OKACOM

Okavango River Basin Groundwater Overview

Specialist Report prepared by Interconsult Namibia for :

PERMANENT OKAVANGO RIVER BASIN COMMISSION

Angola
Ministério da Energia e Águas
GABHIC
Cx. P. 6695
LUANDA

Tel: +244 2 393 681
Fax: +244 2 393 687

Botswana
Ministry of Mineral Resources and Water Affairs
Department of Water Affairs
Private Bag 0029
GABORONE

Tel: +267 360 7100
Fax: +267 303508

Namibia
Ministry of Agriculture, Water and Rural Development
Department of Water Affairs
Private Bag 13193
WINDHOEK

Tel: +264 61 296 9111
Fax: +264 61 232 861

PERMANENT OKAVANGO RIVER BASIN COMMISSION
(OKACOM)

OKAVANGO RIVER BASIN PREPARATORY ASSESSMENT: GROUNDWATER OVERVIEW

Report prepared by:
Interconsult Namibia (Pty) Ltd
P. O. Box 20690
Windhoek

With input from **Wellfield Consulting Services**, and **E. Bereslawski**

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1 INTRODUCTION

1.1. BACKGROUND

OKACOM (Permanent Okavango River Basin Commission) is an initiative of the three Okavango River Basin states, Angola, Botswana and Namibia. The Commission has the functions of advising the governments on the sustainable development of the Basin and of co-ordinating investigations and research activities.

The Okavango River, which contains unique environmental and ecological features, is one of the few undeveloped river basins in the world and plays a key role in the lives of the people of the region. Recognising this there is a need to manage the mounting pressure for regional development through the formulation of an Integrated Basin Management Plan. Such a plan would span international boundaries and interests and promote the sustainable development of the Okavango River Basin through a process of open consultation at all levels.

A preparatory Assessment Programme was established to facilitate stakeholder participation in the Environmental Assessment and the development of the Integrated Basin Management Plan. Phase I of the programme concludes with a Diagnostic Assessment identifying gaps in knowledge of the physical and socio-economic systems of the Basin. This will be based on review of the current state of information and knowledge.

Phase I will be followed will be followed by a Strategic Action Programme through which an Environmental Assessment will be undertaken to address issues, priorities and gaps in information and understanding. This will lead to the formulation of the Integrated Basin Management Plan.

1.2. TERMS OF REFERENCE

The terms of reference (ToR) for the geohydrological study require a brief overview of the geohydrology of the Okavango River Basin as gleaned from existing reports and information. As one purpose of this study is a Diagnostic Assessment, aimed at the establishment of an outline of work required for a full Environmental Assessment, it is important to establish the sufficiency of existing data and information. Mention is therefore to be made where gaps are identified in the existing knowledge of the Basin and the work needed to close them.

In concluding the Diagnostic Assessment the following is thus required:

- A full description of data gathered for the study including a statement on their availability to the study;
- Description of previous studies assessing their relevance, reliability and usefulness;
- Diagnostic assessment of the situation;
- Description of shortfalls in knowledge and a clear definition of work required rectifying these.

2 OVERVIEW OF THE GEOHYDROLOGY OF THE BASIN

2.1 BASIN GEOLOGY

Figure 1 gives an overview of the geology of the Okavango River Basin. The area is underlain by early to late Proterozoic material accreted to the core of the Archean Kalahari Craton. In the highlands of Angola the basement comprises early Proterozoic granitic and gneissic strata and in northeastern Namibia and northwestern Botswana the terrain is underlain by late Proterozoic, variably metamorphosed strata of the Damara Sequence, consisting of quartz schist, quartzite, dolomitic marble and limestone. These strata are also exposed in the western sector of the Basin forming the high ground of the Tsodilo, Gcwihaba and Ahah Hills.

To the south of the Delta the late Proterozoic strata comprise sandstones, shales and quartzites of the Ghanzi Group, which were deformed by Damara age tectonic events. Such events created the Ghanzi - Chobe Fold Belt, along which the Ghanzi Ridge is the predominant topographical feature. These rocks are exposed just south of Lake Ngami within the Basin area.

The Okavango Delta lies within a northeast trending graben bounded by seismically active, southwest trending, continental scale faults, which have been demonstrated to conform to the southwestern arm of the African Rift System (Hutchins, *et al.*, 1976; Scholz *et al.* 1976). To the northwest the Gomare fault forms the Gomare Ridge, and probably extends to the other side of the Delta to create the southern boundary of the Linyanti Swamps along the and Chobe River. It is the slight drop in elevation south of the fault that causes the Okavango River to split into several main channels below the Panhandle. To the southeast, about 160 km, delta waters are dammed by an upward moving block bounded by the Kunyere and Thamalkane Faults. North of the Delta the Panhandle is structurally controlled a prominent northwest linear trend.

Faulting is thought to have been active throughout the period during which the Kalahari Group was deposited, implying that this was into a continually deepening, intra-continental basin.

Within the graben Karoo sediments (Palaeozoic age) have been preserved, whilst having been eroded in surrounding areas outside this structural trough. The Karoo Sequence comprises sandstone, conglomerate and basalt; the latter capping the sequence. Palaeozoic strata are exposed at isolated localities along the Okavango River between Rundu and Bagani, both on the Namibia - Angola border and just south of Lake Ngami. A northwest trending post Karoo dyke swarm, which is a predominant geological feature across northern Botswana, is also present in the area. Owing to the thick cover of sediments carried into the Delta, not much is known about the nature or distribution of Karoo strata beneath the Okavango Delta.

Overlying the bedrock in most of the Basin area vast expanses of deltaic and windborne, medium to fine grained sands and silts collectively known as the Kalahari Group of Tertiary to Recent age. In the dryland region to the northwest and southeast of the Panhandle, north of the Gomare Fault, the Kalahari is of windblown origin and surficially takes the form of large sand dunes. Associated with this terrain are hard calcretes and silcretes, especially along the bottom and sides of fossil river valleys such as those originating from eastern Namibia. Closer to the Delta wind blown deposits are likely to be underlain by deltaic sediments which were deposited when the lateral extent of the Delta was much larger. In the Delta itself the Kalahari Group comprises lacustrine, deltaic and alluvial sand, silt and clay. The material has been carried from Angola along the Okavango River and deposited in the Okavango Graben in the form of a gently sloping wedge, thickening towards the southwest faulted boundary. Continued sinking of the graben prevents the Delta from being filled in. The Kalahari Group reaches a thickness of up to 350 m along the southeastern portion of the Kunyere Fault at Lake Ngami, where downthrown displacement of the fault has been greatest.

2.2 GEOHYDROLOGY OVERVIEW

The main hydrostratigraphic units within the Okavango Basin include shallow Kalahari Group aquifers and fractured, bedrock aquifers within the deeper Karoo and Proterozoic strata.

2.2.1 Shallow Kalahari Bed Aquifers

The hydrogeology of the Kalahari Group is complex due to the variation in regional geology and intense local facies variation. The Kalahari Group sediments comprise fine to very - fine and silty sand and sandstone with some clayey horizons. As a whole the Kalahari therefore has relatively low porosity and permeability. In places semi-regional aquifers are developed in the Kalahari, which may be saline in certain areas. Basically Kalahari aquifers can be subdivided into deltaic and aeolian aquifer types.

2.2.1.1 Deltaic Aquifers

Deltaic sediments underlie most of the modern delta area. The sedimentary pattern is one of anastomising channels, which have progressively migrated across the delta as a result of tectonism and/or channel blockage by vegetation. Away from active channels clay and silt accumulation occurs (overbank deposits). In the central part of the delta very little settlement of people has taken place and consequently there is a lack of information regarding aquifers from drilling. Near Maun these aquifers are usually multilayered, with fine to medium sands comprising aquifer units; and clays, sandy silts and sandy clays forming semi-confining units. The upper or shallow freshwater aquifers are unconfined to semi-confined while the middle freshwater aquifers range from very leaky semi-confined to confined systems. The thickness of the zone of transition from fresh to brackish and saline water is generally within 5 - 20 metres, with all systems usually hydraulically interconnected.

The shallow aquifer systems southeast of the Kunyere Fault are generally confined to river channels (Lower Boro, Shashe, Thamalakane and Nxotega) and thus contain relatively limited groundwater in storage compared to aquifer systems northwest of the fault. The thickness of freshwater systems range from less than 40 m in the Lower Thamalakane to as much as 70 m in the upper reaches of this river. Northwest of the Kunyere Fault freshwater systems (Kunyere and tributaries, Marophe) are characterised by wider valleys or floodplains, often greater than 3 km wide. Groundwater storage in these areas is far more substantial than that south of the fault, with freshwater systems of at least 110 m thick in the area around the Upper Boro.

The delta flood is the main source of recharge to the shallow and semi-confined aquifer systems. In the absence of recharge from floodwaters, the aquifer systems become depleted of freshwater. The areas northwest of the Kunyere Fault have larger storage capacities and can withstand longer periods of no flow conditions. Stable isotope analyses indicate that surface water infiltration is the principal recharge mechanism for the shallow unconfined and deeper semi-confined aquifer systems that underlie the river and flood plains at the distal end of the delta.

Water levels are highest close to the seasonal and perennial swamps and decrease in the direction of the three major regional sinks: Lake Ngami, the Mababe Depression and the Makgadikgadi Pans. The overall direction of shallow groundwater flow is radially away from the delta. A steep head drop usually occurs at the fringes of the delta, probably due to the generally low hydraulic conductivity of the Kalahari Group.

At the western fringe of the delta recharge is not likely to be as significant as that at the dammed distal boundary of the delta. However according to water level piezometry some recharge is likely to occur from the Thaoge River system. Similar recharge processes are likely to occur along the Chobe River, Selinda Spillway and the Savuti Channel, although these have not been confirmed by piezometric measurements.

2.2.1.2 Aeolian Aquifers

Outside the fringes of the delta the Kalahari Group comprise aeolian and fluviatile sediments, predominantly fine to medium grained sand and silt with calcrete and silcrete intercalations. The beds form a widespread aquifer with a maximum thickness of about 150 m. The location of wells and boreholes in these areas is unevenly distributed and mostly related to where shallow, fresh groundwater occurs, such as along the western fringe delta area and in some areas at the bottom of major fossil river valleys. No major regional hydrogeological study has been carried out in northwestern Ngamiland, thus limiting knowledge of this area.

Due to the fine grained nature of the Kalahari sands, porosity and permeability are low which in turn limits recharge potential. Rainwater, rather than infiltrating the sand to any great depth, tends to be held in the upper layers from where it readily evaporates or is evapotranspirated. This is particularly true on dune crests, which usually support denser vegetation cover than interdune valleys. As a result water levels tend to drop quite significantly away from the delta fringes; for example depths of greater than 100 m in the sandveldt area west of the delta are encountered. Perched aquifers are developed where widespread calcrete deposition has occurred.

Recharge via surface runoff takes place only in areas of raised ground such as the Aha, Gcangwa and Tsodilo Hills to the west from where ephemeral channels originate. In the fossil river and interdune valley bottoms, though water during the rainy season collects in a series of small pans along them, direct infiltration is unlikely or minimal because of the accumulation of a relatively thick clay or silt cover.

