APPENDIX A

INITIAL ENVIRONMENTAL EVALUATION

SPECIALIST REPORT ON:

THE HYDROLOGY OF THE OKAVANGO RIVER SYSTEM UPSTREAM OF THE OKAVANGO DELTA

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1. INTRODUCTION

1.1 Scope of this hydrological assessment

This assessment aims at describing the hydrological characteristics of the Okavango River upstream of the Namibia-Botswana border at the start of the Okavango Panhandle, with particular emphasis on the Okavango River and its tributaries between Rundu in Namibia, and Mohembo in Botswana.

1.2 Description of the Okavango River catchment

As shown in **Figure 1**, the Okavango River drains three countries, Angola, Namibia and Botswana. The river rises in the Angolan highlands as the Cubango River and has one major tributary, the Cuito River. In Angola the Okavango River is known as the Cubango River; after reaching the border with Namibia at Katwitwi, the Okavango River continues as the Okavango River for the remainder of its length.

The various references available provide conflicting estimates of the catchment area of the two rivers. At the same time, the parts of the catchment that are included in the quoted figures are not always clearly specified. Figures as different as 65,000 and 73,000 km^2 have been quoted for the Cuito River, while the Okavango River is generally quoted as having a catchment area of 115,000 km^2 (excluding the Cuito) at the confluence. It is suspected that most references have relied on previous studies for their estimates and that the previous studies themselves may not have had access to good quality mapping.

In order to clarify matters, the catchment areas were digitised for this study from mapping considered to be of good accuracy. The estimates are broken down into catchment sub-sections and are provided in **Table 1**. The Angolan and Namibian portions of the catchment (excluding the non-functional Omatako River catchment) are shown in **Figure 1**.

The mainstream length of the Okavango River from source to confluence with the Cuito River has also been carefully remeasured at 930 kilometres. The mainstream length of the Cuito River is 710 kilometres from its source to the confluence with the Okavango River. The Omatako River is 635 kilometres long, from its source in the Waterberg Plateau of Namibia to its confluence with the Okavango River downstream of Rundu.

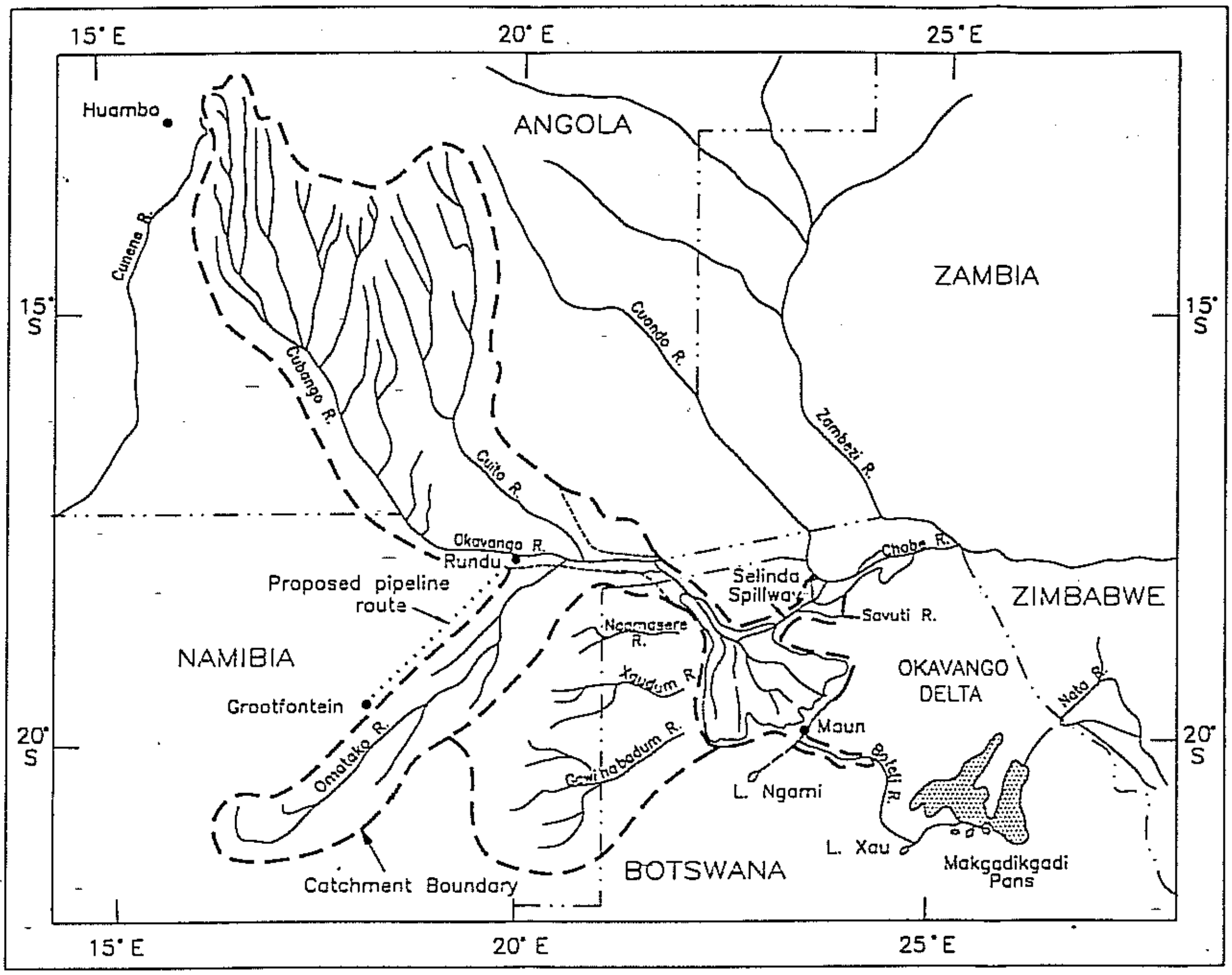

Figure 1: Map of the Okavango River catchment upstream of the Cuito River confluence (see **Table 1** for details).

Mean annual precipitation (MAP) over the headwaters of the Okavango River, at an elevation of up to 1,700 m, is between 700 and 1,150 mm. The river flows through rough terrain for about 600 kilometres, until close to the Namibian border where it enters the Kalahari Sands zone. At the border, it turns eastwards and forms the Namibian/Angolan border for the next 415 kilometres. At this stage the rivers meanders through a shallow valley, with floodplains of between 2 and 6 kilometres wide. The confluence of the Cuito and Okavango Rivers takes place about 300 kilometres after the Okavango River first reaches the Namibian border.

Table 1: Areas of the different sections of the Okavango River catchment in Angola and Namibia.

Section of Catchment Area	Surface Area (km^2)
Cubango (Okavango in Angolan territory)	88 700
Okavango (in Namibian territory; upstream of Omatako River Confluence and excluding Omatako River)	15 350
Okavango (in Namibian territory; downstream of Omatako River Confluence, and excluding Omatako River)	760
Cuito (all in Angolan territory)	60 600
Omatako River (all in Namibian territory)	55 700
Total catchment area :	**221 110**

The Cuito River rises further to the east than the Okavango River but mean annual precipitation is of the same order as for the upper Okavango River catchment. Being further east, rainfall over the lower (southern) part of the catchment may be slightly higher than over the lower portion of the Okavango River in Angola resulting in a higher runoff per unit of catchment area.

Unlike the upper Okavango River in Angola, the Cuito River meanders through some very wide floodplains in southern Angola before joining the Okavango River. These floodplains have the effect of creating a more even flow regime. Minimum flows are much higher than those in the upper Okavango River, and maximum flows are considerably lower. The seasonal peak of the Cuito River is usually several weeks later than that of the upper Okavango River, especially during low and medium flow years.

Just after the village of Mukwe, the river turns more southwards and crosses the Namibian "Caprivi Strip" and enters Botswana. Seventy kilometres further downstream the mainstream starts to divide and the Okavango Delta is formed.

The 635 km long Omatako River in Namibia is the biggest Namibian tributary to the Okavango River, but there is no record of this ephemeral river system ever having flowed as far as its confluence with the Okavango River. Indeed, there are observations that when the Okavango River is in flood, it also floods back up the Omatako River for several kilometres (Bethune, personal communication). The catchment of the Omatako River, some 39,500 square kilometres in extent, is therefore considered to be non-functional in terms of contributing runoff to the Okavango River.

2. CLIMATOLOGICAL AND HYDROLOGICAL CHARACTERISTICS

2.1 Rainfall

2.1.1 Available data

While rainfall data have been collected at a number of locations in the region, it is considered that the rainfall records for Rundu and Andara, which go back to 1937/38 and 1920/21, respectively, provided the necessary information for this study.

