SODA ASH BOTSWANA (PTY) LTD

SUA SODA ASH PROJECT

Phase III Investigations

Memorandum No.13

# PROCESS AND DOMESTIC WATER SUPPLY

November 1984
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# 1. SYNOPSIS

The interim findings presented in Memoranda 4 and 7 on process and domestic water supply from underground sources and Memorandum No.8 on surface sources are drawn together in this report and the results of subsequent investigations are described, leading to a recommended exploitation strategy to meet the long term demands, estimated at 25.5 l/s for process use and 0.5 l/s for domestic consumption, over a period of at least 25 years with 100% reliability.

The alternative groundwater sources are reviewed and their long term reliability is assessed. The possibility of drawing a process water supply in the long term from shallow depths in the brine wellfield area is discussed and it is concluded that this should not be relied upon as a viable option on the basis of data currently available.

In addition to the dam site identified in Memorandum No.8 (Dam Site 2), where the Mosetse River passes through the Kgwana Hills,a further site (Dam Site 1) is appraised lying some 18 km downstream, which would deliver water under gravity to the township and plant site over a distance of 46 km.

The option of off-channel storage in the Mosetse wellfield area is further examined and it is concluded from reservoir trials using 50 years of synthesised Mosetse River flows that a 500 x 500m reservoir with a storage depth of 5m would offer long term reliability of about 90%. Similar reservoir trials based on storage at Dam Sites 1 and 2 indicate a comparable level of long term reliability.

An appraisal of all available options confirms that none of the sources identified can alone meet the long term demands of the Project with complete reliability and it is concluded that a conjunctive use approach should be followed in which surface storage fed by the Mosetse is supplemented in drought periods by groundwater abstraction.

Three conjunctive use options are identified, each of which would meet the estimated demand with long term reliability.

A recommended exploitation strategy is put forward to provide a basis for optimisation and costing. A process of progressive resource evaluation and exploitation is advocated. The capital cost and phasing of expenditure will depend on the firming up of process and domestic demand estimates and on the build up of demand over the construction phase and early years of operation of the process plant.

## 2. DEMANDS

Estimated demand figures remain as given in the terms of reference presented to WLPU by the S.A.B. Project Manager on 24th May, 1984, as follows:

| | |
|---|---|
| Process demand | 25.5 l/s |
| Domestic Demand | 0.5 l/s |

It is understood that a dissolved solids concentration of 7 000mg/l is acceptable for process use.

Sources of supply and recommendations for their development as discussed in this report are accordingly based on meeting these demands over the predicted life of the scheme, assumed to be at least 25 years.

However, recognition is given to the need to provide water during construction of the process plant, to the likely staggered build up to full production potential of the plant over the initial years of operation and to the resulting staged increase of water demand, up to a total of 26 l/s, over this period.

## 3. POTENTIAL SOURCES OF SUPPLY

Potential groundwater and surface water sources are examined with a view to meeting the project demands defined in Section 2 with 100% reliability.

Memorandum No.8 (presented in June 1984) summarised investigations into solar distillation and storage within the river bed sediments, concluding that neither of these was likely to meet the demand criteria and accordingly, that these sources did not merit further investigation.

The following potential sources were deemed worthy of further study:

1) Groundwater abstraction.

2) Conventional surface water scheme, involving dam and storage reservoir.

3) Off-channel storage, probably used in conjunction with another source.

Potential groundwater abstraction schemes based on the Mosetse, W8/E3, and Dukwe wellfields were discussed in Memorandum No.7, presented in May 1984, and the conclusions therein have been updated to include more recent studies, and summarised in Section 3.1 of this Memorandum. Additionally, the possibility of abstracting fresh water in the long term from shallow depths in the Sua Pan wellfield is considered.

The Nata, Mosetse and Mosope Rivers were all originally identified for investigation as potential sources, but studies are concentrated here on storage sites on the Mosetse River, which offer most benefits from engineering and economic viewpoints. These are summarised in Section 3.2.

Section 3.2.3 discusses the feasibility of off-channel storage schemes, extending the appraisal made in Memorandum No.8.

### 3.1 Groundwater Sources

Of the four potential groundwater sources discussed in the following sections, three (Mosetse, W8/E3 and Dukwe wellfields) are located along the eastern downthrown block (or graben) associated with the Mosetse Fault. These sources have been investigated by the Institute of Hydrology under assignment to WLPU.