2.2.2 Bedrock Aquifers

Fracture aquifers in bedrock are important where Kalahari aquifers are absent, such as the upper reaches of the Okavango (Cubango) River in Angola, the highlands of central northern Namibia, the Aha - Tsodilo Hills area of the Namibia - Botswana border and the Ghanzi - Chobe Foldbelt area just south of Lake Ngami. The latter includes Karoo Sequence and Ghanzi Group sediments, whereas the former three areas include Proterozoic rocks of Damaran age and older strata.

Where Kalahari sediments are thin (less than say 50 m) and unsaturated, or absent, direct recharge of fracture aquifers from meteoric sources is likely. In some parts of eastern Namibia greater thickness of Kalahari is encountered which is devoid of aquifers and the only source of groundwater is buried fracture aquifers. In this latter case recharge is thought to originate from through-flow from distal sources such as shallow aquifers or exposed bedrock, which receive direct recharge.

Bedrock aquifers exhibit no primary porosity with water being entirely controlled by fracturing. Although the Karoo sandstone may in places be an exception, fracture flow is likely to dominate over intergranular flow in this formation. Lying above the

bedrock and largely derived from it is the weathered zone grading outwards into regolith. This zone has extremely variable permeability and porosity, the aquifer properties being controlled by basement lithology and weathering products. Highly productive horizons may occur towards the base of the weathered profile where the rock still has its original structure and clay minerals are absent. The regolith can represent a good and easily located groundwater source where it is anomalously thick.

Groundwater potential from carbonate rocks is variable, and is dependent upon the presence of karstic features (e.g. caverns), fissures or faults. Such carbonate rocks are found at the Aha Hills to the west of the delta and in the Grootfontein area of central northern Namibia.

2.3 GROUNDWATER USE

2.3.1 Rural Consumption

Rural consumption of groundwater in the Okavango Basin is predominantly for domestic and livestock purposes. Two factors generally determine the method of abstraction and the construction of the well from which the water is abstracted. These are the level of demand (numbers of people and livestock) and the depth, below ground level, to the water table (i.e. static water level). Where demand is low and the static water level is shallow hand pumps are commonly used, but where water levels exceed approximately 30 m it is preferable to use motorised pumps, wind or solar energy. For higher demand situations, irrespective of the depth to static water level, motorised pumps, powered by diesel or electricity, are necessary to deliver the requisite amount of water.

It is generally the nature of the aquifer formation, consolidated or loose, and the depth to water that will determine the nature of the well used for water supply. In situations where the water table is shallow and the aquifer material is easily excavated, hand dug wells are feasible. In several parts of the Basin, often along dry, ephemeral watercourses, use is made of such wells from which bucket and rope are used to withdraw water. These types of wells are commonly found at cattle posts. The aquifer formation in many places is semi-consolidated and tends to collapse when inundated. As a result such wells seldom penetrate more than 1 m below the water table and suffer collapse after rainfall and runoff. Collapse is prevented by the installation of well linings, which are used in places but requires wider application.

Where water levels are deeper or where formations are too hard for manual excavation, mechanically drilled boreholes are constructed. Boreholes which are not properly constructed with suitable lining (casing and screen) and artificial filter pack are prone to silting up. The fine-grained nature of the Kalahari Group prevents development of natural packs. Screen slot sizes also play and important role. If too large, the borehole will draw in too much fine material. If the slots are too small, high frictional forces will reduce the efficiency of the borehole. For Kalahari sands, a 20-

slot (0.50 mm openings) screen seems to be ideal. The type of drilling method also affects the productivity of a borehole. It has been found that mud-rotary drilling in Kalahari sediments, one of the more successful techniques, causes significant formational damage, which in turn decreases the efficiency of boreholes. Boreholes drilled by reverse circulation lend themselves to a higher level of development resulting in higher efficiencies although this method is commonly extensive and the diameter of drilling limited. The use of rotary air percussion is often met with complete failure, through the formation of "wall cake" within the borehole. This wall cake effectively seals off the borehole wall and the hole is deemed dry and abandoned.

Most rural villages in Botswana are supplied with a borehole source through the Integrated Rural Village Water Supply Programme under the auspices of the Department of Water Affairs. Private consultants are commissioned to carry out siting and drilling supervision, while private contractors carry out drilling. Reticulation systems are also designed and constructed by the private sector. A representative from each village is chosen to carry out borehole and pump maintenance and keep records. It is the duty of this pump operator to report to the district council authorities.

In the Ngamiland District, village borehole yields are generally less than 10 m^3/h, however yields of up to 60 m^3/h have been obtained in some Karoo bedrock aquifers. Kalahari boreholes are seldom deeper than 50 m, however bedrock boreholes can reach over 200 m in depth. Boreholes, on average, tend to last 5 - 10 years before requiring replacement or rehabilitation. Decreased yields due to silting up or aquifer overexploitation, loss of equipment down the hole, and increased demand are the most common reasons for borehole failure.

Rural water supply in the communal farming areas of Namibia is the responsibility of the Department of Water Affairs Directorate of Rural Water Supply. Settlements in the communal areas were supplied water for domestic and livestock stock consumption free of charge but during recent years an effort has been made to change this policy. Water point committees have been formed that are slowly assuming a role in making the rural communities more self sufficient in terms of water supply. Although the provision of boreholes, pumping, storage and reticulation systems still remains the responsibility of the Government, the cost of pumping and equipment maintenance is slowly being handed over to the recipient communities.

2.3.2 Bulk Water Supplies

In Botswana, major town centres are usually supplied by a ***wellfield***, i.e. a group of boreholes contained within a relatively small area near the town. The higher demand in towns necessitates the use of a wellfield to provide an ample supply of water. Within the Okavango Basin, Maun is the only town of considerable size. Two wellfields and the Thamalakane River at Wenela currently supply the town, which is located at the distal end of the Delta. The Shashe Wellfield is the primary source of

water to Maun, producing from 60 - 80 % of the total water supply of about 1.2 Mm^3. The Thamalakane Centre Wellfield produces about 20 - 25 % of the supply, with the Thamalakane River making up the remaining 10 - 20 %.

A total of 36 boreholes have been drilled at the Shashe Wellfield since 1984. Of these, 19 were drilled in the shallow unconfined aquifer system in the Shahse River valley. Yields from these boreholes are influenced by periods of low flow in the Shashe River, which acts as the main source of recharge. The remaining boreholes were subsequently drilled into the middle semi-confined aquifer. Of these, twelve are currently used for production, accounting for 84% of the total abstraction from the wellfield. The remainder is provided by three of the shallow boreholes.

Production from these three sources is currently insufficient to meet the demand for Maun. Furthermore, pumping from the middle semi-confined aquifer at the Shashe Wellfield is inducing upward leakage of brackish/saline water from a deeper aquifer unit. Hence the Maun Groundwater Development Project was started in 1995 with the main objective of securing a safe sustained supply until the year 2012. Phase I of the project, exploration and resource assessment, was completed in 1997. Phase II, resource development, is currently underway.

2.4 GROUNDWATER QUALITY

2.4.1 Hydrochemistry

Groundwater quality within deltaic Kalahari aquifers at the distal end is fresh with TDS concentrations in the range from 100 – 2,000 mg/l. The lower values are associated with shallower (< 30 m) aquifers near seasonal sources of recharge. The TDS content increases with depth in the Kalahari aquifers from fresh to brackish to saline conditions. In areas where a low permeability lithological contact is found, the transition from fresh to brackish is abrupt. Outside stream valleys, within the interfluvial areas where hydraulic gradients are shallow and active recharge is poor, groundwater quality also deteriorates with distance from the stream valleys.

It has been suggested that, in aeolian Kalahari aquifers, groundwater quality deteriorates with depth and distance away from modern ephemeral drainage lines. Numerous freshwater boreholes have been drilled in the northwest Ngamiland along ephemeral channels where TDS content is generally less than 1,500 mg/l. Data from boreholes further away from such channels is scarce and the above suggestion is therefore considered speculative.

In Botswana it is thought that most bedrock aquifers buried under a significant thickness of Kalahari Group are characterised by brackish to saline water. However not enough boreholes have been drilled through a significant thickness of Kalahari sediments to confirm this. Evidence from the Namibian sector shows that water quality is variable and in places fresh groundwater may occur in bedrock aquifers under deep Kalahari cover.

Where bedrock outcrops or Kalahari cover is thin, groundwater is generally fresh due to continuous recharge. To the west (Dobe, Qwangwa and Xai Xai) groundwater in the Damaran quartzites and schists may have enhanced magnesium concentrations.

2.4.2 Groundwater Pollution Vulnerability

The following activities are usually associated with pollution:

- Sanitation
- Urban and Industrial Development
- Agricultural land use
- Waste Disposal

All of the above activities occur in the Okavango Basin Area. Pollution can occur either from discrete or separate sources, known as *point sources*, or from wider, more difficult to pinpoint sources known as *diffuse* sources.

In rural areas sources of contamination include pit latrines, soakaways, graveyards, natural fertiliser (manure), cattle and other livestock kraals and small refuse disposal sites. In areas of intense agriculture chemical fertilisers, pesticides, herbicides and insecticides pose an additional pollution threat.

Sources of contamination in larger villages and towns additional to those listed above include septic tanks, sewerage systems, abattoirs, tanneries (metals), dry cleaners (solvents), panel beaters (paints and solvents), filling stations (fuel leakages), waste disposal sites and mines.

Pollutants arising from both point and diffuse sources are transported downwards by infiltrating rainwater through the unsaturated zone and into the saturated groundwater zone. The effectiveness of such a process depends on the amount of groundwater recharge, the characteristics of the soils and underlying geological strata, and their thickness above the water table. Aquifer vulnerability can be determined on a point rating system based on these parameters, and presented in the form of aquifer vulnerability maps.

According to the Groundwater Pollution Vulnerability Map of Botswana, the Okavango Delta (including Linyanti) contains a groundwater resource requiring comprehensive protection. Sediments beneath the perennial swamps are *extremely* susceptible to groundwater contamination due to the direct hydraulic continuity with the floodwaters and the high permeability of the deltaic sediments. Groundwaters in the surrounding floodplain extending from the villages of the western fringe down to the Motshabeng Flats, up through Toteng, Maun and Kudumane are considered to be *highly* vulnerable to pollution. The Karoo sandstone outcrop south of Lake Ngami is also *extremely* vulnerable to groundwater contamination.

In the sandveldt area of western and northern Ngamiland in Botswana the groundwater resource in the Kalahari Group and underlying bedrock is considered to require only minimal protection, as groundwater vulnerability here is *low* or *negligible*. Significant depth to the water table and a reasonable attenuation capability of the Kalahari sands account for this. However bedrock outcrop areas such as the Aha

Hills and Tsodilo Hills are considered to be *moderately* to *extremely* vulnerable to groundwater contamination. This is due to shallower water levels, lack of soil cover and the dominance of fracture flow within these systems.

More detailed vulnerability assessments of the Maun area, in particular around the Shahse and Thamalakane Wellfields, have been conducted within the past few years. The findings of these projects are discussed in further detail in the next section.

No detailed assessments of pollution vulnerability in those parts of Namibia and Angola that lie within the Okavango Basin have been conducted.