2.1.2 Proposed estimates

The mean monthly rainfall figures for these two stations are presented in **Table 2.** During the record periods, the minimum and maximum annual rainfall totals recorded for Rundu are 317.6 mm and 1113.3 mm, respectively. For Andara, the respective values are 251.9 mm and 1217.0 mm.

Table 2: Average monthly precipitation (mm) at two measuring stations.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Rundu	20.4	57.3	93.5	148.9	146.3	93.4	31.9	2.1	0.1	0.0	0.2	2.4	596.5
Andara	17.4	60.2	101.4	140.8	143.1	91.6	28.8	3.3	0.4	0.0	0.1	2.9	590.0

2.2 Evaporation

2.2.1 Available data

Very few reliable evaporation data exist for the study area. From time to time evaporation measurements have been made using a class-A evaporation pan at various sites including Rundu, Andara and Bagani. These data, together with other information, were used in the compilation of the Evaporation Map for Namibia (Crerar & Church, 1988), and it is proposed that the values suggested in this publication be adopted for the study.

2.2.2 *Proposed estimates*

The Evaporation Map for Namibia suggests annual A-pan gross evaporation rates ranging from 2,620 mm at Mupini down to 2,580 mm at Shadikongoro. This has been converted to an open water figure in **Table 3** which also shows the average distribution of evaporation through the year. Conversion coefficients used were 0.7 (reduction factor) for July to december and 0.8 for January to June (Sivertson, 1991).

Table 3: Long-term average values for open water monthly gross evaporation at two measuring stations (mm).

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Mupini	220	174	152	163	155	174	159	151	131	128	158	186	1951
Shadikongoro	217	171	150	161	153	171	157	149	128	126	156	182	1921

2.3 Runoff

2.3.1 *Available data*

Good quality records exist at two gauging stations in Namibia where the Department of Water Affairs operates autographic water level recorders. The stations, one upstream of the Okavango/Cuito confluence at Rundu, and one downstream of the confluence at Mukwe, have un-broken records dating back to 1945 and 1949, respectively. The Botswana Department of Water Affairs also operates a gauging site at Mohembo, about 40 kilometres downstream of the Namibian velocity gauging site at Mukwe. The accuracy of the Mohembo station is suspect at higher water levels when rising floodwater starts to bypass the velocity gauging site on the left bank.

Velocity gaugings have been carried out by the Namibian Department of Water Affairs in order to derive an accurate water level/discharge relationships. Although no flow gaugings have been carried out at Rundu since the 1970's, gaugings are carried out to check the Mukwe rating on a regular basis. In addition, a number of joint gaugings (Crerar & Child, 1991) at both the Divundu (Mukwe velocity gauging site) and Mohembo sites have been carried out with the Botswana Department of Water Affairs and there is agreement between the two countries that the flows gauged at Mukwe are accurate. There is, therefore, international consensus on the volume of water flowing in the Okavango River through Namibia to Botswana.

2.4 Water Quality

The quality of the water in the Okavango river is relatively good (Bethune, 1991). The concentration ranges of certain parameters measured at 35 mainstream and 10 backwater sites during a 1984 survey are presented in **Table 4** (Bethune, 1991).

Table 4: Chemical concentrations recorded in Okavango River water samples collected from 35 mainstream sites and 10 backwater sites (After Bethune, 1991).

Parameter	Unit of Measurement	Mainstream sites	Backwater sites
Conductivity	µSiemens/cm	30 - 45	45 - 205
pH		6.8 - 7.2	6.7 - 7.5
TDS	mg/ℓ	25 - 42	30 - 172
Alkalinity	as $CaCO_3$ mg/ℓ	10 - 20	20 - 95
Na^+	mg/ℓ	1 - 3	3 - 10
K^+	mg/ℓ	1 - 2	1 - 3
Ca^{++}	mg/ℓ	6 - 16	7 - 46
Mg^{++}	mg/ℓ	3 - 8	6 - 22
SiO_2	mg/ℓ	8 - 15	9 - 36
Cl^-	mg/ℓ	0.5 - 1.0	1.0 - 5.6
Total N	mg/ℓ	0.1 - 1.5	0.1 - 6.2
PO_4 - P	mg/ℓ	0.01 - 0.07	0.02 - 0.15
Org P sol	mg/ℓ	0.01 - 0.10	0.02 - 0.32
Total P	mg/ℓ	0.01 - 0.15	0.04 - 0.37

The Okavango River water is typically soft, with very low conductivity values and circum-neutral pH values. Chemical and nutrient concentrations are also low.

A detailed analysis of water quality is outside the scope of this report. For this reason, further water quality data collected by the Namibian and Botswana Departments of Water Affairs have not been consulted.

2.5 Sediment Transport

A number of silt samples were collected at Rundu between 1973 and 1980. Only a very limited number of samples have been taken at Mukwe (Hatutale, 1994). Silt concentrations varied between 16.4 and 59 mg/ℓ, and thus never comprised more than 0.01 %. However, it appears that no samples have been taken during periods of heavy flooding when higher suspended sediment loads could be expected to occur. It is also certain that the movement of bed load will be significant, especially during periods of high flood. No data on this aspect have been located. The usefulness of the above estimates is therefore questionable. In view of the fact that sedimentation would seem to be a major factor contributing to the dynamic nature of the Okavango Delta, the collection of data on sediment transport is an important aim for the future.

2.6 Water Demand

In order to evaluate the quantity of water currently being abstracted between specific points of interest a survey was carried out by the Water Transfer Consultants in order to get the best possible estimate available. In addition, figures of water supplied by the Department of Water Affairs as well as permits for abstraction have been obtained. The detailed approximate consumption figures are presented in the report entitled: "Report on Water Use Survey Along the Okavango River from Rundu to the Botswana Border". For the purposes of this study, estimates of the total consumption for the following stretches of the Okavango River have been made:

a) Upstream of Rundu gauging station;
b) Between the Rundu and Mukwe gauging sites; and
c) Between the Mukwe and Mohembo gauging sites

2.6.1 Upstream of the Rundu gauging station

The total quantities of water abstracted directly from the Okavango River and from boreholes in the vicinity of the river are provided in **Table 5**. The figures exclude abstraction at the town of Rundu itself since the velocity gauging site at Rundu was upstream of the extraction works.

Table 5: Water abstracted upstream of Rundu gauging station (excludes Rundu).

Unit of Measurement	Water Abstracted	
	Direct from River	From Boreholes
m^3/day	3	44
Mm^3/annum	0.001	0.016
m^3/s	0.00003	0.0005

2.6.2 Between the Rundu gauging site and the Cuito River confluence (includes Rundu)

The total quantities of water abstracted directly from the river and from boreholes in the vicinity of the river are provided in **Table 6**. The figures include abstraction at the town of Rundu itself since the velocity gauging site at Rundu was upstream of the water extraction works.

Table 6: Water abstracted between Rundu gauging site and Cuito River confluence. (includes the town of Rundu).

Unit of Measurement	Water Abstracted	
	Direct from River	From Boreholes
m^3/day	11 391	634
Mm^3/annum	4.158	0.231
m^3/s	0.132	0.0073

2.6.3 Between the Cuito River confluence and the Mukwe gauging site

The total quantities of water abstracted directly from the river and from boreholes in the vicinity of the river are provided in **Table 7**. The figures include water abstracted at Bagani which is upstream of the velocity gauging site at Divundu.

Table 7: Water abstracted between the Cuito River confluence and the Mukwe (Divundu) gauging site.

Unit of Measurement	Water Abstracted	
	Direct from River	From Boreholes
m^3/day	2 351	37
Mm^3/annum	0.858	0.014
m^3/s	0.027	0.0004

2.6.4 *Between the Mukwe gauging site and the Mohembo gauging site in Botswana*

The total quantities of water abstracted directly from the river and from boreholes in the vicinity of the river are provided in **Table 8**. The figures only include water abstracted in Namibia itself.

Table 8: Water abstracted between Mukwe (Divundu) and Mohembo gauging sites.

Unit of measurement	Water Abstracted	
	Direct from River	From Boreholes
m^3/day	168	6
Mm^3/annum	0.061	0.002
m^3/s	0.019	0.00007

2.6.5 *Conclusions*

According to the survey only 5.078 Mm^3/year are abstracted directly from the Okavango River in Namibian territory, plus a further 0.263 Mm^3/year from boreholes located on or near the floodplain. This is significantly less than the sum of agreed commitment for domestic water supply (river and borehole) and permits issued for irrigation as shown in **Table 9** (Hatutale, 1994).