The Dukwe and W8/E3 wellfields were investigated initially by SWECO in 1976, whilst the Mosetse wellfield has been investigated exclusively by the IOH as part of the current studies. All three potential sources were discussed in Memorandum No.7, to which reference should also be made.

For ease of reference, the results of all pump testing undertaken to date are summarised in Appendix II.

The potential for fresh water abstraction from the brine wellfield at Sua Pan has been raised as a result of the recharge studies recently undertaken for the brine production wells, and is considered further in this Memorandum.

### 3.1.1 Regional Hydrogeology

The predominant structural feature of the region is the Mosetse Fault which trends north-south approximately 25 km east of Sua, essentially forming a barrier to the western flow of groundwater.

Basement complex rocks occur generally to the east of the Mosetse Fault. To the south-east and generally south of the Mosetse River they outcrop at the surface, whilst in the north-east they occur within an upthrown, faulted block (or horst) at a depth of 45 to 55m. Between these two areas is located a downthrown, faulted block (or graben) which features major north-east and north-west trending faults with sedimentary layers approximately 200m in depth. The faulting divides the eastern graben into a series of separate blocks, which show variable potential for groundwater development. Three of these areas, referred to as the Mosetse, W8/E3 and Dukwe wellfields respectively, are discussed in the sections that follow.

Recharge of the defined aquifers and groundwater flow patterns are aspects which are of crucial importance to the prediction of long term production well performance, although current knowledge is limited by the hydrogeological complexity of the area. As this report is being prepared, an environmental isotope study on water samples from Mosetse and W8/E3 wellfields is being undertaken, with a view to extending knowledge of these aspects. The results of this study will be issued in an Addendum to this Report by the end of December 1984.

3.1.2 Mosetse Wellfield

To the east of the Mosetse Fault, and within an area of complex major faulting, a downthrown block or graben centred on the Mosetse River has been identified as a potential groundwater source. The block has been downthrown by at least 170m from a north-west striking fault to the east, which, together with major faults to the north-west and the south, forms the boundary of the area.

The direction of the river appears to have been controlled by the faulting, and other faults probably exist to the north, beneath alluvial deposits. Basement Complex rocks occur on the upthrow side of the fault and to the south of the fault delineating the southern boundary of the block.

Alluvial deposits of a few metres in thickness occur over most of the Mosetse Block, generally overlying calcrete. Beneath the calcrete deposits, the water bearing micaceous siltstones and Mea Arkose formations are present. The calcrete deposits decrease in thickness towards the east of the block. Scattered outcrops of Mea Arkose are also evident along the Mosetse River, the course of which appears to have been influenced in part by their presence.

Whilst high quality potable groundwater is available from the narrow zone centred on the Mosetse Block, the effect of complex faulting has been to confine individual storage zones, restricting the capacity for groundwater movement and recharge.

Drilling and well testing undertaken during recent investigations have concentrated on a 6.5 km stretch of the Mosetse Valley, from well 3129 (on the eastern boundary of the Mosetse Block) downstream to WW7.

Higher well yields appear to be associated with the siltstones. This sequence is absent from both WW7 and 3129 and the lower specific capacities (0.1 l/s/m) and transmissivities (approximately $3m^2/d$) associated with these wells are more typical of the aquifer characteristics to be found outside of the Mosetse Block.

One kilometre downstream of 3129, WW14 was drilled to a depth of 108m into the Mea Arkose. Calcretes are absent here, but siltstones are present and the main inflow to this well was found to be below 50m depth. A specific capacity of approximately 1 l/s/m and a transmissivity of approximately 600m$^2$/d were recorded at this well. A recent long term constant rate pump and recovery test in adjacent well WW14/P has generally confirmed these results.

Further downstream, WW8 was drilled through a 7m layer of calcrete, to a total depth of 108m into the Mea Arkose. The main inflow was recorded at 60m depth giving a specific capacity of 14.1 l/s/m and a transmissivity of 1 450 m$^2$/d. However, adjacent wells WW8/T and WW8/P gave much lower transmissivities, which is indicative of the localised nature of high yielding zones resulting from the complex faulting within the area.

