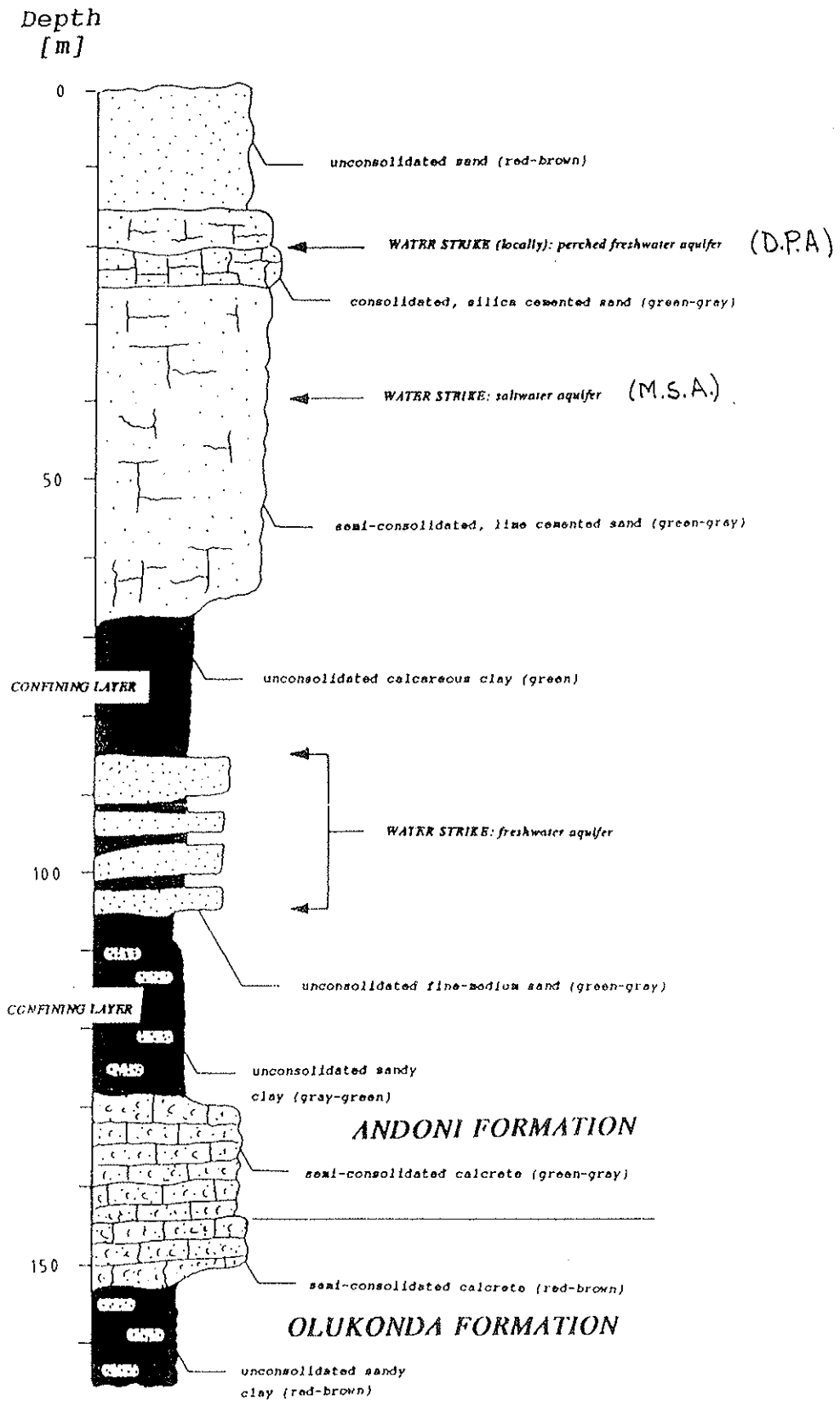


Figure 10 Generalised lithology and aquifer positions at King Kauluma. [after Bittner, 1993]

## APPENDIX 1: TERMS OF REFERENCE

# PROPOSAL FOR DROUGHT RELIEF DRILLING FOR SE OWAMBO

## TERMS OF REFERENCE

### **Assumptions**

1. The Department of Water Affairs will prepare all available geological maps and hydrogeological studies relevant to the region ready for study by the hydrogeologist.
2. The High commission/MAWRD arrange 4WD transport and driver for the duration of the visit.

### **Length of Visit**

3. A field trip will be made to the sites to inspect existing water supply systems, interview users and determine access. The duration of the visit will be approximately two weeks to allow for above.