Table 9: Agreed Commitment (from boreholes and the Okavango River) for domestic water supply and abstraction permits for irrigation.

Item	Quantity of Water (Mm^3/year)
Ground water for Domestic Supply	0.488
Surface Water for Domestic Supply	4.153
Permits for Irrigation	13.223

Estimates of total Namibian demand from the Okavango River made in 1993 for 1995 (Hatutale, 1994) were just over 23 Mm^3/year. These are much higher than the consumption figures found in the recent survey. A large percentage of the difference may be due to irrigation schemes using much less than their permits originally allowed. Figures for domestic consumption are comparable.

Combining both water abstracted directly from the Okavango River and from boreholes gives a total of 5.341 Mm^3/year. This represents approximately 0.170 m^3/s or 0.1 % of the mean annual runoff of the Okavango River at Rundu or of the Cuito River at Dirico.

For the purposes of modelling the inflow from the Cuito River, the recent survey figures are used since they are taken to more closely represent the current situation, and the situation of the recent past. In fact, since the model is based on records kept since 1949 when abstraction was minimal, abstraction plays an insignificant role in the modelling process.

3. HYDROLOGICAL ANALYSIS OF RUNOFF DATA

3.1 General

As indicated in **Section 2** of this Report, daily water levels have been recorded at Rundu, Mukwe and Mohembo for several decades. Flow gaugings carried out at these sites by both the Namibian and Botswana Authorities, as well as during joint gaugings, have allowed the derivation of runoff records with mean daily discharges. These data have been obtained from the relevant authorities and used to calculate the runoff statistics for each of the three stations. These statistics are presented in **Section 3.2.**

Section 3.3 presents the runoff statistics that have been calculated for the Cuito River at its confluence with the Okavango River near the town of Dirico on the Angolan side of the border with Namibia. These statistics have been calculated using the Rundu and Mukwe records, an examination of abstraction between these two stations, an estimate of other losses (evapotranspiration, seepage, etc.) and an estimate of local inflow contributions (local runoff, direct rainfall).

3.2 Long-term runoff statistics

Observed annual volumes, as well as maximum and minimum discharges for all three stations (Rundu, Mukwe and Mohembo) are presented in **Table 10.** Observed mean monthly discharges, mean, maximum and minimum monthly flow volumes are provided in **Table 11.** Note that the figures for the Rundu gauging station provided in both **Table 10** and **Table 11** correspond to the revised "best-fit" rating curve of February 1997 as released by the Hydrology Division in the Namibian Department of Water Affairs. The detailed runoff data for Rundu, Mukwe, Dirico and Mohembo are provided in **Appendix 1.**

Table 10: Annual runoff statistics for gauging stations on the Okavango River.

Parameter	Runoff Volume (Mm^3)			Seasonal Max. Discharge (m^3/s)		Seasonal Min Discharge (m^3/s)	
	Rundu	Mukwe	Mohembo	Rundu	Mukwe	Rundu	Mukwe
Seasons	51	46	64	51	46	51	46
Mean	5263	9876	9935	527.8	701.1	29.7	133.1
Median	4765	9461	9455	485.4	644.0	27.9	134.0
Standard Deviation	1920	2158	2230	208.7	262.7	10.1	19.6
Coefficient of Variation	0.36	0.22	0.23	0.40	0.38	0.34	0.15

This rating results in a reduction in mean annual runoff of 4.0 % from the value derived from the previously accepted rating. Detailed runoff data for Rundu, Mukwe, Dirico and Mohembo are provided in **Appendix 1.**

The Mohembo data are derived from three different periods (Manley, personal correspondence, 1997). From 1932 to 1946 the data were measured as water levels at an unknown site near to the present-day Mohembo flow gauging site. From 1947 to 1965, Namibian data (mainly Mukwe) were used as an estimate of flows at Mohembo. From 1966 to date, the current Mohembo flow gauging site was used. The discharge values for the early period are based on a rating derived by Manley, rather than that originally derived by the Botswana Department of Water Affairs.

Table 11: Monthly discharge statistics for gauging stations on the Okavango River (all records).

Month	Mean Monthly Flow Volume (Mm^3)			Mean Monthly Discharge (m^3/s)			Median Monthly Flow Volume (Mm^3)			Minimum Observed Monthly Flow Volume (Mm^3)		
	Rundu	Mukwe	Mohembo	Rundu	Mukwe	Mohembo	Rundu	Mukwe	Mohembo	Rundu	Mukwe	Mohembo
Oct	107	398	431	40	149	161	112	391	429	57	288	268
Nov	115	387	431	44	149	161	116	379	429	42	232	242
Dec	255	544	574	95	203	215	210	532	555	58	353	277
Jan	482	770	814	180	288	304	420	737	760	114	413	392
Feb	671	986	1022	277	404	382	602	871	901	213	363	404
Mar	950	1351	1397	354	505	522	893	1261	1326	251	633	626
Apr	1019	1504	1500	393	584	560	964	1388	1323	379	786	777
May	689	1277	1223	257	477	457	663	1267	1168	310	653	640
Jun	358	855	820	138	330	306	365	845	814	157	463	392
Jul	265	692	674	99	258	252	275	687	665	138	418	349
Aug	206	574	571	77	214	213	219	563	552	115	391	308
Sep	144	472	475	56	182	177	153	460	470	69	333	265

Note: Rundu record starts 1945/46
Mukwe record starts 1949/50
Mohembo record starts 1932/33

At Rundu, October and November are the worst months, with a median flow volumes of 100.5 and 105.4 Mm^3, respectively. The minimum monthly flow volume measured at Rundu is 34.2 Mm^3. At Mukwe, November is the worst month with a median monthly flow volume of 379 Mm^3, and a minimum observed monthly volume of 232 Mm^3. There is clearly a much larger quantity of water downstream of the confluence than above, *especially during the critical low flow periods of the year.*

For Mohembo, the median monthly volume for November is 428.5 Mm^3 and the minimum monthly volume is 242 Mm^3. From these simple comparisons and a close examination of **Table 11** it can be seen that there are some apparent discrepancies between the Mohembo and Mukwe data with neither one being consistently higher than the other. With the stations located so close to one another, it could be expected that the monthly volumes between the two stations would be comparable.

In order to make a more useful comparison of the volumes recorded at each station, only the record for the period 1966/1967 to date is now analyzed since this corresponds to the period of concurrent record for all three stations. **Table 12** provides a comparison of the monthly and annual flow characteristics for all three stations for the concurrent record period.

Table 12: Monthly and annual discharge statistics for gauging stations on the Okavango River (29 year concurrent record period only).

Month	Mean Monthly Flow Volume (Mm^3)			Mean Monthly Discharge (m^3/s)			Median Monthly Flow Volume (Mm^3)			Minimum Observed Monthly Flow Volume (Mm^3)		
	Rundu	Mukwe	Mohembo	Rundu	Mukwe	Mohembo	Rundu	Mukwe	Mohembo	Rundu	Mukwe	Mohembo
Oct	108	388	405	40	145	151	100	384	403	53	290	269
Nov	117	381	391	45	147	146	104	375	391	54	267	242
Dec	251	530	521	94	198	195	194	502	505	49	353	277
Jan	452	743	738	169	277	276	370	686	675	102	413	392
Feb	633	957	960	259	392	359	520	822	813	200	363	404
Mar	889	1301	1285	332	486	480	753	111	1083	236	633	626
Apr	974	1446	1454	376	558	543	907	127	1254	363	786	777
May	673	1231	1245	251	460	465	660	127	1259	294	653	641
Jun	351	801	811	135	309	303	334	84	817	209	463	441
Jul	263	643	646	98	240	241	251	668	662	149	418	397
Aug	205	536	536	77	200	200	201	533	535	119	391	361
Sep	143	443	451	55	171	168	140	437	459	59	333	315
Year	5060	9401	9445	160	298	299	4625	9106	9143	2260	6333	6048

Looking at only this concurrent period, the mean annual runoff figures for Mukwe and Mohembo differ by less than 0.5 %. In view of the level of inaccuracy inherent in discharge measurements (± 2 %) on a single well-conducted gauging, this can not be considered as a major difference. Looking at the 29 year sequence as illustrated in **Figure 2**, the difference in seasonal totals is never large. It is interesting to note, however, that during the first half of the concurrent period the annual volume measured at Mohembo was consistently higher, whereas for the second half of the record Mukwe was consistently higher. This implies that there has been a shift in the rating over time for one or both of the stations, and reinforces the general opinion that there is no significant difference between the total runoff record at each station.