3 REVIEW OF PREVIOUS WORK

3.1 ANGOLA

There is very little information available on the groundwater resources of the Cubango River Basin. Hydrogeological information is available from:

- “Servicos Geologicos de Portugal” (the Portuguese Geological Service) in Portugal;
- “Instituto de Investigacao Cientifica Tropical” (the Institute for Tropical Scientific Investigation) in Portugal;
- Articles published by the Junta de Ultramar, Lisbon, Portugal;
- Ministry of Geology and Mines (Angola);
- Documentation Centre of the DNA (Angolan Department of Water Affairs);
- “Hidrominas” the national enterprise devoted to hydrogeological research in the southern region of Angola;
- the University of Agostinho Neto (Geological department);
- the Laboratory of Engineering.

The most useful documents relating to different hydrological/hydrogeological aspects of the Cubango River Basin were obtained from these sources. During the investigation in became clear that none of the Angolan centres have been properly organised or updated for a long time. At times it is therefore difficult to identify and find the documents and reports required. After numerous visits to these centres in Luanda several of the reports and articles on the Cubango River Basin were found, dating back to 1917. They include information and data on the following features of the Cubango River Basin:

- Water resources: analysis of the hydrological, climatological and hydrometrical data
- Navigation : possibilities for the navigation in the Cubango River
- Geomorphology
- Soils; Suitability of the Cubango River Basin's soils for agricultural purposes.
- Water Resource Development: Identification of appropriate sites for the location of water resource development projects.

From the discussions held with the DNA, it was clear that this institution has not undertaken groundwater research in the Cubango River Basin at any stage, and that they do not have any hydrogeological data for this region.

The following paragraph describes the situation during the 60's and 70's:

> "The Cubango River Basin flows through one of Angola's least known and under-populated regions, known until now as 'land at the end of the world' (terras do fim do mundo" (from *Scheme of Water Resources Uses of Cubango River*, Carlos Quinteira Gois, Lisbon, 1973*).*

However, it should be noted that the principal water supply system of Menongue's population (Capital of Cuando Cubango District) are the "cacimbas" (manually dug wells of 10 to 20 m depth). A large proportion of these wells was built during recent years.

For this reason, it was decided to widen the search to include the collection of hydrogeological information from the neighbouring hydrological basins. Some geohydrological articles and reports on the "Lower Cunene" Region during 1950's and 1960's were discovered, and this information was considered to be an important contribution for this study.

At Hidrominas located in Lubango (province of Huila) a complete file of the hydrogeological data of a large number of boreholes drilled in the south of Angola since 1948 is held in this office. McDonald *et al*. (1990) report that the data for a large number of boreholes have been entered on a Lotus-123© database named AGADB. At the time of their reporting some 300 records of 13 fields each had been entered on this database. In Figure 2 the distribution of some boreholes from the AGADB system are shown. Although these are outside the Basin it serves to illustrate the fact that a) some data are available and b) the density of water point data in an adjacent area.

It is also necessary to refer to the most recent hydrogeological information prepared (1997) for the area covered by the Kalahari Sands in the south of Angola. This information was obtained from the conclusions of Project No 5 (Humpata 's project), "Water Resources study of the southwest region of Angola". This project was implemented by the Geological Department of the Agostinho Neto University, and the Geophysics Section of the Italian Ministry for Co-operation. The project is part of the existing development plan of the South of Angola and was designed to study the groundwater resources of the southwestern region of the country.

The Geological Map of Angola (1: 1,000,000) compiled in 1988 is available from the Ministry of Geology and Mines in Luanda. Although geological maps at scales of 1:100,000 and 1:250,000 are available for various parts of the country these do not cover any part of the Okavango (Cubango) Basin.

The World Bank (under UNDP) commissioned a hydrological assessment of Angola as part of a SADCC initiative in 1990. The report (MacDonald and Partners, 1990) is the most comprehensive account of the groundwater resources and includes a hydrogeological map of the country.

3.1.1 Description of the Documents Collected by Bereslawski (1997)

The most relevant paragraphs of the majority of documents collected are included, as well as a brief comment of the principal characteristics of each of the documents analysed.

José Bacelar Bebiano (1917)

Relatório sobre reconhecimentos geológicos no distrito de Benguela, Huambo, Cubango e Cassinga (Mapa geológico, Annexo 1).
Report on the geological reconnaissance of the districts of Benguela, Huambo, Cubango and Cassinga.

This report contains the description of the geological reconnaissance carried out between Huambo and Cassinga's towns, in 1917. The geological map compiled on the basis of this visit is included in Annex 1. The paragraph of most interest is:

"From the 175 to 204 kilometre mark, there exist granites and granulites, as well as soils with slime and quartz. In the Calomba River, the soil consists of microgranites. Close to Ecucha River the soils include microgranites and in Cativa (also close to Ecucha River) there is one basic porphyries rock, the porphyry "labradorico", which shows crystals with a size of 3 to 4 cm. The augite shows significant signs of decomposition; and from here on metamorphic formations can be found such as "gneiss's amphibolicos" nearby the Mission Station. The Cubango River shows this type of rock, which originates in the north. Between Cubango and Cassinga the soil is formed from granites and gneiss and close to the Ulonda River in a big area we have slime (??)".

Vieira, E., (1951)

Pesquisa e captação de águas subterráneas no litoral e sul de Angola.
Groundwater data collection and research in the northwest and southern part of Angola.

This document was compiled in 1951. It includes the annual isohyetal map of the country, one colour map of the phytogeografic areas of Angola, and another map showing the hydrogeological research carried out and programmed in the south of Angola. It includes a brief description of the different water abstraction methods used in southern Angola. Unfortunately, no hydrogeological information is available on the Cuando Cubango District.

Palm, C., (1954)

Plano de Estudos da Bacia Hidrográfica do Rio Cubango, em Angola, para fins de rega, produção de energia e navegação.
Study plan of the Cubango River Basin in Angola on irrigation, energy generation and navigation.

This document, prepared in 1953/54, presents the following hydrological information (Annex 1):

- Data series with a maximum of 12 years of annual rainfall records..
- Climatological data (temperature, humidity) from the climatological station of Chitembo, period 1944/1952.
- Annual evaporation data for Artur de Paiva (Cuvango) and Serpa Pinto (Menongue) stations.
- Hydrometric data at Mohembo (Okavango River in Botswana)

This document includes several photographs of the Cubango River. The annual isohyet maps presented in this document are not of major interest, as they are based on a very short series of precipitation data.

Martins, J. A., (1960)

Estudo duma prospecção geológica na região do Menongue.
Geological prospecting in the Menongue Region.

This is a short geological description from the mineralogy point of view, and includes names of the principal minerals identified in this region.

Unknown (1960)

Desenvolvimento do Sul de Angola, II Volume.
Development of the south of Angola. Volume II.

This document was compiled in 1963, and includes a complete description of the natural resources in the South of Angola: District of Moçamedes (today Namibe), Huila and Cuando Cubango.

Since it was produced 34 years ago, most of the information, such as population data, number of schools, types of economic activity etc is outdated. Nevertheless, it contains useful data and interesting information relating to geology, mining resources, hydrology, hydrogeology, climatology, environmental aspects, soils, fauna etc.

From the water resources chapter:

"In the south of the Huila district, as a result of the absence of any permanent water course except that of the Cunene River, a large number of well drillings have been carried out, either in the crystalline rocks or in the Kalahari sediments. In general, the majority of groundwater investigations carried out were successful. In wells with an average depth of 30 m depth built either in the granite or gabro-anorthositic rocks, maximum yields of 15,000 l/h were obtained. Groundwater investigations in the Kalahari sediments were less successful, due to the low

permeability values, and particularly when a considerable sediment thickness exists.

It was verified that when the Kalahari sediments contact crystallite rocks at a conglomerate formation it is possible to find water, either in the first part of the altered and fractured crystalline rock or in the conglomerate formation when its shows an adequate permeability value. Groundwater yields rise up to 10,000 l/h.

With regard to the Cuando Cubango District, no data and information are available. Nevertheless, this does not seem to be a problem, since there are permanent water courses."

Marques, M. M. (1965)

Notas sobre a geomorfología de Angola. (testemunhas da aplanação do terciario médio no leste de Angola - Distrito de Moxico).
Notes on the geomorphology of Angola.

Scientific article issued by the Garcia da Orta editions, carried out in the "Tropical Pedology study centre of Lisbon". It describes the different morphological units of the Moxico District (Annex 1) in Angola.

The most interesting paragraphs are those relating to the geomorphological description of the Cuito River area:

"The western sandy, plateau area with shifting relief.
This geomorphologic unit was formed by shifting relief (relevo movimentado) made up of different plateaux whose altitudes decrease slowly from west to east and from north to south.

Within the climatic conditions, the morphologic features of this relief are characterised by its lithology. The lithology is formed by sand deposits of wind-blown origin, which in some areas are 200 m thick. The erosive action of Cuito and Cuando Rivers over this sandy formation forms has formed deep valleys with long planes, seldom with swampy bottoms, but with quite steep slopes (often 15 %). The plateau summit is horizontal with dense vegetation of medium height.

Summing up: the stream network, due to its erosive nature, has quickly incised into the topography due to the erosive character of the rock. For this reason the polymorfic sandstone has been eroded away leaving dolerite outcrops. At some points basement complex or rocks of the Karoo series can be seen.

The part of the Cubango River Basin included in this study is the Cuito River. The Cuito River and its tributary, Cuanaval, runs in approximately a north - south direction, parallel to the Cuando River in the western area of the Moxico Region.

In conclusion, the principal facts to be noted are:

1) The Cuito, Cuando, Luanguinga, Lungué, Bungo, Luena and Cassain Rivers have their origins in the same morphological unit, i.e. the sandy plateau area with shifting relief;
2) The principal importance of the Atlantic Ocean hydrography network in comparison with the Indian Ocean hydrography network, is that in the Cameia Region, where the east - west divide is to be found, being on the edge of the left-most tributary of the Zaire River. (Cameia River);
3) The Cuando River may have captured the streams having a NNW - SSE direction and a N - S direction which may at one stage have belonged to the Cubango River system;
4) Finally, the balance to the north of the tertiary flattened (aplanação do terciario) area appears not to have great influence on the actual hydrography network of Moxico Region, and from this it can be concluded that these rivers could have been formed later than the sandy formation of the high plateaux."

Marques, M. M. (1965)

Contribuição para o conhecimento da Estrutura Geológica da região de Silva Porto (hoje cidade de Cuito).
Contribution to the knowledge of the geological structure knowledge of the Silva Porto (now Cuito) Region (capital of Bie Province).

Article issued by García da Orta technical editions in Lisbon. It describes all the conglomerate formations of the Cuito River Valley. The article has the following summary:

"Conglomerate formations occur in the Cuito Valley between Silva Porto and Silva Porto-Gare, at an elevation of 1,650 m. Observation of new geological formations seems to show:

1) there exists a conglomeratic formation of glacial origin overlying gneisses of the Basement Complex;
2) over this formation there is a relatively deformed schist clay - sandstone complex;
3) this complex is covered by another conglomerate formation, coarse on the base and fine on top.

These formations allow the following hypothesis:

With respect to the evolution of the local relief: after formations 1) and 2) had covered the Basement Complex a local depression would have occurred with the formation of an inner basin, which was later filled by relief erosion. If these observations are proved to be correct and once the chronology of the geological formations is established, the date of the planation that levelled formation 3) with the Basement Complex and, consequently the date of the lower planations that occur on the Angolan Antique Plateau can be determined."

