MAUN GROUNDWATER
DEVELOPMENT PROJECT
PHASE- 2

HYDROLOGY OF THE OKAVANGO DELTA

(Summary)

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Written by:

Dr. F. Alemaw (University of Botswana).
J.M. Ashworth (www.aqua3000.com**),**
Dr. D. Hughes (Rhodes University, South Africa)

On Behalf of Water Resources Consultants (Pty) Ltd.

For

The Department of Water Affairs
Ministry of Minerals, Energy and Water Resources

SUMMARY

1. INTRODUCTION

This Hydrology Report presents meteorological and surface water data for the Okavango Delta including the Project Area of the Maun Groundwater Development Project, Phase-2 (MGDP2).

The data availability, climate, rainfall patterns, and hydrology of the Okavango Delta and Project Area are described. Detailed river flow and frequency analyses are presented for river-gauging stations located at Mohembo and Boro Junction. River flows in Kunyere and Dipshiping are also described.

The objectives of this study were as follows:

- ☐ To present and comment on the available hydrological data for the Project Area.
- ☐ To summarise the climate of the Project Area.
- ☐ To summarise the rainfall characteristics of the Project Area.
- ☐ To provide analyses and results of river flows at Mohembo (inflows into the Delta).
- ☐ To provide analyses of river flows and stage in selected lower Delta tributaries, including Boro Junction.
- ☐ To provide analyses and information to aid the Collector Well Feasibility Study (part of the Project objectives), which was carried out near the Boro-Thamalakane Junction.

Most rivers in Botswana are ephemeral channels, except for the Okavango River above its delta and part of the Chobe River. Rainfall over Angola, southeast of the Lunda Divide, is the primary source of water for both these rivers. The Okavango Basin, between its source and Mohembo, is 1,800 km long and drains an area of about 785,000 km^2.

During the rainy season floodwaters move slowly downstream reaching Mohembo during November and, historically, the lower parts of the delta in February. From Mohembo, the Okavango River flows southeast to Seronga before dispersing into a series of complex and poorly understood vegetation-choked channels and shallow basins that form the largest inland delta in the world. The river gauging station at Mohembo provides a measure of the inflow into the delta.

2. HYDROMETEOROLOGICAL STATIONS

On the southern and northern peripheries of the Project Area there are two meteorological stations; one station is located at Maun Airport the other at Shakawe. The location of these stations is shown on **Figure 1**.

A rainfall gauge was first installed at Maun Airport in November 1921. Available monthly records for this gauge extend over the period January 1925 to September 2002. In November 1963 records of maximum and minimum temperature, maximum and minimum humidity, pan evaporation, number of sunshine hours, wind speed, and wind direction were started at Maun Airport. A rainfall gauge was first installed at Shakawe in October 1923. Available monthly records for this gauge extend over the period October 1932 to September 2002. Collection of rainfall data at this station has not been as thorough as that at Maun and a number of monthly records are missing. The only wind speed records that are available from Shakawe are from 1965 (calendar year), which seriously affects the reliability of potential evapotranspiration (ETo) calculations at this station.

In addition to these two meteorological stations the Department of Meteorological Services (DMS) lists 15 other rainfall stations on the periphery of the Okavango Delta. In addition, five rain gauges (Santawani, Boteti, Shashe, Shorobe and Xudum) were also installed during MGDP-1 for the DWA:

these stations all in a state of disrepair. Out of all these rainfall stations, only Sehitwa and Toteng have near-continuous amounts of rainfall data that cover a period in excess of 5-years. It is considered that only Maun, Shakawe, Sehitwa and Toteng can be used to examine rainfall trends, patterns and make long-term predictions. It is concluded that there is scope to greatly improve data collection at existing stations.

Mohembo River Gauging Station, located 210 km to the north of the Project Area, is an important gauge that measures inflows into the Okavango Delta. This gauge has provided nearly 28 years of continuous data (October 1974 to September 2002).

DWA reports that there are 19 river gauging stations located within the immediate vicinity of the Project Area, in the lower delta. Five additional, Project gauges, were installed in August 2001 by WRC. Out of all these stations, the Consultant judges that only five stations have worthwhile records. That is to say the records from these stations cover a significant period of time and, most importantly, have few missing data. These stations are Shashe Bridge, Boro Junction, Matsibe, Toteng and Ditshiping. Only Boro Junction falls within the Project Area. It is concluded that there is scope to greatly improve data collection at the lower delta river gauging stations.