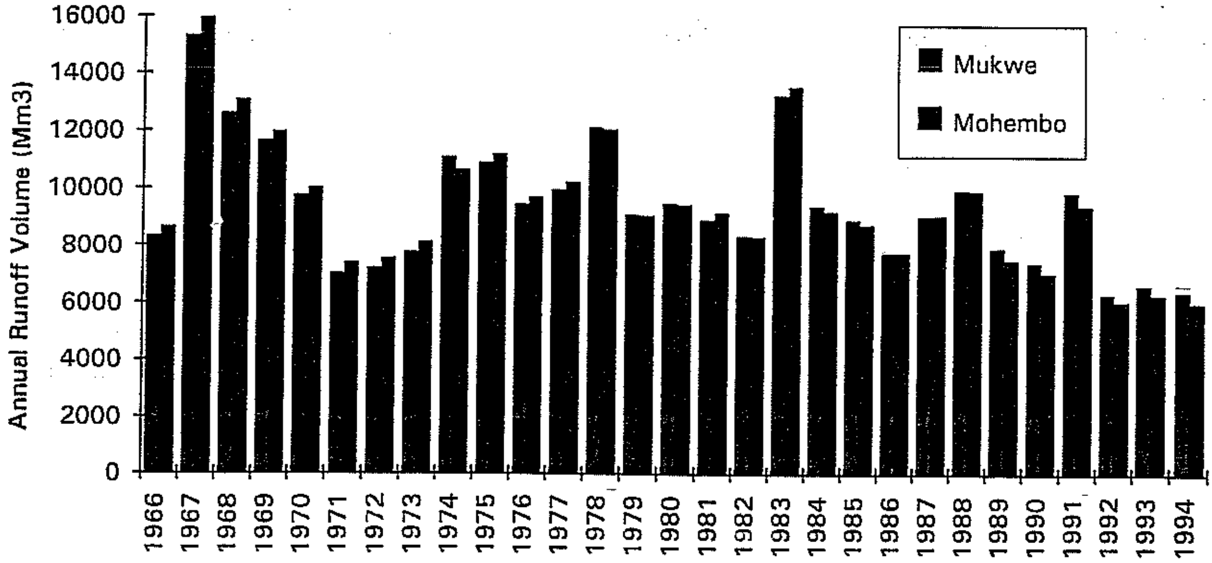

Figure 2: Annual runoff volume at Mukwe and Mohembo for concurrent record.

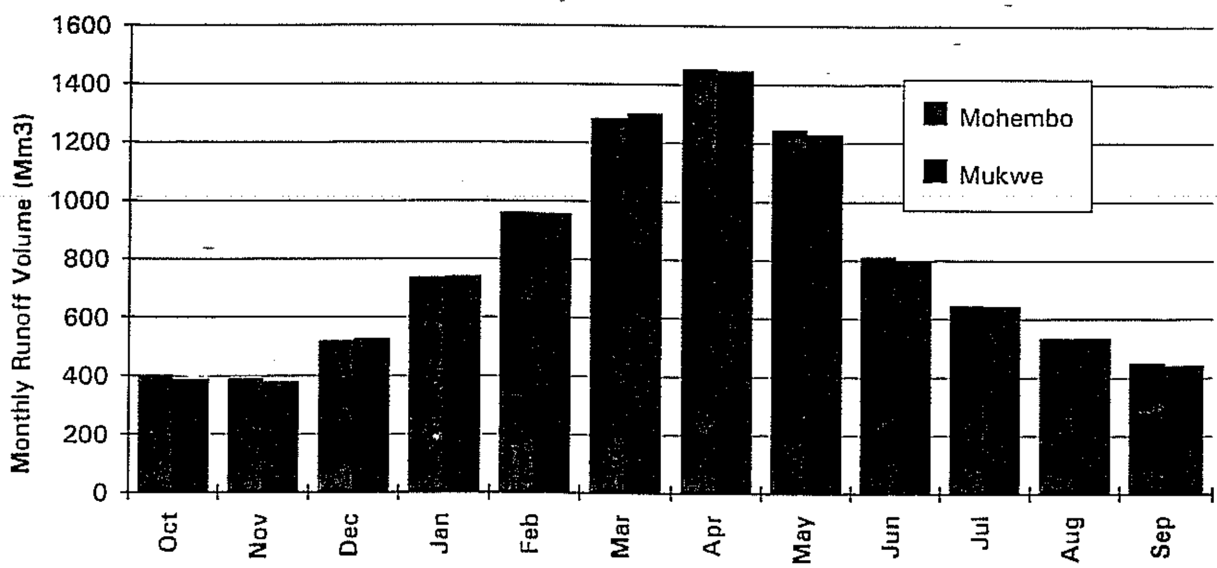

Figure 3: Mean monthly runoff volumes at Mukwe and Mohembo.

However if the monthly totals are examined, as indicated in **Figure 3**, there are clearly some larger differences for certain months than for others. This can largely be explained by lag factors.

During the months where the hydrograph is generally rising (December to March), the Mukwe volumes are marginally higher. For the other months the Mohembo volumes are higher. This is exactly what would be expected. The conclusion is that there is no significant difference between the flow recorded at Mukwe and Mohembo. Evapotranspiration and seepage losses between the two stations are probably more than made up for by direct rainfall onto the river and local runoff during intense rainstorms. This conclusion is supported by the results of combined gaugings carried out by the Namibian and Botswana water authorities. The results of these joint gauging exercises are provided in **Table 13.**

Table 13: Joint discharge measurements carried out by Namibian and Botswana authorities (data taken from Hatutale (1994)).

Date	Mukwe Gauge Plate Reading (m)	Gauged at Mukwe (Divundu) (m^3/s)	Gauged at Mohembo (m^3/s)	Mukwe Stage/Discharge rating (m^3/s)
24 May 1984	3.59	(N) 552 (B) 567	(N) 550 -	554
20 March 1985	3.18	(N) 364 (B) 358	(N) 361 (B) 354	362
16 October 1991	2.48	(N) 117	(B) 109	118
18 November 1992	2.55	(N) 127	(B) 127	137
10 November 1993	2.47	(N) 107 (B) 110	(N) 115 (B) 117	117

Note: (N) means gauging carried out by Namibian team
(B) means gauging carried out by Botswana team

In modelling inflow into the Okavango Delta it is recommended that Mukwe flow record be used with attention paid to the small time lag. The rating of the Mohembo station is suspect at higher levels. If it is desired to use the Mohembo record because of its early starting date, it is recommended that the Mukwe record be used on a monthly basis for checking purposes.

3.3 Statistics for the Cuito River

There is no record available for the Cuito River at its confluence (Dirico) with the Okavango River, although at least one gauging was carried out by the Namibian Department of Water Affairs in the early seventies.

A simplified hydrological model, based on the Rundu and Mukwe observed record, was drawn up to create a synthetic record for the Cuito River at Dirico. It is believed that the monthly runoff figures derived are a good estimate, with an accuracy of 2 to 3 per cent. The full monthly runoff record is shown in **Appendix 1**. Because of the fact that the estimate of the lag time between Rundu and Mukwe is fundamental to the model, and that this lag time fluctuates depending on the level of discharge, the accuracy of the flood peak estimates and, to a lesser extent, of the minimum discharges, it will not be quite so good. A comparison of the annual statistics for Dirico and Rundu are presented in **Table 14.**

Table 14: Comparison of the runoff statistics for the Cuito River at Dirico (all data are drawn from a synthetic record), and those at Rundu (derived from measured data).

Parameter	Annual Runoff Volume (Mm^3)	
	Dirico	Rundu
Seasons *	45	45
Mean	4350	5391
Median	4367	4962
Coefficient of Variation	0.14	0.22

* For the sake of comparison only the concurrent Cuito and Rundu records have been used. This corresponds to the period during which the Mukwe station has been open.

The mean annual runoff at Mukwe for this period is 9875 Mm^3. Therefore, approximately 45.4 % of this is contributed by the Cuito River. Despite the similar mean annual runoff (MAR) values, there is a significant difference in seasonal flow regimes of the two rivers. This is further illustrated in **Table 15.**

It can be seen from **Table 15** that the peak discharge in the Cuito River normally occurs during April. Average discharge for this month is 175 m^3/s. This is also true of the Okavango River at Rundu where the average discharge for April is much higher at 405 m^3/s.

Table 15: Comparison of runoff characteristics at Rundu and Dirico (Cuito River).