Hydroconsults (1969)

Popa Falls - Hydro power scheme, preliminary feasibility investigations – 1969.

This document was prepared in 1960 by the Department of Water Affairs, South Africa. This report presents a preliminary feasibility study of the Popa Falls dam which was planned for the Okavango River, just a few kilometres to the south of the Angola and Namibia border.

Góis, C. Q. (1968)

Esquema do aproveitamento hidraúlico da bacia do Rio Cubango. Estudo hidrológico.
Utilisation Plan for the Cubango River Basin; Hydrology study.

Data included in this report are:

- Annual precipitation; 1943/44 - 1966/67 (several stations)
- Statistical study of annual precipitation.
- Monthly runoff and flows of the Cubango River at the following stations:
  - Chinhama (Lat. 13° 03'S; Long. 16° 07'E; 1,799 km^2) 1963/64 - 1966/67
  - Artur da Paiva (Lat. 14° 28'S; Long. 16° 07'E; 7,185 km^2) 1963/64 - 1966/67
  - Caiundo (Lat. 14° 22'S; Long. 16° 30'E; 38,486 km^2) 1957/58 - 1966/67
  - Mucundi (Lat. 16° 13'S; Long. 17° 41'E; 50,135 km^2) period 61/62 - 66/67
  - Runtu , 1946/47 - 1966/67
  - Sambio, (Lat. 17° 53'S; Long. 20° 04'E; 84,368 km^2) 1963/64 - 1966/67
- Monthly flows and runoff in the Cutato River at:
  - Cutato (Lat. 14° 22'S; Long. 16° 30'E; 3,683 km^2) 1963/64 - 1966/67
- Monthly flows and runoff in the Cuchi River at:
  - Cuchi (Lat. 14° 39'S; Long. 16° 54'E; 9,214 km^2) 1963/64 - 1966/67
- Monthly flows and runoff in the Cuvelai River at:
  - Cuvelai (Lat. 14° 41'S; Long. 17° 22'E; 1,390 km^2)
- Monthly flows and runoff the Luauca River at:
  - Serpa Pinto (Lat. 14 ° 40'S; Long. 14° 41'E; 976 km^2) 1964/65 - 1966/67
- Monthly flows and runoff in the Cuebe River at:
  - Serpa Pinto II (Lat. 14° 40'S; Long. 14° 41'E; 1,340 km^2) 1961/62 - 1966/67
  - Capico (Lat. 15° 32'S; Long. 17° 35'E; 9,758 km^2) 1964/65 - 1966/67
- Monthly flows and runoff in the Lussinga River at:
  - Lussinga (Lat. 14° 35'S; Long. 18° 10'E; 575 km^2) 1964/65 - 1966/67
- Monthly flows and runoff in the Longa River at:
  - Longa (Lat. 14° 36'S; Long. 18° 28'E; 1,122 km^2) 1964/65 - 1966/67
- Monthly flows and runoff in the Cuiriri River at:
  - Cuiriri (Lat. 14° 41'S, Long 18° 40'E; 1,769 km^2) 1964/65 - 1966/67
- Monthly flows and runoff in the Cuito River at:

  - Cuito (Lat. 15° 07'S; Long. 19° 10'E; 15,193 km^2) 1965/66 - 1966/67
  - Cuito Cuanavale (Lat. 15° 10'S; Long. 19° 11'E; 22,198 km^2) 1966/67
  - Ponto de Passagem (Lat. 15° 40'S; Long. 19° 10'E) 1963/64 - 1966/67
- Peak floods statistical analysis at the Rundu station.
- Monthly evaporation data (open water surface, several stations)
- Annual isohyetal maps of the Cubango Basin
- Several graphs relating to monthly flow records.

Góis, C. Q. (1973)

Esquema do desenvolvimento dos recursos hídricos da bacia do Rio Cubango.
The Water Resources Development Plan of the Cubango River Basin.

The Water Resources Development Scheme of Cubango River was compiled in 1973, and consists of five volumes. Each volume comprises:

- General description (Table 1 - Ref. 10)
- Designs (located in DNA library)
- Hydrological study (Table 1 - Ref. 9)
- Agronomic study (Table 1 - Ref. 11)
- Geological study (not located)

In volume one, several sites for the construction of surface water resource works were defined. It clearly identified 22 sites for the location of dams to be used for water resources regulation and energy production purposes.

The paragraphs of main interest are:

Geology chapter:

From observations, it was found that three groups of rocks are present in this basin. The igneous and metamorphic are located in the region with most pronounced relief, in the northeast part of the Basin, the sedimentary rocks are found in the flat area, located in the northeast, and in the south, (i.e. the remainder of the Cubango River Basin.)

Igneous rocks occupy are to be found in some parts of the northeastern region. They include:

- ante-permic formations, which generally includes, granites, porphyries and porphyrites, and a little portion of sienitos located in the Northeast of Arthur da Paiva town.
- Un-dated "ante-cambric formations", continued by granites granodiorites and quartzodiorites, and in the Arthur da Paiva Region (now Cuito), a small portion of dolerites.

Metamorphic rocks occur close to the northeast limit of the Basin, and they are represented by Basement Complex, and are made up of various gneisses, metamorphic schists, quartzite's, schists quartzite's and crystalline calcareous.

The metamorphic formation from the superior group of Oendolongo System looks similar to igneous rocks. They are dispersed in small pockets, and are found in the form of weak metamorphic rocks with banded ironstone (principally), and quartzites, sandstone crossed by felsites and porphyric dikes.

Sedimentary formations form the majority of the Basin. Geologically they characterise the Cubango River Basin, and dictate the watercourse regime and economic potential of this region.

These formations are the Kalahari superior formations from the Pleistocene and more recent ones, essentially sandy with some levels of gravel and lateritic deposit overlaying polymorphic sandstone, quartzite's, sandstone and "milicificados" (?) calcareous from the lower Kalahari formation.

Relating to the water supply system found in the Cubango River Basin:

"…The uniform distribution of the stream channel network together with the good water quality and the permanency of the main water courses has allowed the establishment of an simple water system supply based on a pumping system from the water course, followed by a distribution water system with a complexity related to the number of inhabitants supplied. In some extreme cases when this water supply system is not possible, (essentially in the arid region of the south of the Basin between Cuito and Cubango Rivers), the population has been supplied by "cacimbas" (manually dug wells)."

Diniz, A. C. and de Barros Aguiar, F. Q. (1973)

Recursos en terras com aptidão para o regadío na Bacia do Cubango.
Suitability of the Soils of the Cubango River Basin for irrigation purposes.

Document drawn up in 1973 by the Agronomic Investigation Institute of Angola, and contains a detailed inventory of the Cubango Basin's soil suitability for irrigation. Ten maps were included (1:100,000) showing the suitable irrigatible soils which are located along the Cubango and Cuito Rivers. The coloured maps were well detailed and well presented.

Also included were some black and white photographs showing different soil types, and one black and white Pedology Map of Angola (1:2,500,000) which was drawn up from the Pedology schemes carried out by the Pedology team working in Angola and Mozambique at that time.

Neto, M. (1973 a and b)

Plano de Coordenação para o abastecimento de água ás regiões pastoris do Sul de Angola.
Co-ordination plan for water supply to the cattle regions of the south of Angola.

Estudos hidrogeológicos e Aproveitamento de águas. Relatório da execução 1973. Plano de Coordenação para o abastecimento de água as regiões pastoris do Sul de Angola.
Hydrogeological studies and water research. Completed works reports from 1973, Co-ordination plan for the water supply to the cattle regions of the south of Angola.

Both these reports were produced between 1954 and 1973, and describe the groundwater surveys carried out in the south of Angola by the Hydrogeological team (brigade) of the Angolan Ministry of Geology and Mines. These documents represent the only source of hydrogeological information available in Luanda, relating to the groundwater surveys carried out during the 20 year period of 1954 - 1973) in the south of the country, and include the Cuando Cubango District.

The most relevant information presented in these documents is: names of the wells built, groundwater yields (flow rate obtained), human and material resources in charge of this work.

These documents do not contain much hydrogeological information, due to the lack of information on well localisation or geological data, as well as to the absence of any technical data relating to successful boreholes.

Courtesy of Mr Paca Vira, from the Centre of Documentation of the Ministry of Geology and Mines, it was possible to examine a large number of hydrogeological annual reports (1958 - 1973) with information on the hydrogeological surveys carried out in the south of Angola. The following table, drawn up from these reports, summarises some characteristics of the boreholes drilled in the Cuando Cubango District.

CUANDO CUBANGO – DISTRICT

Name	Nº of construction proposal	Borehole hypothesis	Flow rate litres/hour
Lupire	2/71	S.2	3,100
Vila N. da Armada	-	S.1	1,800
Vila N. da Armada	-	S.2	2,000
Vila N. da Armada	3/71	S.4	3,400
Nordatlas	13/AM/73	S1.H1(mechanical research)	800 - depth. 66 m
Nordatlas	13/AM73-4/73	S2.H3(mechanical research)	10,550 - depth. 42 m
Flecha	68/AM/73		

Note: each construction proposal represents the result of several works and studies carried out to identify water point sites.

From these reports it was apparent that in 1971, five boreholes were drilled in the Cuando Cubango 's District, with a total depth of 221 metres, but only two of them were finally built.

According to the 1968 report, only one borehole was built in the Cuando Cubango's District with a flow rate of 6,500 l/h (From Biennial report 67/68, of Mascarenahs Neto).

Marques, M. M. (1977)

Esboço das grandes unidades geomorfológicas da Angola (2a aproximação).
An idea of the geomorphology units of Angola (second approximation).

Scientific article written in 1976 by the Tropical Pedology Study Centre, from the Junta de Ultramar, Lisbon. In this report seven large geomorphologic units were defined:

- Antique plateau,
- Range marginal mountains,
- Transition area,
- Northern belt of Congo's Basin,
- Northern belt of Caalari's Basin,
- Zambezi Basin and
- Coastal belt.

To make this geomorphologic classification the environment equilibrium was first considered, taking also into account the relationship between pedelogy and morphology. The following most relevant paragraphs are transcribed:

"V Northern belt of Kalahari's Basin:

This is a geomorphologic unit whose relief is influenced by the Namibe endorreic's basin evolution. Three sub-units were considered:

a) Endorreic depression of Cuvelai - Lueque, the flattening (aplanação) medium Tertiary's residual region, covered by thick windy sandy deposits, accepting that it constitutes a recently stabilised region, from this reason it could be accepted that an equilibrium in the pedogenesis/morphogenesis relation exists.
b) Cubango's Basin, this is a similar region to the other one a) although it was probably stabilised long time before, as it seems to be because the pedogenesis predominance over the morphogenesis.
c) Cunene's depression - depressioned area influenced by the antique quaternary Cunene's capture to the Atlantic Ocean, this region is considered as "intergrade" region.

In the geomorphological map of Angola included in the article, the three geomorphologic areas were well identified, and it indicated that the Cuvelai - Lueque area belongs to the region delimited by the Cunene and Cubango's Rivers, usually referred to as the "Lower Cunene Region".

Unknown

1º Encontro da Cooperação Universitária - Italo – Angolana - Universidade Agostinho Neto. Luanda 1997

First meeting of the Italo - Angolan University Co-operation. University of Agostinho Neto, Luanda 1997

Mr. Morais, from the Faculty of Science, Department of Geology, made it clear that it had been impossible to carry out any hydrogeological research in the Cubango River Basin due to difficulties within the institution (budget, lack of qualified personnel, etc.) and to security problems in this region over the past 20 years.