### **Technical Requirements**

4. A summary report will be written in Namibia which will identify all sources of information including references to earlier reports, maps and feasibility studies.
5. The geology and hydrogeological system will be described.
6. An appraisal of the feasibility of the provision of sustainable water supply including up to 10 boreholes will be prepared, including short-term feasibility of drilling boreholes in the area and an indication of how long the resources is likely to last.
7. An assessment will be made of the environmental impact of the project, in particular the long-term implications for saline intrusion into the aquifer and land sterilisation. In particular the probability of reducing spring or artesian borehole flow in the nearby National Park will be assessed.
8. Comments on the long-term policy for water development and management and other water supply options for the area.
9. An evaluation of the social groups who will benefit from an increase in water availability through drilling new boreholes.
10. An evaluation of the technical competence of different organisations capable of drilling boreholes.

**APPENDIX 2: ITINERARY**

## ITINERARY

### Tuesday 12 October 1993

- 06.30 Arrive Windhoek International airport (SW682) from London Heathrow; met by R Fry, Acting Deputy Permanent Secretary, Department of Water Affairs (DWA).
- 09.00 Introductory meeting R Fry and G Christelis (Acting Chief, Rural Geohydrology Division) at DWA.
- 10.00 J Rice, British High Commission.
- 11.00 P Waldon, Geophysicist, Groundwater Consulting Services (GCS).
- 14.30 G Christelis, DWA.
- 15.15 G Lukowski, Planning Division, DWA.
- 16.00 N Hoad, Geohydrology Division, DWA.
- 16.50 A Bittner, Geohydrology Division, DWA.

### Wednesday 13 October 1993

- 09.00 W Princlloo, Namibia Drilling Consultants.
- 10.30 M Harris, Acting Chief, Planning Division, DWA.
- 12.00 R Fry and P Robinson, DWA.
- 16.00 R Fry, DWA.

### Thursday 14 October 1993

- a.m. Study various reports.
- p.m. Surveyor General - obtain base maps. Study reports.

### Friday 15 October 1993

- 10.00 V Stuart-Williams, Managing Director, GCS.
- 14.00 D Hutchins, Chief Geophysicist, Namibia Geological Survey.
- 15.30 Collect data at DWA.

Saturday 16/Sunday 17 October 1993

Study reports/data.

Monday 18 October 1993

Travel to study area.

Tuesday 19 October 1993

a.m. Meeting at Oshivelo with R Fry (DWA), the Assistant to District Governor, the local Councillor and members of the Regional Water Committee.

p.m. Visit KK7 boreholes site.

Overfly study area.

Meeting with R Wartha and G Canahai (GES) at a drilling site at Onayena.

Wednesday 20 October 1993

Overfly study area and return to Windhoek.

Thursday 21 October 1993

09.30 Collect additional data from DWA.

10.30 V Stuart-Williams, GCS.

11.30 Surveyor General Department - collect additional maps.

12.00 P Hutchinson, Weather Bureau.

14.00 E Taylor, British High Commission.

16.30 Collect data, DWA.

17.30 Present informal lecture on "groundwater pollution and pollution studies" to Hydrogeological Association of Namibia at the Thuringerhof Hotel.

Friday 22 October 1993

10.00 G Schneider, Chief Economic Geologist, Namibia Geological Survey.

11.00 N Hoad, DWA.

12.00 V Stuart-Williams, GCS.



14.30 R Fry, DWA.

15.30 Weather Bureau - data collection.

Sunday 24 October 1993

22.45 Depart Windhoek International airport (SW681) for London Heathrow.

**APPENDIX 3:**

**REPORT ON THE INTERPRETATION OF A LANDSAT IMAGE  
FOR THE AREA AROUND ETOSHA PAN**

**Short Report: Processing and preliminary interpretation of  
Landsat MSS data for the area around the Etosha Pan, Namibia**

S H Marsh & A J W McDonald, 5 November 1993

### **Background**

This note is a short report describing the interpretation of satellite data for the country surrounding the Etosha Pan, Namibia. The work was undertaken on behalf of the Hydrogeology Group, BGS Wallingford, as a component of an ODA funded project on borehole siting for drought relief. The interpretation, a rapid study with minimal field information, should be regarded as preliminary.