Parameter	Rundu (Okavango)	Dirico (Cuito)
Month with highest mean discharge	April	April
Mean discharge for above month	401	175
Maximum Flow recorded (m^3/s)	962	550 - 600
Date of maximum flow	April 8	February 3*
Minimum Flow Recorded (m^3/s)	11.1	64
Month of Minimum Flow	November 17 - 20	October 24

However, in the Cuito River the peak is often only recorded in May and hence the average discharge for May is still as high as 172 m^3/s and for June still 167 m^3/s. In the Okavango River, the average discharge for May is already down to 258 m^3/s and to only 139 m^3/s in June. The reason for this is that despite its relatively shorter mainstream length, floods in the Cuito River are significantly attenuated due to the presence of wide floodplains in the lower part of the catchment. Only a very large flood, such as the one of February 1968, would be relatively unaffected by these floodplains.

A comparison of the average monthly flow volumes at both stations in shown in **Figure 4**. It is interesting to note from this graph that on average the runoff in the Cuito River is greater than that of the Okavango River for 7 months of the year. **Figure 5** illustrates a comparison of the maximum and minimum monthly volumes.

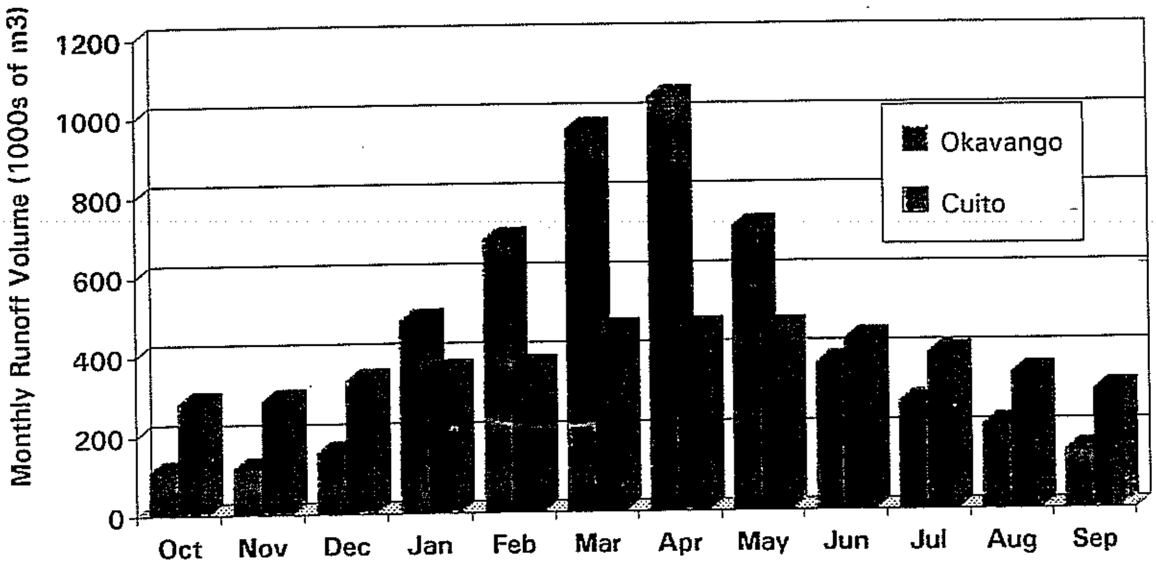

Figure 4: Mean monthly runoff volumes at Rundu and Dirico (Cuito River).

The 1968 flood which produced a peak of between 550 and 600 m³/s in the Cuito River was as an unusually early flood in both tributaries. In the Okavango River at Rundu, a maximum flow of 909 m³/s was recorded, and the resultant peak at Mukwe, though only recorded on February 7, was 1,473 m³/s and represents the highest flow on record for this station. It seems that the flood in the Cuito River was an extreme event, having a return period in excess of 50 years. Under more normal circumstances the peak discharge in the Cuito River occurs in April or May.

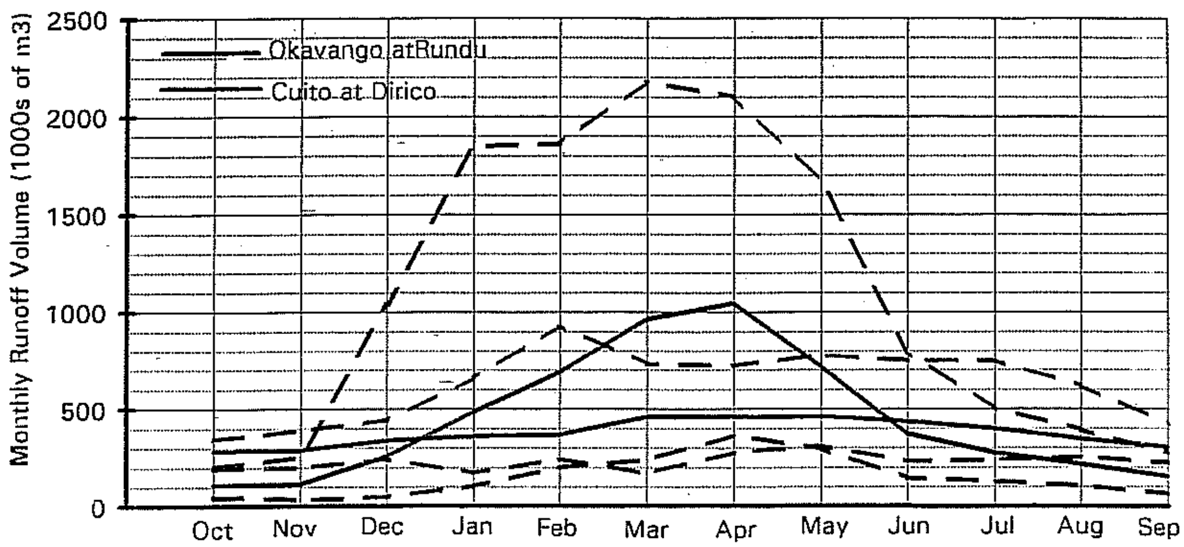

Figure 5: Minimum, mean and maximum runoff volumes for Rundu and Dirico.

Figure 6 shows a comparison of the season total for both rivers for the period 1949-1993. It is interesting to note from this graph that there are 17 seasons (marked with "x"), where the seasonal runoff volume in the Cuito River at Dirico was greater than that of the Okavango River at Rundu. Of particular interest is the fact that for all ten of the lowest seasons recorded at Rundu, the runoff volume of the Cuito River at Dirico was higher.

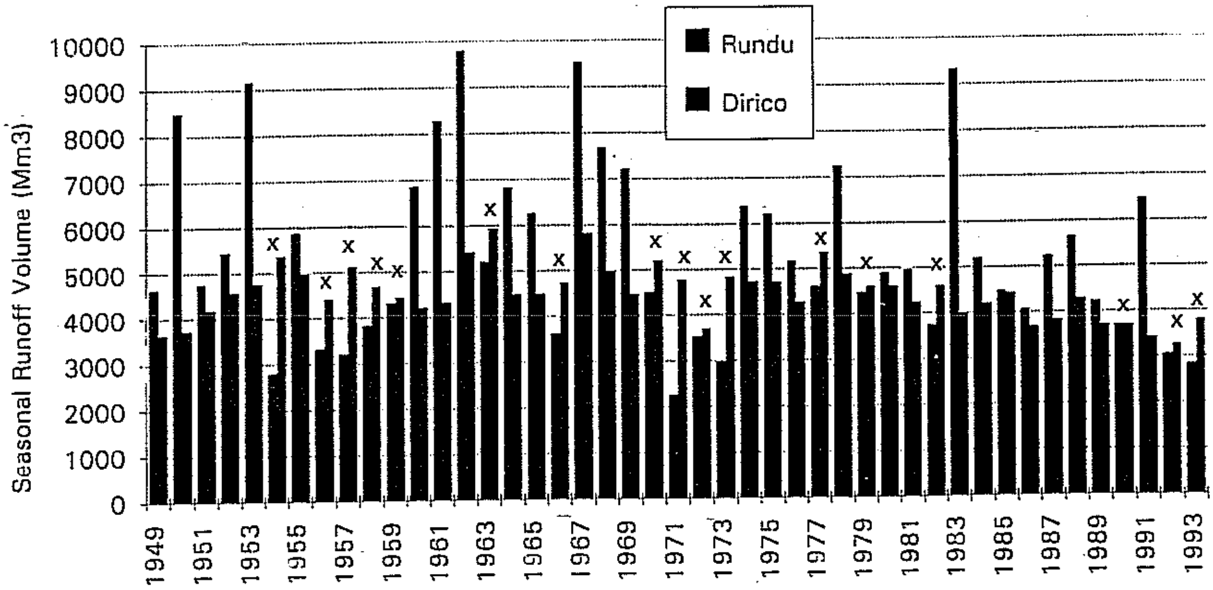

Figure 6: Seasonal runoff volumes at Rundu and Dirico (1949/50-1993/94).