Mr. Morais recommended that the conclusions derived in the "Project 5, Water Resources study of the southeast region of Angola" could be used as a guideline for any future hydrogeological study to be carried out in the Cubango area.

The most important conclusions from the this study related to the Kalahari area:

"In 1994,95,96 three geophysical missions took place in the southwestern region of Angola, the principal purpose was to identify new water supply sources, and to define the most appropriate methodology for the hydrogeological surveys according to the aquifer's characteristics. It should be remembered that Hidrominas and UNICEF also participated in these hydrogeological research studies.

On the bases of the different aquifers' typology in this region, four areas were therefore defined: Namibe, Lubango - Humpata, Chiange and Kalahari. The vertical electric and the electromagnetic methods were chosen for the aquifers in tectonised areas and the seismic vertical (refraction/reflection) method in the contacted and fractured aquifers (aquíferos de contacto e fracturação) with sedimentary porous bodies and altered surface.

In the Kalahari area, where the gabro-anortosite complex of rocks are covered by Neogene - Quaternary continental deposits which are hundreds of meters thick, it was firstly recommended to use the seismic refraction - reflection method, and secondly to use the seismic vertical electrical method as a support method, to identify the porous and saturated water levels inside the continental formations."

LOWER CUNENE REGION

During the hydrogeological research process it was clear that the Lower Cunene Region has been widely studied, and that various hydrogeological surveys have been carried out since 1951.

The lower part of the Cunene Region is situated between the Cunene and Cubango Rivers, inside the Kalahari northern belt, and shows very similar geological and geomorphologic characteristics to those of the Cubango River Basin (Monteiro Marques article, Angola main geomorphologic units. Ref. 14).

Several geohydrological research studies were carried out between 1950 and 1976 (Table 2, Ref. 1, Ref. 2) due to the absence of permanent water courses, taking into account the water supply demands as well as the water requirements for the numerous herds of cattle that used to be in this region.

As a result of these studies, a considerable number of hydrogeological reports were written. The complete borehole data are included in these reports, as well as relevant information such as geological profile, flow rate, groundwater chemistry, geological schemes, general hydrogeological behaviour of the various aquifers existing in this region.

Ferràо, C. A. N. (1961)

A Hidrogeologia e o problema de Abastecimiento de Agua ao Baixo Cunene.
The Hydrogeology and the Water supply problem of the Lower Cunene Region.

The article "The hydrogeology and the water supply problem of the Lower Cunene Region" written by Carlos Neves Ferrao, in 1961 synthesises and summarises the information gathered from all those reports.

The following hydrogeological conclusions have been drawn from this article:

"The Lower Cunene Region is located in the extreme northwest of the Kalahari interior basin, and belongs to the 'Ovamboland' depression, limited to the south by the Otavi axis. The whole region constitutes a vast plain delimited by the Cunene and Cubango Rivers. It shows a smooth and apparently uniform slope, with north - south direction, close to 50 cm/km. The altitude in the northern area is approximately 1,200 m and in the south 1,130 m. The annual precipitation decreases progressively from the north (900 mm) to the south (528 mm).

The Water Resources balance carried out according to the Thornthwaite method, considering 100 mm as the soil storage capacity, demonstrated that the Lower Cunene Region is characterised by a marked water deficiency, which increases gradually from north to south.

The Lower Cunene Region is occupied by typical continental sediments from the Kalahari formations. Its maximum depth is unknown. The deepest borehole drilled in this region, was 210 m deep without exceeding the sand and sandstone area.

The sandstone thickness plays a very important role in the groundwater occurrence (development).

Only big storms result in a rise of the groundwater table level. In the northern part of the region it was noted that the rains caused a rise of the water table levels, even during the years of low precipitation.

The groundwater mineralisation shows lateral and deep variability. Taking into account that the flow velocity is very low, it can be accepted that the mineralisation increases from the north to the south. Nevertheless, it is evident that the mineralisation reflects the aquifer's composition and nature of its sediments.

Data on evaporation recorded in superficial wells (depth of less than 10 m) during 1951 to 1955, showed an average of 100 mm/day or sometimes more. Measurements of the water table, carried out at the same time, verified that the water level decreases more quickly when the levels of evaporation are high. It was also verified that the water levels could decline by 50 cm per month.

It is relatively easy to identify the water table in the superficial sands. Its occurrence depends on the existence of the sandstone layer as well as its thickness, which in general does not exceed 6 m in deep. The best indicator of the existence of these phreatic waters (water table) is the fact that thousands of "cacimbas" were built in this region by the local people.

Due to the irregularity of the shallow artesian aquifers as well as the type of mineralisation, in some cases it is necessary to carry out several drillings before deciding on the most appropriate site for the construction of the borehole.

Deep artesian water: Nothing is known relating to the nature and depth of the sediments bed. From the boreholes drilled of hundreds of meters in depth, it was verified, that the sands are wet and are submitted to large pressures, which gradually increase in depth.

The Geological and Mine's team drilled 478 boreholes. A large proportion of them was installed for hydrogeological surveys, and the others for hydrological observations and water resources research.

The flow rates obtained were between 150 l/h to 10,000 l/h. In general flow rates of less than 5,000 l/h could be expected. The results from the borehole water samples collected, showed that they are of good chemical quality.

Some plant species such as: *Ficus hererorensis*, *Ficus thonningii* and *Diospyros mespiliformis* are important from the hydrogeological point of view. The latter's roots penetrate deep into the soil and sometimes reach the artesian aquifer. This is an rare situation and may be a unique example of a plant that can indicate the existence of groundwater."

3.2 BOTSWANA

3.2.1 Early Work of Significance

The following list of references outlines the major works carried out in the 1970's and early 1980's to help establish the geology, and to some degree the hydrogeology, of the Okavango Delta and the Ngamiland District in northwestern Botswana. These works are still widely referred to in today's literature.

Baillieul, T.A. (1979)
Makgadikgadi Pans Complex of Central Botswana. Bulletin of the Geological Society of America, Pt 2, 90, 289 - 312 (available from Botswana Geol. Survey).

The Makgadikgadi Pans Complex forms a large and unusual surface feature in the central part of Botswana. The two major pans of the complex, Sus and Ntwetwe, comprise an area in excess of 8,400 km^2. The pans occupy a basin that is the lowest point in a drainage system extending into Zimbabwe, Angola and Namibia. The history of the pans is complex and is closely tied to the great climatic changes and tectonic activity that have affected this area since late Tertiary time and which continue today.

Continuing seismic activity in Botswana has been linked to the East African Rift System. Considerable work has been undertaken to trace the rift zone beneath the Okavango Swamps, scene of the most intense earthquake activity. Little published information exists, however, on the adjacent Makgadikgadi Pans and their relation to this same rifting process. This paper provides a review of knowledge about the pans at the time of writing, and correlates investigations of nearby areas with some new data.

Hutchins, D.G., Hutton, L.G., Hutton, S.M., Jones, C.R., & Loenhert, E.P. (1976)
A Summary of the Geology, Seismicity, Geomorphology and Hydrogeology of the Okavango Delta. Geological Survey Department Bulletin 7. Lobatse, Botswana (available from Botswana Geological Survey).

The first significant summary of the geology and hydrogeology of the Okavango Delta, still widely quoted to this day. The report followed upon numerous geophysical surveys conducted since 1970 by the Geological Survey Department. Inference is made from geophysical investigations on the extension of different bedrock units under the swamps. The structure, seismicity and geomorphology are interpreted from the results of remote - sensing surveys. The summary of the hydrogeology is somewhat limited due to lack of information at the time. The hydrochemistry report provides a useful description of swamp water chemistry, groundwater major ion chemistry and isotopic composition of waters. Very useful maps accompany the report, including solid geology, structural geology, satellite imagery, geomorphology and hydrochemistry maps.

Meixner, H.M. & Peart R.J. (1984)

The Kalahari Drilling Project. A report on the geophysical and geological results of the follow-up drilling to the Aeromagnetic Survey of Botswana. Geological Survey of Botswana, Bulletin 27, 224 p (available from Botswana Geological Survey).

This drilling programme carried out jointly by the Canadian International Development Agency and the Geological Survey of Botswana, was a follow-up to the 1975 - 1977 Reconnaissance Aeromagnetic Survey. Its aim was to obtain more information about the geology and mineral potential of those areas covered by Kalahari sands, by drilling selected major magnetic features identified by the aerial survey, and thereby establishing criteria for the interpretation of other magnetic anomalies.

In the first phase, ground magnetic surveys were carried out over twentysix selected aeromagnetic anomalies. During the second phase, seventeen boreholes were drilled essentially to confirm pre-Karoo depths in thirteen of these anomalies. The interpretation of the air and ground geophysical data was correlated with the geological data from each borehole drilled. Finally, a map of the solid geology of western Botswana and adjacent areas was compiled from all the available data.

It is concluded that the programme of follow up drilling to a great extent confirmed the general accuracy of the magnetically interpreted regional deep geology of the area. The existence of magnetic basic intrusives of the Tshane and Xade Complexes was confirmed, as was the continuity of the coal-bearing Karoo strata throughout western Botswana and of the possibly mineralised Ghanzi - Chobe Foldbelt in northern Botswana.

Reeves, C.V. (1978)

The gravity survey of Ngamiland, 1970 - 1971. Geological Survey of Botswana. Bulletin 11, 84 p (available from Botswana Geological Survey).

During 1970 and 1971 some 1,500 gravity observations were made over an area of 70,000 km^2 in Ngamiland. Studies of Botswana have shown that the vast inland swamps of the Okavango Delta are an area of considerable earthquake activity, thought to be associated with rift faulting. However, Ngamiland is characterised by extremely low topographic relief and the solid geology is nearly everywhere concealed by Kalahari sands and recent fluviatile sediments. The gravity survey was designed to investigate the gravity anomalies which major geological structures concealed below these sediments might be expected to produce.

Part I of this Bulletin describes the field procedure and the reduction of the gravity data to produce a Bouger Anomaly Map of the area. In Part II a geological

interpretation of the Bouger Anomaly Map is discussed. Control provided by the Okavango seismic refraction survey of Greenwood and Carruthers (1973) and commercial aeromagnetic coverage is used in the interpretation of anomalies associated with major faults bordering the Okavango Delta, and some limits are set to the thickness of recent sedimentary cover overlying the solid geology within the delta. The geological structure of Ngamiland as a whole is reviewed in light of the new data at the time.

Wright, E.P. (1978)

Geological studies in the northern Kalahari. Geographical Journal. 144 (2), 234 - 249 (available from Botswana Geological Survey).

The geology of the northern Kalahari Region in Botswana is described. The discussion is concerned with the Kalahari Group, which may range in age from Cretaceous to recent. The older Kalahari beds of residual and fluviatile silcretes and calcretes are relatively thin compared to probably equivalent formations in the main Kalahari Region to the south and it is considered that they accumulated in an independent drainage system separated from the main Kalahari Basin by the stable Ghanzi Ridge. The dune bedded Kalahari sands are common to both regions although they may have been attenuated over the ridge. The youngest deposits are the sands and silts of the Okavango Delta, which accumulated in a downwarped area. A hypothesis is presented linking the early flow of the Okavango with the Zambezi and relating a major change of course and consequential formation of the swamps to Plio - Pleistocene cymatogenic movements.