3 CLIMATE AND RAINFALL

In Botswana the year is divided into two distinct seasons. During the summer months (October to March) a prolonged low-pressure system develops over the region, drawing in air from the surrounding land and oceans. Most rainfall occurs during summer downpours between December and March, which also marks the season for ploughing and planting.

In winter months (April to September) low-pressure areas move northward and the influx of high-pressure leads to stable dry conditions. The lack of cloud cover in winter can lead to ground frosts, which may damage plants.

Using the Penman-Monteith Equation (FAO, 1998), the monthly mean of daily potential evapotranspiration (ETo) was calculated using the FAO CROPWAT™ Program. At Maun, the mean annual ETo is calculated to be 1,867 mm y^{-1}. Comparative climatological data for Shakawe meteorological station are also presented, but the estimate of ETo at Shakawe is considered to be unreliable because of the lack of wind speed data for this station.

Annual rainfall in the 77-year period, 1925/26 to 2001/02, for Maun varied from 172.5 mm to 1201.5 mm. The lowest recorded annual rainfall occurred in 1994/95 and the highest in 1973/74. The arithmetic mean annual rainfall for these data is 447.2 mm y^{-1}. The median annual rainfall for this period is 412 mm y^{-1}. The annual rainfall distribution is positively skewed, suggesting that the median annual rainfall is more representative of average precipitation than the mean. The prevailing rainfall pattern is characterised by the main wet season of 5 months between November to March. These five months account for nearly 90% of the total annual rainfall.

A comparison of the rainfall patterns at Maun with Shakawe, Sehitwa and Toteng indicates that all these stations have similar seasonal rainfall patterns, however, the total annual rainfall and its distribution is often different. Using the records of three stations (Maun, Shakawe and Sehitwa) an index of the annual rainfall, as a proportion of the mean for the 77 longest hydrological years (1925/26 to 2001/02), was made. This suggests that there were substantially more years of below average rainfall than of above average. The 1930s, 40s and 80s are periods of prevalence of below average rainfall. 1973/74 was an exceptionally wet year right across the delta. 1994/95 was a drought year in the southern part of the delta (Maun and Sehitwa) but was not exceptional in the northern part of the Okavango (Shakawe).

An isohyetal map (**Figure 15**) shows that for the decade 1989-99 annual rainfall increased in a northeasterly direction from approximately 320 mm near Toteng to 540 mm near Shorobe. The variation in rainfall over the Project Area during 1989-99 was approximately 220 mm.

4 RIVER FLOW ANALYSIS

The data for the Okavango River at Mohembo River Gauging Station (No. 7112) are of primary interest to the Project because they represent the majority of inflows into the Okavango Delta.

Daily records of flow are available from this station for the period October 1974 to September 2002 from DWA. Additional monthly flow data are available, for the period 1932 to 1987, from the National Water Master Plan study (SMEC, 1990). However, it is not clear whether these additional data are observed or simulated data, and so this study has been based on the data obtained from the DWA hydrometric archives.

Figure 19 shows the annual flow at Mohembo in $Mm^3\ y^{-1}$ superimposed with a 5-year moving average values. The annual total flow data have distribution characteristics which are close to normal. This graph indicates that over the period 1998 to 2002 annual inflows into the delta were only 20% lower than the long-term mean of 8,173 $Mm^3\ y^{-1}$ and it is therefore a little surprising that during this period no surface water flows were recorded further into the delta at Shashe.

Figure 20 shows that mean monthly river flows at Mohembo generally start to increase in December, peak in April, and decline to a minimum in October. A comparison of the daily discharge for the last 12 years from 1990/91 to 2001/02, shown in **Figure 21,** shows that peak flows can occur more than once a year. Sightings of floodwater in the Project Area, in 2001 and 2002 indicate that the flood peak recorded at Mohembo takes between two to three months to reach the Project Area.

Examination of the historical daily flow duration curves was undertaken with a view to determining the percentage of time a given magnitude of flow was exceeded. **Figure 22** indicates that the daily discharge rate generally exceeds 100 $m^3\ s^{-1}$ (99.45% of the time). For 50% of the time discharge rates exceeded 250 $m^3\ s^{-1}$.

The statistical properties of the annual series of daily maximum, daily minimum and minimum mean monthly flows were examined for the Mohembo gauging station. With respect to maximum flows, the statistics of the annual series of maximum daily flows suggests that a Log-Normal distribution will be suitable as the skewness coefficient of the log transformed data is close to zero. The following table shows the results of applying this distribution for floods with return periods of 2, 5, 10, 20, 50 and 100 years. The 100-year results need to be treated with extreme caution because the length of record is only 28 years.