4. LOW FLOW ANALYSIS

4.1 General

These analyses are carried out to investigate, in statistical terms, the likelihood of a discharge less than a specified low flow threshold occurring. It is clear that low flows are particularly important relative to the quantities of water that are proposed to be abstracted. In order to evaluate the environmental impacts associated with unusually low discharges and their associated water levels, it is clear that the frequency with which certain minima are attained, and at what times of the year, need to be considered. Since certain environmental effects / impacts may be associated with particular times of the year, a low flow analysis on a monthly basis has been carried out for both the Rundu and the Mukwe gauging sites.

A low flow analysis using annual minima (the most extreme case) has also been carried out. Previous studies (Crerar, 1986; Hatutale, 1994) have shown that a two parameter log-normal distribution is appropriate for the low flow analysis, and this has been utilised throughout. Data are not of a sufficient accuracy to merit the same in-depth analysis for the Cuito River at Dirico. Low flows in the Cuito River are briefly discussed in **Section 4.4** of this Report. Following on from the low flow analysis is the derivation of low water levels. Output from the low flow analysis is therefore used in **Section 5** of this Report.

4.2 Okavango River at Rundu

4.2.1 Analysis using "best-fit" rating

The 51 year record from 1945/46 to 1995/96 was utilised for the analysis. Minimum flows with return periods of 2 (median), 5, 10, 20, 50 and 100 years were calculated. **Figure 8** shows the results for all months of the year. **Table 16** provides the data including an analysis of annual minima.

In recent years, some doubt as to the validity of the stage/discharge rating for the Rundu station has been raised with the suggestion that it may be slightly overestimating, especially at low and very low flows. As a result the Hydrology Division in the Department of Water Affairs have re-calculated the rating and produced two new equations. The first of these is the so-called "best-fit equation" is described in **Appendix 2**, and has been used for the re-calculation of the entire Rundu record. Another equation, corresponding to the minimum flow, or worst case scenario, was also derived and is used in this report only for the purpose of carrying out a sensitivity analysis (**Figure 7**).

From **Table 16** it is clear that flow in the Okavango River reaches very low levels during October and November of each year.

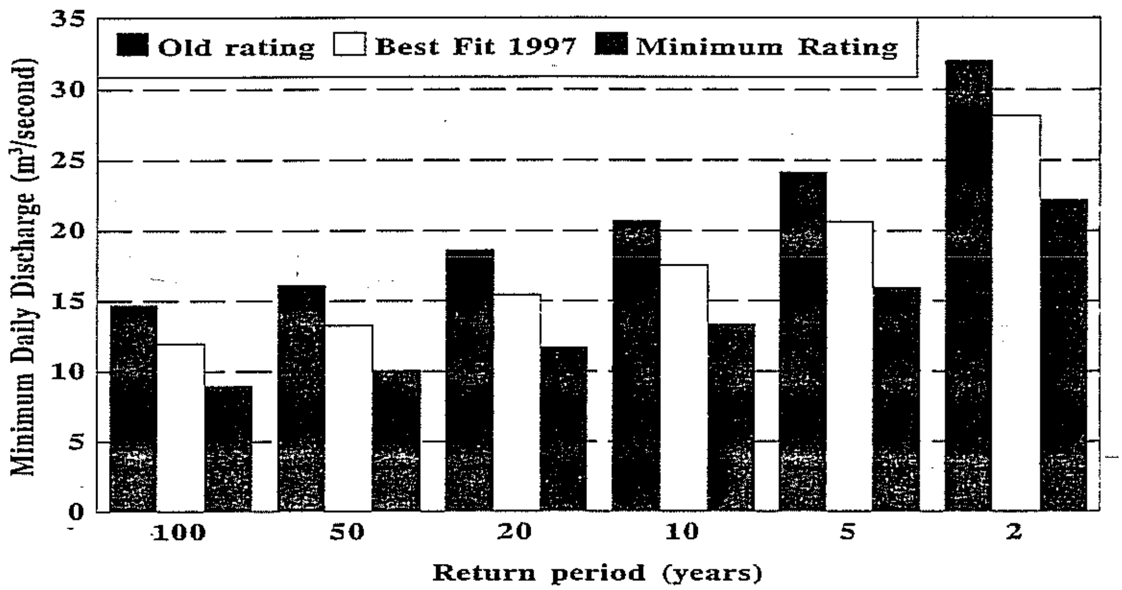

Figure 7: Minimum flow at Rundu according to old, best-fit and minimum ratings.

Table 16: Rundu Monthly low flow extreme values (m^3/s) and their return periods.

Month	**Return Period (Years)**					
	100	**50**	**20**	**10**	**5**	**2**
Oct	13.1	14.6	17.1	19.6	23.3	32.2
Nov	12.5	14.0	16.6	19.2	22.9	32.1
Dec	14.8	17.1	21.3	25.8	32.7	51.1
Jan	21.6	26.2	34.8	44.7	60.6	108.5
Feb	35.1	43.2	58.0	72.4	98.0	171.3
Mar	52.5	63.2	83.0	105.3	140.9	245.7
Apr	95.6	108.7	131.0	154.5	188.9	277.3
May	60.2	67.9	81.0	94.5	114.2	163.7
Jun	43.7	48.5	56.5	64.7	76.2	104.4
Jul	33.6	37.3	43.6	49.9	59.0	81.0
Aug	27.1	29.9	34.6	39.4	46.0	61.9
Sep	18.5	20.4	23.8	27.2	31.9	43.5
Annual	**11.9**	**13.2**	**15.3**	**17.5**	**20.6**	**30.0**

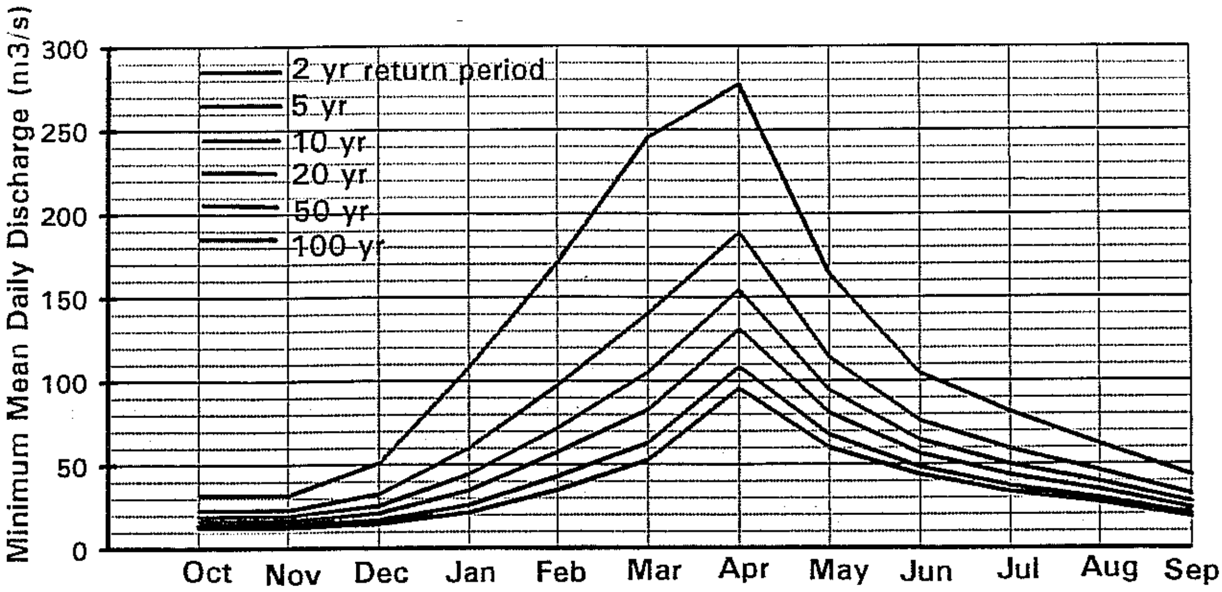

Figure 8: Monthly low flow analysis for Rundu for various return periods.

4.2.1 *Sensitivity analysis for worst case scenario*

As already stated, there is a question mark over the accuracy of the Rundu rating, especially at low levels. This has resulted in a derivation of a new "best-fit" rating, (by Van Langenhove & Görgens in February 1997), which has been used for the complete re-evaluation of the Rundu runoff record. However, it is possible that this rating may still be an overestimate of the discharge at low levels.