3.2.2 Recent Work of Significance

The following list contains work carried out over the past 10 years, focusing primarily on understanding of hydrogeological processes, groundwater resource assessments, water supply projects and aquifer contamination issues.

Gabaake, G. (1989)

A report on an Investigation of the Hydrogeological and Hydrochemical Conditions in Northwest Ngamiland - Botswana. Department of Geological Survey, Unpublished Report, 1989 (available from G. Gabaake, Principal Hydrogeologist, DWA).

This unpublished post graduate thesis provides a good overview of the hydrogeology and hydrochemistry in the large region in the west of Ngamiland adjacent to the Okavango Delta. Previous accounts from this area focussed primarily upon geology, with only very little attention given to hydrogeological aspects.

The main practical part of the study included establishing the piezometry amongst a number of strategically selected boreholes to determine regional groundwater flow

patterns, and to provide some insight into recharge and discharge processes. Regional groundwater flow, as previously suspected, was found to be from west to east. Recharge areas identified in the Aha Hills, Nxauxau area and Tsodilo Hills and further areas in eastern Namibia. Southern regional discharge suggested to be just north of Lake Ngami or the Thamalakane Fault, the latter acting as a groundwater flow barrier. In the central - northern area of western Ngamiland, regional flow beneath the Okavango Delta into the Linyanti System or the Mababe Depression is hypothesised, although this cannot be confirmed with great deal of certainty. Regional discharge processes still remain a large unknown with respect to Okavango Basin hydrogeology.

Hydrochemical and environmental isotope analyses were also carried out as part of the project. Hydrochemical evolution along groundwater flowpaths identified, in particular and as expected, an increase in chlorides, calcium, TDS and a decrease in sulphate. Low TDS in areas close to pans suggest a probable recharge mechanism associated with these features. Over the whole study area, the presence of bicarbonate type water attributed to significant amounts of recharge. This, however, could not be confirmed by the isotopic analyses.

McCarthy T.S., Ellery, W.N., & Gieske, A. (1994)

Possible Groundwater Pollution by Sewage Effluent at Camps in the Okavango Delta: Suggestions for its Prevention. Botswana Notes and Records, 26, 129 - 138, 1994 (available from The Botswana Society).

Although the title implies a pollution study, the report mainly describes hydrogeological process that occur in and around islands of the Okavango Delta and offers suggestions to how effluent should be discarded taking these processes into account. Thus no reference to any particular contamination incident is made. The paper is useful for understanding island hydrogeology of the Delta, an area, which is usually poorly understood due to the lack of groundwater data.

The findings are based upon a number of other studies conducted by the authors (see next section). It has been found that the interiors of islands, both permanent and seasonal, act as groundwater sinks and that recharge takes place from around the outer edge of the vegetation fringe. The sensitivity of vegetation to groundwater salinity provides a ready means of assessing the salinity distribution in groundwater, and hence the location of effluent discharge and borehole sites.

Mokokwe, K., Mabua, I., Busch, K. & Stampe, W. (1995)

Groundwater Pollution Vulnerability Map of the Maun Area. 1:50,000. Sheet Nos. 1923 C4 (Maun-N) and 2023 A2 (Maun-S). Report No 10. Technical Co-operation Botswana Department of Geological Survey and Federal Institute of Geosciences and Natural Resources, Federal Republic of Germany (available from Department of Geological Survey).

This report accompanies and describes the development of a groundwater pollution vulnerability map for the Maun area. The map demarcates areas of extreme, high, moderate, low and negligible groundwater vulnerability. Additionally water protection zones of wellfields are indicated. The map is intended to be of particular use for land use planning, selection of waste disposal sites and water supply development.

The study reveals that septic tanks are the main sources of pollution, particularly those at two lodges along the Thamalakane River upstream of the Thamalakane Wellfield. Other significant risks identified include sewage oxidation ponds, the BMC treatment plant, filling stations/fuel depots, the town landfill and concentrations of livestock.

Extreme areas of vulnerability identified include the flooding areas of the Okavango Delta and along the Boro, Shashe, Xotego, Thamalakane, Boteti and Nhabe Rivers. These areas coincide with important aquifers where the water table is located with 7 m of the surface, in highly permeable sediments. Most of the area west of the Thamalakane River is classified under high vulnerability, including the adjacent areas discharging from the Delta where the water table is shallow and groundwater recharge occurs. Areas of low vulnerability, ideal for waste disposal sites, are east of the Thamalakane River and South of the Nhabe and Boteti Rivers. The current landfill, located in a high vulnerability area, is recommended for closure. A new proposed site is located in a area of low vulnerability.

Water Resources Consultants (Pty.) Ltd. (1997)

Maun Groundwater Development Project - Phase 1: Exploration and Resource Assessment. Final Report for Botswana Department of Water Affairs. October (available from Department of Water Affairs).

The Department of Water Affairs initiated the Maun Groundwater Development Project to assess groundwater potential to meet the current shortfall and future water demands for Maun. Initially eight areas were identified for shallow exploration in the Kalahari Group. Four were located along river valleys that commonly receive outflow from the delta (Thamalakane, Boro and kWh); two along river valleys that receive outflow only very intermittently (Nxotega and Kunyere) and two north of the Kunyere Fault in areas closer to the perennial swamps where recharge during the annual flood events would be expected to occur over a broad area. As the exploration advanced and with the input of airborne electromagnetic survey (AEM), these areas were readjusted and refined into six final exploration areas. Further AEM surveys were conducted, and coupled with ground Transient Electromagnetic (TEM) soundings to establish fresh water thickness.

A total of 111 boreholes were constructed over a 13 month period. In addition to evaluating the shallow groundwater potential in the six shallow exploration areas, two deep boreholes were drilled to evaluate the groundwater potential of the underlying

bedrock aquifers. Two shallow boreholes were drilled using a reverse circulation method to compare against mud rotary drilling. An artificial recharge spreading basin was designed, installed and tested to assess artificial recharge feasibility. Modelling of the Shashe River Valley aquifer system and evaluation of long-term sustainable yield and alternative production borehole configurations were conducted, as well as preparation of a management report for the Shashe Wellfield.

The results of the study showed that the freshwater groundwater system rests on brackish/saline groundwater. Southeast of the Kunyere Fault, the lateral extent of the freshwater lens is limited. Northwest of the fault, the freshwater body is much broader and thickens to the northwest in the direction of the perennial swamps. The depths to the water table are variable and range from less than 3 m in areas that receive regular flood facilitated recharge to more than 20 m in areas that have not seen flood recharge events in a few decades. The quantity of fresh groundwater in storage ranges from less than 120 to 1,000 Mm^3 in aquifers southeast of the Kunyere Fault, to several thousands of Mm^3 in systems northwest of the fault. It was also demonstrated that recharge potential is greatest along river systems that lie along the present outflow system from the delta such as the Boro and Upper Thamalakane. Furthermore it was shown that groundwater in deeper semi-confined and confined aquifers in the Kalahari Group and shallow aquifers located away from the active river systems is consistently brackish to saline.

Modelling of the Shashe Wellfield indicated that pumpage is presently significantly greater than natural recharge and that the present volume of fresh groundwater storage is on the order of 40 Mm^3. The simulations show that, without recharge, the wellfield can produce 2,000 - 3,000 m^3/d over the next 10 years. The TDS of the pumped water will continue to increase, however a reconfiguration of the wellfield with less abstraction from the lower part of the valley and increased production from the middle and upper reaches of the valley will extend the life of the wellfield. Furthermore, the Shashe Valley aquifer was shown to be capable of accepting large quantities of artificial recharge water through spreading basins. A significant quantity (2 - 4 Mm^3) of recharge water can be taken from the Thamalakane, Boro and Santantadibe Rivers during most years from July to October with minimal impacts to flows.

Two bedrock boreholes were drilled; one was completed in the Karoo sandstone and the other in Ghanzi Group rocks. Both produced saline water in excess of 20,000 mg/l TDS. Based on these results it seems that finding significant potable water supplies at depth in bedrock around Maun are very remote.

Boreholes drilled by reverse circulation shown to be significantly more efficient than those drilled by mud rotary techniques. Reverse circulation drilling, however, is constrained by a need for an onsite supply of water.

Water Surveys (Botswana) (Pty.) Ltd. (1993)
Protection Zones and Guidelines for Major Wellfields, Aquifers and Dams in Botswana. Final Report for DWA (available from Department of Water Affairs).

This report forms part of an overall programme to delineate zones of protection around all major wellfields, major aquifers and Dams in Botswana to protect them from pollution. For each site, the present degree of pollution and any potential pollution hazards were identified. The zones are intended to be legally enforced on the basis of recommended guidelines and legislation from this study.

Protection zones were developed for the two major wellfields in Maun, the Shashe and Thamalakane Wellfields. Local geology and hydrogeology was studied and incorporated into a groundwater flow modelling exercise to develop protection zones based on contaminant travel times and patterns.

An extensive evaluation of contamination sources in the Maun area was conducted, and their degree of threat to either of the wellfields evaluated. It was concluded that the Shashe Wellfield lies upon a highly vulnerable aquifer due to its high permeability and shallow depth to the water table. The present contamination risk is from livestock concentrations around the wellheads. The Thamalakane Wellfield is less vulnerable due to the greater depth to the water table. However the boreholes in this wellfield do face contamination via pumping induced leakage to the aquifer from the river. The presence of microbiological contamination suggests vertical access to the aquifer occurs, and that other contaminants such as hydrocarbons also gain access. Other risks to the wellfields include sewage in the Thamalakane River, a new road crossing the Thamalakane, fuel depots at the Government Camp, airport and generation station, storage of pesticides for tsetse fly control, oxidation ponds of NWDC and BMC and various pit latrines/septic tanks.

Water Surveys (Botswana) (Pty.) Ltd. (1998)
1997/98 Rural Village Water Supply, Northwest District Group of Villages - Godigwa, Etsha, Gumare, Nokaneng, Makakung and Sehitwa. Individual Village Final Reports for DWA (available from Department of Water Affairs).

These reports comprise the most recent Consultant rural village water supply studies in the Ngamiland District. Such reports are available for most villages since the start of the programme in 1987. The summary of findings and implemented works below gives a general idea of the water supply situations in most villages:

Village	1991 Pop.	2008 Pop.	Existing supply (m^3/day)	2008 supply (m^3/day)	No. new boreholes	depth (m)	total yield (m^3/hr)
Makakung	249	591	42	60	3	69	42

Godigwa	234	434	tanker	50	3	20,89,102	17.3
Gumare	3,539	7,122	176	500	6	20 - 32	74.5
Etsha 1/6	1,160	2,335	110	210	4	94 - 97	45
Etsha 13	1,554	3,128	150	180	4	85 - 110	39

These reports outline siting, drilling, borehole construction and pumping test procedures / results used to develop the village water supplies. Brief descriptions of geology, hydrogeology and hydrochemistry are given, and a resource evaluation conducted in each case.

Water Surveys (Botswana) (Pty.) Ltd. (1998)

Ngamiland Border Veterinary Camp - Water Supply Programme. Final Report for DWA (available from Department of Water Affairs).