Estimated maximum and minimum daily flows of Okavango River at Mohembo Gauging Station

	Log-Normal distribution		**EV III distribution**	
Return Period (Years)	**Maximum daily flows ($m^3\ s^{-1}$)**	**Standard Error ($m^3\ s^{-1}$)**	**Minimum daily flows ($m^3\ s^{-1}$)**	**Minimum mean monthly flow ($m^3\ s^{-1}$)**
2	554.0	24.5	112.0	122.2
5	680.6	41.7	93.5	102.4
10	758.0	56.3	84.1	92.5
20	827.9	71.1	76.8	84.7
50	915.4	90.8	69.0	76.6
100	980.4	105.7	64.3	71.6

Note: The standard errors of the minimum estimates range from 4 $m^3\ s^{-1}$ for a 1:2 year low-flow to 16 $m^3\ s^{-1}$ for a 1:100 year event.

The results of the extreme low-flow analyses based on both minimum daily flows and minimum mean monthly flows using an EV III distribution (parameters based on the sample skewness) are also shown on this table.

An analysis of the data for Boro River at Boro Junction Gauging Station was directed at assisting the Collector Well Study. **Figure 24** shows the mean annual discharge rate at Boro Junction in $m^3 s^{-1}$ for the period October 1969 to September 2002 (the total length of the available data). A feature of this graph is the very large annual flows in the 1970's and the subsequent general decline in flows thereafter. The annual data series do not conform to a normal distribution and have a positive skew of 1.1. The long recession of this hydrograph has two small rising limbs; one between 1988 and 1991 and the other less visible one covering the period 1996 to 2002. The mean annual flows in 1995/96 were the lowest on record (0.03 $m^3 s^{-1}$) and the discharge record suggests there was only flow during October 1995. However, the stage record suggests that some standing water was present during several other months too.

Figure 25 shows that over the long-term average monthly river flows at Boro Junction generally start to increase in February, peak in August and reach a minimum in January. The prevailing discharge pattern at Boro Junction is characterised by relatively high discharges between June and November and low discharges between December and May.

Figure 28 shows the annual mean monthly flow duration curve for Boro Junction. This graph indicates that the river, at this point, flows for 85% of the time. For 50% of the time discharge rates have exceeded approximately 2 $m^3 s^{-1}$. Calendar month flow duration curve percentage points, based on mean monthly flow data were calculated (see **Table 9**). These data show that flow during April and May only occurs for less than 70% of the time, while for January to June cease to flow conditions occur for at least 10% of the time (i.e. the 90th percentile is zero flow).

At Mohembo River Gauging Station the period 1998 to 2002 was characterised by inflows into the delta that were only 20% lower than the long-term mean. It is therefore a little surprising that during the same period the mean discharge rate at Boro Junction was less than 10% of the long-term average. This decline in flows in the lower Delta has also been noted at other river gauging stations such as Shashe Bridge.

A double-mass plot of cumulative flow of the Okavango River at Mohembo is plotted against cumulative flow of Boro River at Boro Junction on **Figure 29**. This graph suggests three different inflow-outflow relationships. It is considered significant that outflows from the delta have been reducing with time in comparison to the inflows. *Extrapolation of these relationshops would suggest flows in this river might cease in the future. This is a cause of concern for any scheme in the lower delta that is sustained by river flows.*

There seems to be little doubt that the movement of water through the delta is very sensitive to the inflows at Mohembo. The patterns of change at Boro Junction reflect the variation of flow at Mohembo and other factors, which might include changing patterns of vegetation growth in the delta, animal and human impacts, changing sedimentation patterns in the upper delta, and structural adjustments along any of the many faults.

The flow duration curve information for Boro Junction are presented in **Figure 28**. The fact that the flow record is non-stationary makes it very difficult to interpret future flow patterns and extreme values at this site. Despite these problems, the same extreme value analysis methods that were used for Mohembo were also applied to the Boro Junction data. A frequency analysis of the extreme flood events of the annual 1-day maximum time series, for Boro Junction is shown in **Figure 30**. The non-stationarity of the data are apparent in this diagram, but the data points for return periods of greater than 2-years are sufficiently linear to assume that the Log-Normal distribution is applicable for moderate to large flood events. A summary of the results of this analysis are shown in the following table.