### **Image Data and Processing**

The data were recorded by the Multispectral Scanner (MSS) on board the Landsat 5 satellite on 10/5/86. They were pre-processed at the ground station to conform to the Hotine Oblique Mercator map projection with the pixels resampled to 56 x 56 m using cubic convolution. Additional image processing was carried out by the Remote Sensing Group, BGS Keyworth.

The image product is a false colour composite of MSS Bands 7, 5, 4 (displayed in red, green, blue) in which green vegetation appears in shades of red. Spatial filtering has been applied to sharpen linear features. The contrast within the area around the Etosha Pan was improved by applying a contrast stretch which set the mean and standard deviation of the individual spectral bands of the filtered image to values selected interactively. Other processing techniques such as principal components analysis and a decorrelation stretch were attempted but the results appeared more noisy than the standard composite and did not show any additional information.

The false colour composite was transcribed by an external bureau onto photographic film using a laser film writer and photographically enlarged to produce prints at 1:250 000 scale for the full scene and 1:150 000 scale for the specific area of interest northeast of the pan.

### **Interpretation methodology**

The 1:250 000 scale image has been used to produce an interpretation intended to depict the regional structural and lithological trends. Lineaments, thought to relate to fracturing in some form, and ridges or tonal contrasts, thought to relate to lithological or stratigraphical boundaries, have been delineated. This interpretation may help put the area of specific interest in the NE into a regional context. The superficial Kalahari sands have not been depicted at this scale, though they can clearly be seen.

The 1:150 000 scale image has been used to produce a more detailed interpretation for the area of specific interest. Lineaments have again been depicted, together with water features possibly related to springs or artesian boreholes and linear ridges formed by the Kalahari sands. Additional features which are clear in the image include areas of increased vegetation and possible areas of clearance. These have not been delineated on the interpretation but are described in the results section.

## Results

Aspects of the interpretation are speculative, particularly the lineaments in the area of specific interest which are very subtle features largely obscured by the overlying sands. It was felt, however, that in an area where little information exists speculation was warranted. Without the benefit of field knowledge, the results of the remote sensing study should be treated with caution. Nevertheless, the study provides extra information to aid the solution of the hydrogeological problems in the area.

The main features detected and mapped with the Landsat data consist of:

1. **Lineaments** - A consistent pattern of linear features is seen throughout the area. These features are best developed in the south and west, becoming increasingly difficult to detect to the north and east. The majority consist of linear drainage channels, pan-edges or alignments of subtle topographic features. There are two main lineament pairs; ENE/NNW and NE/NW. Variations on this pattern occur in places, particularly in the area of specific interest where NNE trends are seen.
2. **Water features** - Around the margins of the pan several small areas of darker blue/black are seen which are thought to indicate the presence of water. These may be related to springs or artesian boreholes. One appears to lie at the end of a NNE-trending lineament.
3. **Lithological features** - To the south of the Etosha Pan the somewhat higher ground contains outcrops of older lithologies. Strong ridges and tonal contrast are seen which give information about the geological structure of the area and these have been delineated on the interpretation.
4. **Superficial Features** - Linear ridges trending ENE occur in the NE. These have been separately delineated as superficial features, thought to be Kalahari sand dunes.
5. **Other features** - Areas of increased vegetation appear red in the imagery. The vegetational pattern in the area of specific interest is clear and may be of relevance to the hydrogeology. There is some evidence of land-clearing, particularly either side of the main road.

## Discussion

The edges of the many pans in the area including the Etosha Pan are often conspicuously linear, suggesting the basins in which they formed are structurally controlled. There is a contrast between the north and west shores of the Etosha Pan and the south and east shores; the former have other pans and concentric deposits along their margins, while the latter do not. It is possible that the pan has formed in a half-graben with the NE-trending bounding fault, as well as maximum subsidence, occurring along the southeast margin.

In the area of specific interest, the Kalahari sands make interpretation particularly difficult. Nevertheless, subtle linear features with trends broadly consistent with the wider area can be made out cutting across the main Kalahari trend. It may be that the small drainage channels in the area are controlled in some way by the structure below the sands.

## **Future work**

The work presented here could be improved through the use of Landsat TM data. TM's higher spatial resolution would help in the recognition of the subtle geomorphological features on which much of the interpretation is based. In addition, the extra spectral bands in the infrared would enable a greater number of surface components to be discriminated. Given the extensive superficial deposits masking the solid geology, however, the results of hydrogeological remote sensing studies in the area are unlikely to be as conclusive as in areas where the basement outcrops, such as Zimbabwe. Despite this, the imagery contains much information which may be of importance in the hydrogeological investigation of the area.