This study is similar to the rural village water supply projects, however in this case water supplies were established for veterinary camps along the Namibia - Botswana border in Ngamiland. It is unique, however, in that this particular study covers a very widespread area from southwestern to northern Ngamiland, including Godigwa and Tswookwe villages on the fringes of the Okavango Delta. Borehole siting, drilling and test pumping procedures and results are discussed, together with brief descriptions of geology, hydrogeology and hydrochemistry.

3.2.3 Other References

The following is a comprehensive list of additional references pertaining to the geohydrology of the Okavango Basin in Botswana. While most of the references listed are probably readily at hand, the availability of each source has not been established. These references are considered not to be as fundamental in nature as those listed in the annotated list above.

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Department of Water Affairs (Undated)
Data Report on Shashe Maun Pilot Borehole Construction Project, September 1992 - March 1993. Gaborone, Botswana.

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The role of Cyperus papyrus in channel blockage and abandonment in the northeastern Okavango Delta, Botswana. African Journal of Ecology, 33:25 - 49.

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The vegetation of the seasonal swamps, FAO/UNDP. Investigation of the Okavango Delta as a primary water resource for Botswana. BOT/71/506, Technical Note 28, Maun.

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Geophysical, Geochemical and Geological Investigations in the Ngami and Kheis Areas of Botswana 1980 - 1983. Final Report. Geological Survey Department Bulletin 32. Lobatse, Botswana.

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Ground Water Investigation in Maun Copper Venture Lease Area, Ngamiland District. Final Report to Anglo American Prospecting Services, Botswana.

Water Resources Consultants (Pty.) Ltd. (1992a)
Groundwater Development in Five Pilot Ranches, Hainaveld Third Development Area, Ngamiland District. Final Report to Botswana Department of Water Affairs. February.

Water Resources Consultants (Pty.) Ltd. (1992b)
Groundwater Investigation in Bodibeng and Bothatogo Area, Ngamiland District. Final Report to Botswana Department of Water Affairs. September.

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3.2.4 Maps

The following is a list of published maps in Botswana pertaining to the geology and hydrogeology of the Okavango Basin.

Department of Geological Survey (1979 – 1982)
Hydrogeological Reconnaissance Maps. 1:500,000. Sheets 1 - 4.
These maps illustrate hydrogeological features on a regional scale. Sheet 1 encompasses the entire Okavango Delta and most of the Ngamiland Distinct. Sheets 2 - 4 cover the remaining parts of the district. Brief physiography, geology, hydrogeology and groundwater quality descriptions are also provided on the maps. The maps are very useful for visualising groundwater occurrence in the region.

Department of Geological Survey (1984)
Geological Map of the Republic of Botswana. 1:1,000,000.
No published smaller scale geological maps for the Ngamiland District are available, thus the national geological map serves as the only representation for the district. A digital map is also available on CD, from which the geology of Ngamiland may be extracted.

Department of Geological Survey (1978)
Photogeological Map of Botswana. 1:1,000,000
This map is combined with the national geological map on CD.

Department of Geological Survey (1995)
Groundwater Pollution Vulnerability Map - Republic of Botswana. 1:1,000,000
This map classifies areas of groundwater pollution vulnerability over the entire country. The map also illustrates the lithology of important aquifer systems, major wellfields, surface water features, and geological and topographical features. Although the map is useful for identifying broader trends and features, it should not be depended upon for localised studies.

Federal Institute for Geosciences and Natural Resources (BGR)
Groundwater Pollution Vulnerability Map of Maun Area. 1:50,000

This map is included in the aforementioned report produced by the Federal Institute for Geosciences and Natural Resources (BGR) of Germany and the Botswana DGS. Reference to the annotated bibliography should be made for a brief description.

3.2.5 Databases

Department of Water Affairs and the Department of Geological Sciences.

National Borehole Archive - Ngamiland District

This database contains borehole information such as identification number, grid references, drilling date construction details, and yields. The majority of the boreholes are not properly grid referenced, limiting its use. However a Water Point Survey for Ngamiland in the near future will rectify this (see Future / Current Projects). The last major update seems to have carried out in 1996. Figure 2 shows the distribution of boreholes listed in this database, within the project area.

Department of Water Affairs

Water Quality Database - Ngamiland District

This database contains all the analytical results carried out by the laboratory at the Department of Water Affairs. Grid references are usually not included, limiting the use of this database.

3.2.6 Aeromagnetic Surveys

Data for all aeromagnetic surveys are available from Department of Geological Survey. More recent surveys are available in digital form on CD.

CGG (1997)

Aeromagnetic Survey of Western Ngamiland.

Area: 57,000 km^2 Line Spacing: 250 m Mean Clearance: 80 m.

Terra Surveys Ltd. (1975 – 1977)

Reconnaissance Aeromagnetic Survey of Botswana.

Line spacing: 4 km (Western Botswana) Mean Clearance: 300 m.

World Geoscience Botswana (1995).

Aeromagnetic Survey of Maun.

Area: 12,500 km^2 Line Spacing: 250 m Mean Clearance: 80 m.

World Geoscience Corporation (1996)

Airborne EM Survey of Shashe Wellfield and Kudamane Areas.

Part of Maun Groundwater Development Project.

World Geoscience Corporation (1996)

Airborne EM Survey of Maun's Block 1 and Block 2.

Part of Maun Groundwater Development Project. Area: Block 1 – 5,258 km^2; Block 2 - 750 km^2.

3.3 NAMIBIA

A limited number of regional studies of groundwater and groundwater exploration of the northeastern parts of the country have been carried out and several reports have been written on more localised projects aimed at urban and rural water supplies and drought relief.

3.3.1 Recent Work of Significance

Significant reports of regional investigations, listed alphabetically, include the following:

Corner, B. (1994a)

Report on Electromagnetic Surveys Conducted in the Bushmanland (Omaheke) Area for Interconsult Namibia (Pty) Ltd. Corner Geophysics Namibia (Pty) Ltd. 27 June 1994.

As part of the project conducted by Interconsult Namibia in the Gam area (see below) extensive use was made of electromagnetic methods to locate buried tabular conductors. This report by Dr Corner evaluated the appropriateness of the methods applied and their interpretation.

Corner, B. (1994b)

Interpretation of the aeromagnetic survey conducted over the Gam Block in the Otjozondjupa and Omaheke Districts. Unpubl. Rep. Ministry of Lands, Resettlement and Rehabilitation, Namibia.

In order to depict structures in magnetic bedrock beneath deep (50 - 200 m) Kalahari sediments an airborne magnetic survey was conducted. Lithological units and geological structures were interpreted and given to Interconsult to guide groundwork aimed at the selection of suitable water borehole drilling sites. This report describes the methods used and the interpreted bedrock geology.

Corner, B. (1995)

Assessment of the Magnetically Mapped Faults and location of EM lines in the Gam Area, Based on Reprocessed Aeromagnetic Data. Report submitted

to Interconsult Namibia (Pty) Ltd. Corner Geophysics Namibia (Pty) Ltd. 7 July 1995.

Dr Corner re-interpreted the airborne geophysical data using first vertical derivative and analytical signal plots. The latter technique only recently having become commercially available.

De Beer, J.H. & Blume, J. (1983)
Final Report on the 1982 Geoelectrical Survey in Gam and Eiseb Omuramba. Confidential Geophysics Division, National Physics Research Laboratory, CSIR. Contract Report.

This report is a follow-up to the report by De Beer J.H., Blume J., Du Plooy, A. & Kruidenier, J.H.B. (1982), after the completion of some of the drilling. I was demonstrated that there was in fact very little general correlation between the thermal infrared anomalies and geohydrology, whereas a positive correlation was established between all methods and the Landsat in defining the NW - SE trending Gam lineament. A success rate of less than 25% was achieved in the drilling of the first 9 boreholes.

De Beer J.H., Blume J. & Du Plooy A. (1982)
The location of water-bearing structures in Hereroland East by means of Schlumberger soundings and rectangle measurements. Confidential NPRL Contract Report.

The CSIR conducted extensive geophysical survey work aimed at the location of water-bearing structures during 1973 - 1978 and again in 1981 for an emergency grazing programme. The resistivity surveys included some 140 Schlumberger soundings and 18 rectangle profiling measurements. Kalahari depth was shown to be of the order of 200 m underlain by subdued bedrock relief. A correlation between high apparent resistivities and low groundwater potential was established and it was demonstrated that successful boreholes were drilled where profiling gave apparent resistivity values in the range 100 - 310 ohm meters and soundings indicated a deep weathering of bedrock. An overall drilling success rate of 36% (i.e. percentage of boreholes with yields >1 m^3/h) was achieved in the 22 boreholes drilled.

De Beer J.H., Blume J., Du Plooy A. & Kruidenier J.H.B. (1982)
Geoelectrical Survey in the Gam Area and Eiseb Omuramba. Confidential Geophysics Division, National Physics Research Laboratory, CSIR. Contract Report.

Geoelectrical surveying was conducted in the Gam area as a follow up to an airborne thermal infrared linescanning survey, and along the Eiseb Omuramba between the

veterinary control fence and the Botswana border. A positive correlation was concluded between ground geoelectrical, thermal infrared and Landsat interpretations. Some 20 borehole sites were recommended for drilling to test the validity of the conclusions.

De Beer, J.H., Blume, J. & Rundgren, C.D. (1984)
Report on: The 1983 Geophysical Survey Around and to the West of Gam, Hereroland. Geophysics Division, National Physics Research Laboratory, CSIR. January 1984.

Further geophysical surveys were conducted in the Gam area as a continuation of the exploration efforts of the 70's and early 80's. Schlumberger soundings, rectangle measurements and magnetic profiling were conducted to select suitable sites for the drilling of water boreholes. Although no drilling was completed to test the usefulness of the methods applied it was concluded that the area had low potential but there may be sufficient groundwater to meet local demands.

Huyser, D.J. (1982)
Finale verslag oor die Chemiese kwaliteit van die ondergrondse waters in Suidwes Afrika / Namibië (met spesifieke verwysing na die benuttingswaarde van die waters). Nasionale Instituut vir Waternavorsing, Wetenskaplike en Nywerheidnavorsingsraad for DWA. Report C Wat 50. Volume 1 – 4.

Interconsult Namibia (Pty.) Ltd. (1998a)
Groundwater study of the Nyae Nyae Conservancy. Phase 1. Unpubl. Report prepared for the LIFE Programme 1998, 12 p & Appendices.

Results of desk study (data gathering, GIS etc) and borehole siting in the Nyae Nyae Conservancy in the Otjozondjupa Region, formerly known as Bushmanland.

Interconsult Namibia (Pty.) Ltd. (1998b)
Groundwater study of the Nyae Nyae Conservancy. Phase 2. Unpubl. Report prepared for the LIFE Programme 1998, 5 p & Appendices.

Results of rehabilitation, drilling and testpumping and of boreholes in the Nyae Nyae Conservancy in the Otjozondjupa Region, formerly known as Bushmanland.

Leo Hatz Consulting (Pty.) Ltd. (1991)
Report on Phase 1 the Groundwater Investigations of Eastern Hereroland, Namibia. Unpubl. Rep. Dept. Water Affairs, Namibia.

This report comprises a desk study evaluation of the groundwater resources of the region as provided in reports, publications and the DWA groundwater database. The results of a comprehensive hydrocensus are given and a proposal for a second phase of work.