While the values given for the Log-Normal estimates of the floods can be considered reasonable estimates, it should be noted that no maximum daily flows that exceed the tabulated value for the 1:2 year flood have been recorded at this site since 1989. If this trend is indeed a permanent one, none of the values given in this table are appropriate for planning purposes.

Estimated maximum and minimum daily flows at Boro Junction

	Log-Normal distribution		EV II distribution	
Return Period (Years)	**Maximum daily flows ($m^3 s^{-1}$)**	**Standard Error ($m^3 s^{-1}$)**	**Minimum daily flows ($m^3 s^{-1}$)**	**Minimum mean monthly flow ($m^3 s^{-1}$)**
2	12.6	1.81	0.822 (0.16)	0.775 (0.21)
5	21.6	3.08	0.370 (0.28)	0.255 (0.37)
10	28.6	4.15	0.203 (0.37)	0.109 (0.49)
20	36.0	5.24	0.107 (0.47)	0.044 (0.61)
50	46.8	6.69	0.042 (0.60)	0.012 (0.78)
100	56.0	7.79	0.019 (0.70)	0.004 (0.91)

Note: The standard errors for the minimum flows are given in parenthesis

With respect to low-flows, the data indicate a number of months with zero flow at Boro Junction. These appear at regular intervals during summer. A number of zero flows also inevitably occur among the series of the annual minimum daily flows. The EV I distribution is not applicable in such circumstances as it has no defined lower limit, which suggests that the low flows could become negative. The EV II distribution, however, does have a fixed lower limit and therefore can be applied where many of the data in the series are zero. The results of this analysis are summarised in the previous table.

The results indicate that the analysis is very prone to the limitations of the data being used. Despite having the lower mean (see **Table 10**), the estimates for the extreme minimum daily flows are higher than the estimates for the minimum mean monthly flows. There are also no estimates of zero flow, even for the high return periods. This is simply an artifact of the methodology and if the standard error of the estimates are considered, all low-flows with a return period of greater than 5 years will probably be zero. This conclusion is consistent with the actual observed flow data.

Although the Mohembo flows appear to have penetrated greater distances into the delta during the 1970s and 1980s, there would still have been periods of low flow corresponding to the typically dry months of the year (December to March). The extreme low flows are therefore distributed more evenly over the observation period than the extreme high flows. However, it is also apparent that durations of low to zero flow have been substantially extended since the mid-1990s. *This could have serious consequences for any water supply scheme that relies upon river flows.*

Based on the observations made about the data limitations, the flow duration curve information (**Table 9**) is almost certainly more useful with respect to recharge and the design of collector wells. Flows equalled or exceeded some 30% of the time can be considered wet periods, those equalled or exceeded about 50% of the time can be considered average periods, while those equalled or exceeded greater than 70% of the time can be considered dry periods.

The recharge investigations have shown that river stage is important in determining the amount of aquifer recharge and may be more important than flow. For shallow abstractions, such as collector wells, this has important implications. To further investigate the relationship between stage and discharge rating curves have been developed. From the data presented in **Appendix D** it is clear that there are significantly more discharge measurements available than stage data. In order to generate more stage information relationships between flow and discharge were developed that take the form:

$$H = a\,(Q + c)^{b}$$

Where H is stage data in m and Q is the discharge in $m^3\ s^{-1}$. The coefficients a, b and c were optimised to obtain the best curve fit between stage and discharge. Analyses were carried our by examining the R^2 value (proportion of the initial variance accounted for by the form of the rating curve model that was selected) and the goodness of fit using the coefficient of efficiency. While the R^2 statistic will still generate high values when there are systematic errors (e.g. a line that is parallel but much higher or lower), the coefficient of efficiency will not. Both statistics reflect better relationships as they tend towards 1 (or 100%).

A maximum R^2 value of 74% was obtained from the equation:

$$H = 1.07\,(Q + 0.0)^{0.35} \qquad \text{- Equation A}$$

A maximum coefficient of efficiency of 73% was obtained from the equation:

$$H = 0.9\,(Q + 0.1)^{0.4} \qquad \text{- Equation B}$$

Equation A represents the best solution for an equation constrained to give zero stage for zero discharge. Equation B is consistent with the observation from **Figure 31** that stage is non-zero at zero flow, i.e. there is continuous ponding at the gauging site even when there is no flow. Using Equations A and B, likely stages for discharges with defined exceedance percentages were calculated.