Only one gauging has been done in recent years, and this was at the relatively low level of 3.71 m in December 1995. The flow gauged was 34.5 m^3/s. The "best-fit" rating would have predicted 43.9 m^3/s. The minimum formula would have predicted 35.7 m^3/s. There is, therefore, an argument for using the minimum formula in low flow analyses, although an absence of sufficient new velocity gaugings means that there is not yet sufficient evidence to either further change the rating formula or to re-calculate the entire discharge record.

Figure 7 shows the effect of the "old", "best-fit" and "minimum" ratings on the predicted minimum discharges for the whole range of return periods. Discharges as predicted by the minimum formula are, indeed, much less than previously thought. Even for the 1 in 5 year return period, minimum flow in the Okavango River will barely reach the 15 m^3/s mark, compared to the previous figure of nearly 25 m^3/s.

4.3 Okavango River at Mukwe

The 46 year record from 1949/50 to 1949/50 was utilised for the analysis. Minimum flows with return periods of 2 (median), 5, 10, 20, 50 and 100 years were calculated. **Figure 9** shows the results for all months of the year. **Table 17** provides the data including an analysis of annual minima.

Table 17: Mukwe monthly low flow extreme values and their return periods in years (all values in m^3/s).

Month	Return Period (Years)					
	100	50	20	10	5	2
Oct	97.6	101.7	107.9	113.7	121.2	136.9
Nov	90.7	95.2	102.1	108.5	117.0	135.1
Dec	97.9	104.1	113.8	123.2	135.6	163.0
Jan	107.5	117.6	134.0	150.3	172.9	226.1
Feb	141.3	155.7	179.3	202.9	236.0	315.1
Mar	201.6	219.6	248.8	277.7	317.6	410.3
Apr	234.1	255.1	289.2	322.9	369.4	477.7
May	207.9	223.3	247.7	271.3	303.2	375.0
Jun	162.4	173.4	190.7	207.0	229.8	279.5
Jul	139.5	148.0	161.5	174.4	191.5	229.0
Aug	127.4	134.0	144.4	154.2	167.0	194.6
Sep	112.1	117.1	124.9	132.1	141.4	161.3
Annual	91.5	95.6	101.9	107.8	115.5	131.6

A large number of gaugings have been carried out at the Divundu gauging site and these have been satisfactorily tied in with water levels recorded at the Mukwe gauging station about 20 kilometres upstream.

From **Table 17** it is clear that although flows in the Okavango River reach relatively low levels during October and November, the base flow from the Cuito River tributary is sufficient to prevent this from falling significantly below 100 m^3/s.

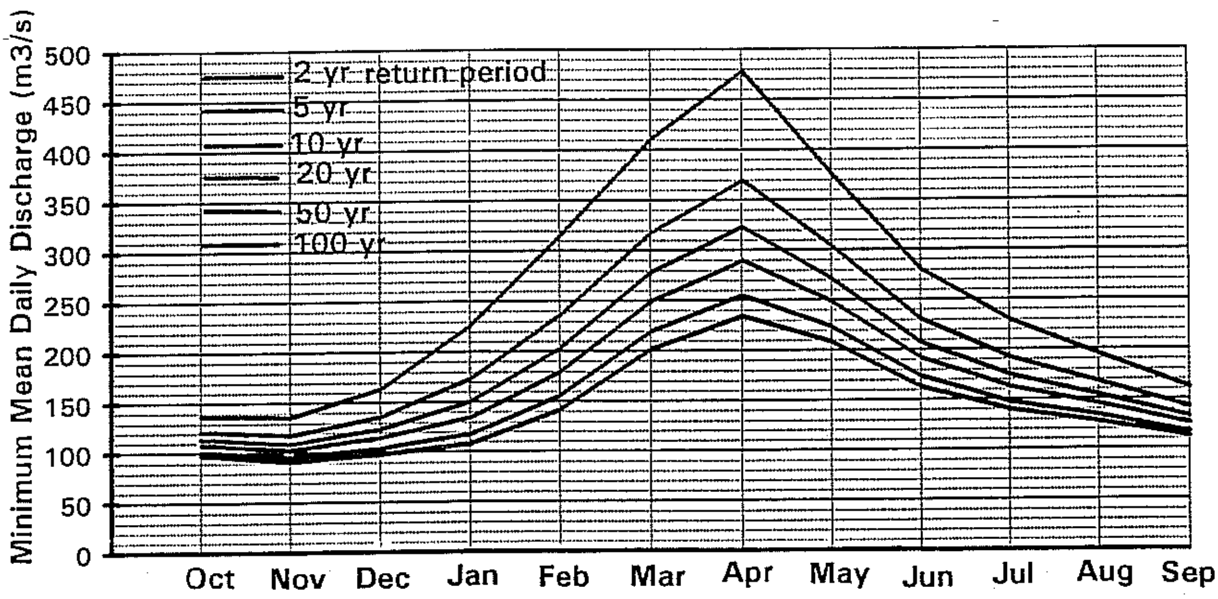

Figure 9: Monthly low flow analysis for Mukwe for various return periods.

4.4 Cuito River at Dirico

An examination of the synthetic record makes it possible to derive a reasonable estimate of low flows for the Cuito River at Dirico. The low flow estimates provided in **Table 18** have not been assigned a return period, but correspond approximately to the lowest flows recorded since 1949/50.

Table 18: Estimate of minimum flows in the Cuito River at Dirico (all values in m^3/s).

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Minimum flow	65	65	70	78	83	83	92	89	86	83	78	70

4.5 Okavango River at Mohembo

Within the framework of the accuracy of the available data it is considered that the minimum flows derived for Mukwe are also applicable to Mohembo.

4.6 Conclusions

Discharges in the Okavango River upstream of the Cuito River confluence can fall to low levels. The accurate quantity is not known and it is strongly recommended that a velocity gauging site should be erected in the vicinity of Rundu as soon as possible.

5. HIGH FLOOD ANALYSIS

5.1 General

High flood analyses are carried out to investigate the likelihood of floods above a certain threshold occurring. Associated with high floods, of course, are high water levels and flood inundation. This is of interest in the environmental study. In order to investigate the likelihood of certain water level thresholds being overtopped it is necessary first to carry out a flood frequency analysis and then to convert the resultant discharges into water levels. These water levels are discussed in **Section 5** of this Report.

5.2 Okavango River at Rundu

The 46 year record from 1945/46 to 1995/96 was utilised for the analysis. Maximum flows with return periods of 2 (median), 5, 10, 20, 50 and 100 years were calculated. **Figure 10** shows the results for all months of the year. **Table 19** provides the data including an analysis of annual maxima.

Table 19: Rundu monthly high flow extreme values and their return periods in years (all values are given in m^3/s).

Month	Return Period (Years)					
	100	50	20	10	5	2
Oct	103	94	83	74	64	49
Nov	169	149	124	105	87	59
Dec	541	449	342	269	201	115
Jan	896	751	581	464	351	208
Feb	1097	943	756	622	491	312
Mar	1268	1103	899	752	604	398
Apr	1252	1103	917	779	638	437
May	967	849	701	592	483	326
Jun	431	385	326	282	236	168
Jul	248	225	196	173	149	111
Aug	194	177	154	136	118	89
Sep	150	136	119	104	90	67
Annual	1315	1167	979	839	695	485

There is some doubt as to the validity of the stage/discharge rating for the Rundu station at high level since there is a wide flood plain on the Angolan side of the river which could not be gauged during high floods.

5.3 Okavango River at Mukwe

The 46 year record from 1949/50 to 1994/95 was utilised for the analysis. Maximum flood peaks with return periods of 2 (median), 5, 10, 20, 50 and 100 years were calculated. **Figure 11** shows the results for all months of the year. **Table 20** provides the data including an analysis of annual maxima.

Table 20: Mukwe monthly high flow extreme values and their return periods in years (all values are given in m^3/s).

Month	Return Period (Years)					
	100	50	20	10	5	2
Oct	258	243	223	207	190	160
Nov	266	251	231	214	196	164
Dec	469	431	381	342	300	233
Jan	756	683	588	516	440	324
Feb	1007	914	792	698	598	446
Mar	1274	1151	994	873	745	551
Apr	1363	1240	1080	957	825	621
May	1126	1032	909	813	709	547
Jun	669	623	561	512	457	369
Jul	481	450	408	375	338	277
Aug	369	348	319	297	271	227
Sep	293	279	259	243	224	193
Annual	1504	1362	1177	1036	886	658

A large number of gaugings have been carried out at the Divundu gauging site and these have been satisfactorily tied in with water levels recorded at the Mukwe gauging station about 20 kilometres upstream. Although the highest levels have not been gauged, the high end of the rating is thought to be reasonably accurate.