Leo Hatz Consulting (Pty.) Ltd. (1993)
Groundwater Resource Evaluation of East Herero, Final Report Unpubl. Rep. Dept. of Water Affairs, Namibia.

As a follow on to the former phase a number of boreholes were sited, drilled and tested in order to fill in any gaps in information identified. This report gives an account of the second phase of the project, work done, interpretation of results and conclusions. Furthermore the report included a summary of the Phase I results. Tabulations of relevant data were appended for completeness.

Simmonds, A.L.E. & Smalley, T. (1996a)
Groundwater Exploration in the Gam Area of Eastern Namibia Unpubl. Rep. Ministry of Lands, Resettlement and Rehabilitation, Namibia

Simmonds, A.L.E. & Smalley, T. (1996b)
Groundwater Exploration in the Eiseb Block of Area of Eastern Namibia Unpubl. Rep. Ministry of Lands, Resettlement and Rehabilitation, Namibia

Simmonds, A.L.E., Smalley, T., Carr, R & George, D. (1991)
Groundwater Study of Kavango and Bushmanland, Phase I Unpubl. Rep. Dept. of Water Affairs, Namibia.

This report comprises a desk study evaluation of the groundwater resources of the region as provided in reports, publications and the DWA groundwater database. The results of a comprehensive hydrocensus are given and a proposal for a second phase of work.

Simmonds, A.L.E., Smalley, T., Carr, R & George, D. (1993)
Groundwater Study of Kavango and Bushmanland, Phase II Unpubl. Rep. Dept. of Water Affairs, Namibia.

As a follow on to the former phase a number of boreholes were sited, drilled and tested in order to fill in any gaps in information identified. This report gives an account of the second phase of the project, work done, interpretation of results and conclusions. An interpretation of the stratigraphy and regional context was achieved through an examination of several hundred borehole logs and regional topography and drainage patterns. Visual interpretation of satellite imagery was also included.

Furthermore the report included a précis of the Phase I report. Tabulations of relevant data were appended for completeness.

Simmonds, A.L.E. & Schumann, F.W. (1987)

The Occurrence and Utilisation of Groundwater in Kavango, S.W.A./Namibia*.* S.W.A. Scientific Society Journal, Vol. XL/XLI - 1985/86, 1986/7.

This paper was published in a journal devoted to the natural history, bio-physical environment and peoples of the Okavango Region of Namibia. Using the DWA database maps of hydrogeological parameters have been compiled to facilitate description and interpretation of the physical occurrence of the groundwater. Hydrochemical data was plotted on Piper Trilinear diagrams to assess the character and quality of the groundwater. It was concluded that a significant amount of recharge to the Kalahari originated from the areas of exposed bedrock in the Grootfontein – Otavi Mountains area.

Water and Environment Team (1999)

State of Environment Report on Water in Namibia. Prepared for Ministry of Environment and Tourism, 310 pp.

This report covers a baseline Environmental Investigation on the water sector in Namibia and identified appropriate, key indicators for long term monitoring of the health and trends of the Namibia's water environment. It provides extensive background material on environment and water covering the physical and climatic determinants of water gain and loss in Namibia, surface water in its several; forms and groundwater in the varied aquifer types found in the country. The study focussed on sustainability of the resource, from environmental, economic and social perspective.

Worthington, P.F. (1977)

Geophysical Investigations of Groundwater Resources in the Kalahari Basin. Geophysics, Vol. 42, No. 4.

Worthington P.F. (1979)

A Preliminary Appraisal of the Groundwater Resources of Hereroland. Confidential Geophysics Division, National Physics Research Laboratory, CSIR. Contract Report.

This report covers an extensive geophysical investigation conducted in the northern parts of both Eastern and Western Hereroland. On the basis of Schlumberger soundings a three-fold subdivision of the Kalahari succession (i.e. Lower, Middle, and

Upper Kalahari units) was put forward. Relating this subdivision to groundwater occurrence it was concluded that the Middle Kalahari had the highest potential. Useful quantities of groundwater may also occur in the Lower Kalahari but these are saline in certain areas. It was concluded that all future groundwater exploration should therefore concentrate on the Middle Kalahari.

On the basis of laboratory determined permeability it was estimated that recharge to the Middle Kalahari from throughflow was around 25,000 m^3/d which exceeded by far the quantity abstracted. A suggested wellfield distribution was put forward to form the basis of a water supply master plan for the region.

3.3.2 Other References

Interconsult Namibia (Pty.) Ltd. (1997)
Annual Drilling Programme 1996 (Okavango Region). Unpubl. Report prepared for DWA (Geohydrology Section), 11 p & Appendices.

Results of deskstudy and the siting and drilling of boreholes in the Okavango Region.

Interconsult Namibia (Pty.) Ltd. (1999)
Annual Drilling Programme 1998 / 1999 (Omaheke Region). Unpubl. Report prepared for DWA (Geohydrology Section), 5 p & Appendices.

Results of deskstudy and borehole siting of eight boreholes in the Omaheke Region.

3.3.3 Maps

The following is a list of published maps in Namibia pertaining to the geology and hydrogeology of Namibia.

Geological Survey of Namibia (1980)
Geological map of Namibia, 1:1,000,000 scale.

Huyser, D.J. (1982)
Finale verslag oor die Chemiese kwaliteit van die ondergrondse waters in Suidwes Afrika / Namibië (met spesifieke verwysing na die benuttingswaarde van die waters). Nasionale Instituut vir Waternavorsing, Wetenskaplike en Nywerheidnavorsingsraad for DWA. Report C Wat 50, Volume 2, 4 maps (F, NO_3, SO_4 & TDS).

3.3.4 Databases

Department of Water Affairs / NamWater

National Groundwater Database. Figure 2 shows the location of boreholes listed in this database for the Okavango Basin within Namibia.

Department of Water Affairs / NamWater

National Water Quality Database.

4 CURRENT / FUTURE PROJECTS

4.1 ANGOLA

Listed below are current and future projects in Angola with respect to the geohydrology of the Okavango Basin. If the projects will proceed with the current increase of war-related violence is questionable.

Unknown (possibly Angolan Department of Water Affairs)

Borehole rehabilitation in Southern Angola

4.2 BOTSWANA

Listed below are current and future projects in Botswana with respect to the geohydrology of the Okavango Basin. Information about these projects may not be part of public domain and may require special permission for referral.

Ministry of Local Government Lands and Housing

A Water Point Survey in Ngamiland District

This project was only put out to tender to private consultants late last year. Proposals were submitted by December 1998. The Terms of Reference calls for the identification of all private and public water points (registered and unregistered) in the district, including their location by GPS methods, and the collection and compilation of a wide variety of technical and socio-economic data pertaining to ownership, usage, allocation and physical status. Water point locations to be plotted on a map of 1:50,000 and 1:250,000.

The project will be co-ordinated and supervised by a Reference Group, which will be composed of members from various government departments, and Ngamiland District Administration.

Department of Water Affairs

Groundwater Monitoring Project - Phase I of the National Groundwater Information System.

This project was awarded to Geotechnical Services (Pty) Ltd early in 1998 and is currently underway.

The fundamental objective of the project is to review, revise and modernise the system(s) of groundwater resource monitoring in Botswana, and to put into place appropriate organisations, procedures, programmes, databases and communications which will constitute a firm, updated foundation for, and will facilitate the further development of the National Groundwater Information System.

The project specifically requires upgrading of the actual database gathering methods, procedures and capacity; strengthening quality control of data; updating of databases in terms of structure, interaction and user requirements and user accessibility; and entering of all existing data in digital form into these databases.

Department of Water Affairs.

Maun Groundwater Development Project : Phase II - Production Development and Implementation.

This study continues from the Phase I Exploration and Resource Assessment, which was carried out by Water Resources Consultants (Pty) Ltd. (WCS) in 1996-97. DWA is currently deciding on whether Phase II should be carried out by WCS, or if the study needs to be put out to tender for other Consultants to bid upon. A decision should be made within the next few months. The project will focus upon implementation of groundwater production supplies for the town of Maun, largely based on the results of Phase I.

4.3 NAMIBIA

Ministry of Environment and Tourism

Okavango Natural Resource Mapping

The Ministry of Environment and Tourism has embarked on a programme of compiling an environmental profile and atlas for certain regions of Namibia. To date the Caprivi Region has been completed and work ahs begin on 2 more Regions. The second of these is the Okavango Region and the initial part of the work entails the Natural Resource Mapping of the Region. This will provide a high level of base data for any future studies. Interconsult Namibia has been contracted to carry out this first phase of the work.

Department of Water Affairs

Hydrogeological Map of Namibia.

The German Geological Survey (BGR) have agreed with the DWA in Namibia to compile a hydrogeological map of the country. This project will use a minimum of local expertise and be completed within some 18 months.

Department of Water Affairs

GROWAS Project.

The DWA intends updating the national groundwater database and to this end have conducted a system analysis of the existing database and requirements. Work is to commence shortly on the design and implementation of a new system which will hopefully incorporate links to the hydrochemical and other databases. The time scale for this project is approximately 18 months.

5 ENVIRONMENTAL ASSESSMENT: SCOPE OF WORK

5.1 INTRODUCTION AND AIMS

The relationship between rainfall, surface water and groundwater is fundamental to effective management of the water resources of the Okavango Basin. For an environmental assessment of the Basin it is therefore necessary that the geohydrology be studied, understood and described. Sustainable use of the resource can only be planned when the biophysical environment, as it relates to water, is fully understood.

In order to ensure meaningful assessment of the geohydrology of the Basin comprehensive data is required. An integral part of any environmental assessment will therefore be the collection of missing data.

5.2 GAPS IN ESSENTIAL INFORMATION AND KNOWLEDGE

At present much data are available for Botswana and Namibia but lacking for the Angolan sector. Data available for Angola is likely to be severely outdated and whereas this may provide some indication of groundwater occurrence it is probably not representative of current exploitation.

Data held for the Botswana sector might also be out of date but the water point survey of Ngamiland planned by the Department of Lands is likely to rectify this before the Environmental Assessment is completed. In Namibia waterpoint surveys have been conducted in the eastern part of the Basin during the past 9 years and a fairly reliable dataset therefore exists. It may however be necessary to acquire additional data for the western part of the area where no waterpoint survey data are available.

Hydrogeological maps exist for Botswana and Angola but not for Namibia. A single hydrogeological map of the Basin is considered essential for assessment of the groundwater environment.

5.3 WORK REQUIRED

For a comprehensive assessment of the geohydrology it is considered important that a single database be generated for groundwater data in the Basin. This should include borehole information and hydrochemistry. As the veracity and completeness of older datasets is likely to be questionable it may be necessary to conduct field surveys to obtain new and accurate data.

It is therefore recommended that the first phase of work includes collection and collation of all available data. After evaluation essential gaps should be identified where field surveys will be required to supplement these data. Thus a programme of

field data collection will be necessary before the overall assessment of the geohydrology can begin.

Assembly of a single database at the end of the first phase should then lead to the preparation of hydrogeological maps showing the distribution of parameters needed to fully understand and describe the occurrence of groundwater in the Basin. Reporting on the geohydrology would include, geological settings of aquifers, groundwater flow, recharge, usage, hydrochemistry and borehole yields. Where time-series data are available it may be necessary to identify trends and comment on their implication.