For planning purposes, it is important to recognise two critical issues with respect to the interpretation of the Boro Junction data:

- ☐ It is difficult to interpret future flow patterns and extreme values at this site because the data is non-stationary.
- ☐ The estimated flood flows with return periods of 20 years and greater exceed the limit of the data used to define the rating curve equations.

The latter issue could be very important in a flat area such as the Okavango Delta. Increased flood flows may not necessarily lead to significant increases in depth in the channel, but rather to increased widths of inundation.

Flows in the Matsibe River (a tributary of the Kunyere River) were also examined. Data from the gauging station in the Matsibe River have been collected intermittently since August 1972. Over the period 1985 to 2001 some river flows occurred in most years, except for the period Oct 1994 to June 1998. Furthermore, there is one long-term groundwater hydrograph (BH8274) available for this river valley. The data for this borehole shows groundwater levels falling over the period March 1997 to May 1999, and then starting to recover again in June 1999 when significant flows were recorded at Matsibe River Gauge. This result shows that the Matsibe River has been getting regular recharge since 1985/6.

Annual inflows of water into the delta at Mohembo have been relatively constant, and so it might be anticipated that a reduction in flow, seen in places such as Boro Junction and Maun Bridge, would be countered by an increase in flow elsewhere in the delta. Double mass plot of river flows in Matsibe, plotted against river flows at Mohembo, appear to provide some evidence for this - with flows increasing in Matsibe whilst decreasing at Boro Junction. Analysis of the flow data from Ditshiping and Mohembo appear to provide confirmation of this observation.

Important conclusions derived from the analysis of the river discharge data include:

- The river flows of the Okavango River, at Mohembo Gauging Station, have reasonably stationary characteristics since the early 1970s. However, it is also possible to identify a generally wet period in the 1970s, a more variable period up to the mid 1990s and a generally drier period thereafter. Statistical analyses of these data have provided useful insights about the inflows into the delta. Of particular note, were the inflows into the delta over the period 1998 to 2002; these were about 20% lower than the long-term mean, of 8,173 $Mm^3 y^{-1}$.

- The river flows of the Boro River, at Boro Junction Gauging Station, have been highly non-stationary over the period since the 1970s, with the period since 1993 experiencing much lower flows than previously recorded. Over the period 1998 to 2002 annual outflows from the delta were less than 10% of the long-term mean for this station. Although statistical analyses of these data have enabled the historic patterns of discharge and stage to be analysed, there are problems with the results of these analyses due to the non-stationarity of the data.

- For Boro Junction, the extreme low flows expected are likely to be zero with recurrence intervals or return periods of greater than 5 years. However, it is important to remember that the analysis is based on non-stationary data.

- Double-mass plots of cumulative inflow in the Okavango River at Mohembo plotted against cumulative outflow at Boro Junction, Matsibe and Ditshiping show that outflows from the delta are affected by inflows and other, yet undefined, human and environmental factors. It is speculated that an important factor is changing reed growth in the river channels. Over time, reed growth can be expected to build up in wet channels. Over several years this growth may clog up a channel, resulting in a diversion of flow into a dry channel, where the reed growth has died off.

- There is evidence to show that when flows decrease (e.g. Boro Junction) in one part of the lower delta they increase (e.g. Matsibe) in another part of the delta. Changes in the flow regimes of the lower delta can be both positive and negative, and tend to last several years before changing again. In other words, river discharges in the lower delta are unreliable in the long-term.

- South of the Kunyere Fault, at river gauges such as Shashe Bridge, Maun Bridge, and Boro Junction, river flows have decreased relative to inflows since the early 1980's. As a result the Shashe River dried up. If these trends continue, lower Boro and Thamalakane may also dry up.

- Solutions to the unreliability of river flow, recharge and sustainable wellfield development include:

    (a) Dispersal of wellfields to several different river channels.
    (b) The active management of the delta environment.

It is considered that option (a) provides the most practical solution to sustainable groundwater development.

It is recommended that the following improvements be made to the hydrometric network:

- The instrumentation at Shakawe Meteorological Station should be improved so that it records wind speed.
- The rain gauges installed in 1996 during MGPD-1 should be rehabilitated, receive regular maintenance, and have their data regularly recorded and reported.
- A digital data recorder should replace the chart recorder at Mohembo Gauging Station.
- In the lower Delta, key river gauges such as those located at Boro Junction and Matsibe should installed in concrete weirs so that accurate river flows and stage can be recorded.

Also, it would be very helpful if DWA provided an annual Hydrological Data Book for the Okavango Delta. This would provide official quality-controlled data to users.