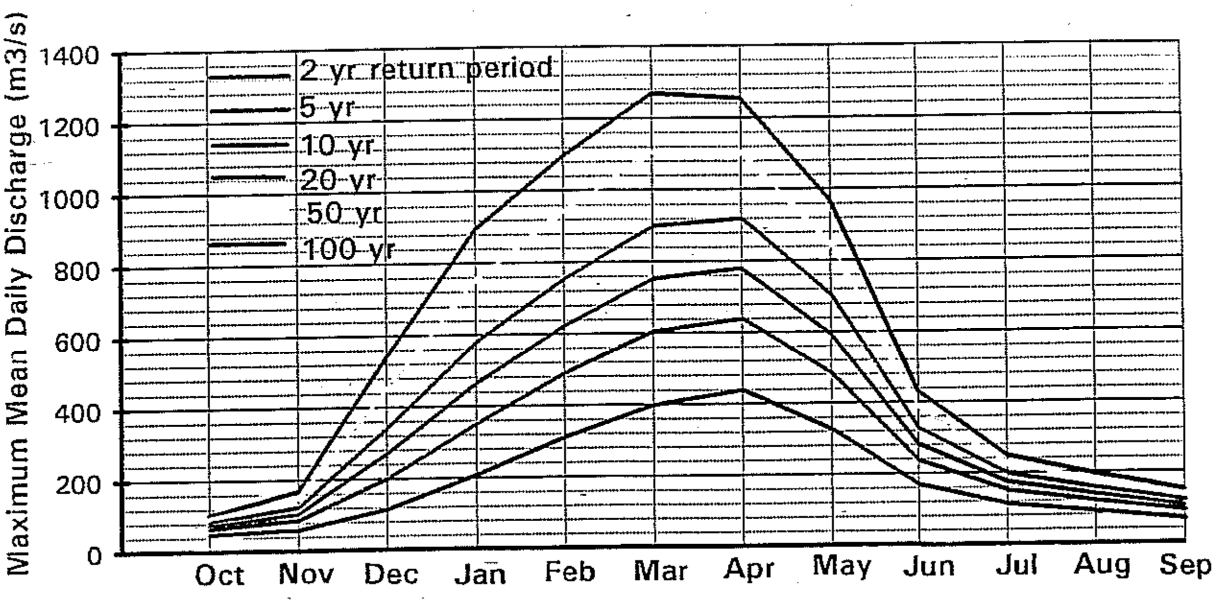

Figure 10: Monthly flood frequency analysis for Rundu for various return periods.

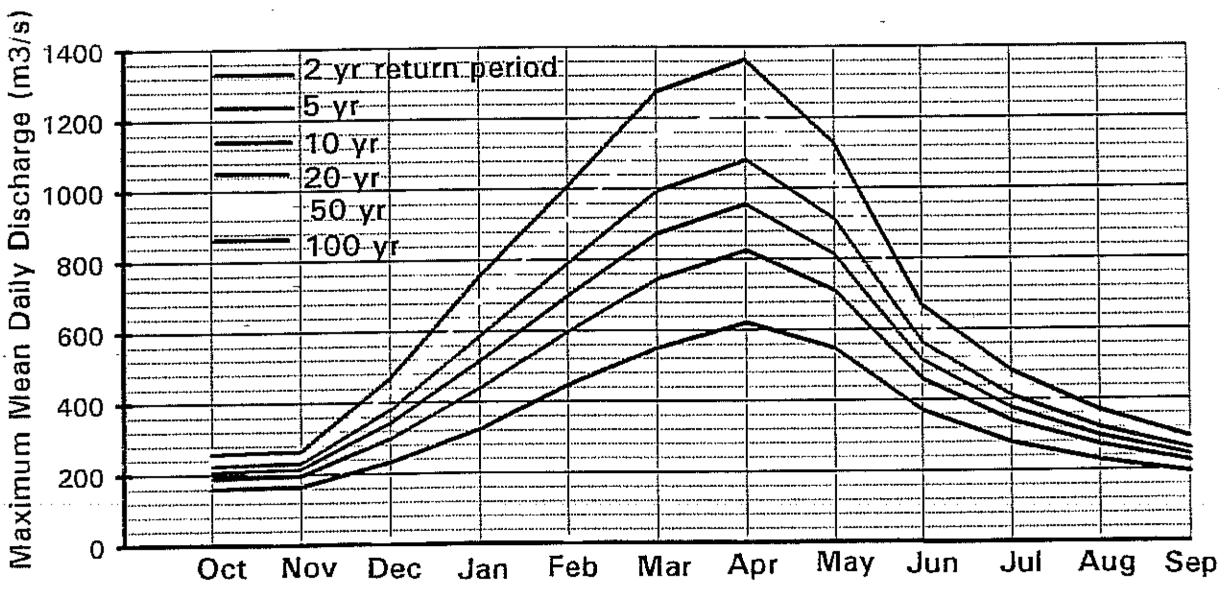

Figure 11: Monthly flood frequency analysis for Mukwe for various return periods.

5.4 Cuito River at Dirico

An examination of the synthetic record makes it possible to derive a reasonable estimate of peak flows for the Cuito River at Dirico. The peak flow estimates provided in **Table 21** have not been assigned a return period, but correspond approximately to the highest flow recorded since 1949/50. The apparent anomaly of February 1968 has been smoothed ou

Table 21: Estimate of maximum flows in the Cuito River at Dirico (all values in m^3/s).

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Minimum flow	135	160	230	400	500	580	600	500	380	300	265	210

5.5 Okavango River at Mohembo

Within the framework of the accuracy of the available data it is considered that th minimum flows derived for Mukwe are applicable to Mohembo too.

6. WATER LEVELS

6.1 General

Other than at the Rundu, Mukwe, Divundu and Mohembo gauging sites, information on water levels is scant. Information on water levels at Rundu, Mukwe and Mohembo are discussed under **Section 6.2.**

For a picture of peak flood levels and resultant inundation, the most useful information is probably in the form of LANDSAT MSS satellite imagery corresponding to the peak flood of 1984 which had a return period of just over 1 in 10 years in terms of discharge. In terms of flood volume the return period was probably closer to 20 years, hence the area of inundation was also great.

6.2 Water levels at Rundu and Mukwe

The water level range at Rundu is much higher than at Mukwe. This is due to the much lower velocities which persist up until a point about 30 kilometres downstream of Rundu (Crerar & Steyn, 1996).

Minimum flow at the Rundu site is unlikely to fall below 3.30 metres (local datum). The level corresponding to the 1 in 50 year flood is 9.52 metres, a range of 6.62 metres. At Mukwe the minimum water level is unlikely to fall below 2.40 metres (local datum), while the 1 in 50 year maximum will have a water level of approximately 4.70 metres, a range of only 2.30 metres. It should be stressed that the reason for such a large difference is an increase in average flow velocity between the two sites rather than a widening of the main channel or floodplains.

In the median year analysis, water levels range between 2.55 metres and 3.72 metres at Mukwe and between 3.6 metres and 6.5 metres at Rundu.

Given the anticipated scale of water abstraction (17 Mm^3/year), it is expected that this could cause a worst-case drop in water level of between 15 and 17 millimetres during the driest months of the year. Translated into area of inundation, the Okavango River is confined to its main channel during these dry months and there would be no measurable change in area of inundation (i.e. area of water surface).

During the wettest (high flow) months of the year, the proposed water abstraction could be expected to cause a worst-case drop in water levels of some 3 to 5 millimetres. Given the gradient of the river channel, and assuming that a similar gradient exists laterally away from the main channel over the floodplain, (i.e. an extremely conservative estimate), this could cause the area of inundated floodplain to be some 15 to 18 metres "narrower" than it would be without the proposed water abstraction.

In reality, however, lateral topographic gradients away from the main channel of the Okavango River are very much steeper than those measured along the river channel (see Specialist report by Ellery). Accordingly, it is anticipated that the worst-case scenario, where water levels could drop by between 3 and 5 millimetres, could result in the inundated area of the floodplain being perhaps as much as 1 to 2 metres "narrower" than it would be without the proposed water abstraction. This scale of impact would be extremely difficult to detect or measure with conventional techniques. In addition, it is anticipated that the available remote sensing technology (e.g. LANDSAT or SPOT images) have a resolution which is probably too coarse (LANDSAT = 30 metres; SPOT = 10 metres) to detect these changes accurately.

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