Geophysical logging recently undertaken at WW8 and WW14, shows overall similarity, probably confirming that both boreholes only penetrate into Mea Arkose. WW8 indicates weathered zones, whereas the logs of WW14 revealed numerous fractures, likely to be bedding planes. These fractures are probably tight, being consistent with the lower yield predicted from analyses of pump testing. A full appraisal by the IOH of the geophysical logging is presented in Appendix III of this report.

Other wells drilled for testing in this area include WW13, located on the river midway between WW8 and WW7 and which penetrated dolerite at 61m, and WW9, located some 1.5 km north of WW8 which encountered very saline water at a depth of 43m. Both of these wells were drilled through some 20m of calcretes.

The extent of the high yielding aquifer can be judged from an examination of water levels and chemistries in the wells, but the southern boundary cannot be assessed with confidence due to the absence of any investigation works south of the Mosetse. Similar water levels and water chemistries link well 3129 to WW8, whilst the high dissolved solids content at WW9 indicates discontinuity with the WW8 aquifer, and the higher water level at WW7 suggests isolation of this well from WW8.

The water at WW8 and WW14 is of a quality suitable for domestic consumption, simply requiring filtration and sterilisation before distribution. Due, however, to the configuration of faulting, and the restricted hydraulic interconnection between individual blocks, not all of the storage will be available and any intensive development of the aquifer would entail the use of a large number of wells, each relatively low yielding. High initial yields have been obtained with pump tests, but these have shown indications of storage depletion during prolonged pumping.

The relatively complex configurations of the faulting, and the limited data available on storage capacity and recharge render firm predictions on the yield of the area difficult. Recharge from rainfall or from the river is likely to be limited to areas where the Mea Arkose outcrops or is close to the surface. This confines recharge potential to a narrow zone extending from WW8 to 0.5 km upstream of 3129. Downstream of WW8 the overlying calcrete deposits restrict infiltration to the Mea Arkose, whilst the Basement Complex formation precludes infiltration upstream of the eastern graben, beyond 3129.

Thus present indications are that abstractions will rely on storage, with permanent depletion resulting from prolonged abstractions. Nevertheless, it is conservatively estimated that the Mosetse wellfield would meet the predicted demand for potable water for the life of the scheme, although abstraction should be accompanied by monitoring of water levels, possible recharge patterns and water quality, to enable long term reliability to be periodically re-assessed.

### 3.1.3 W8/E3 Wellfield

The W8/E3 aquifer is bounded to the west and east by faults predominantly trending north-south, this being the northern flank of the eastern graben, with the Ntane Sandstone representing the main water bearing formation.

Well 3106, drilled through the Ntane Sandstone, marks the northern boundary of the aquifer, whilst the Mmemo well is at the southern extremity. The areal extent of the aquifer is estimated to be approximately 10 $km^2$.

Testing of W8/E3 was undertaken by SWECO in 1976. A long term test was undertaken for 64 days continuously at 1 500$m^3$/d which gave a 0.5m decline in storage for a total pumpage of 96 215$m^3$. This is in general agreement with the change in level recorded during the 23 l/s constant rate test undertaken in March 1984. Extrapolation gives approximately 9m of initial drawdown at an abstraction rate of 26 l/s. As the total available drawdown is approximately 30m, the remaining available 20m (approximately) should sustain supplies for up to 5 years assuming a live aquifer storage of $4 \times 10^6$ $m^3$.

Limited yields are currently derived from existing wells MT2, 3106 and the Mmemo well, but the lack of high-rate test data for these wells precludes a meaningful assessment of specific capacity and long term yield. For example, although the test undertaken at the Mmemo well yielded a theoretical specific capacity of 12.8 l/s/m, this result has to be viewed with caution, taking account of the low pumping rate (0.64 l/s) and the short duration (120 minutes) of the test. Also no details of the well are available, although the conductivity reading of 2 420 mS is similar to that at W8/E3 (2 150 mS) suggesting interconnection, and, from a subjective assessment of the data to hand, it is likely that higher-rate testing leading to controlled abstraction to augment supplies from other high yielding wells, such as W8/E3, is possible.

Data is limited at well MT2, although the different water composition and lower conductivity of 860 mS indicates a shallow source with no interconnection to W8/E3. Similarly, from a comparison of conductivity and chloride content of the water, well 3106 appears to be unconnected with W8/E3, although this well penetrates a 40m thickness of Ntane Sandstone and SWECO reported a yield of 2 l/s.

WW15 is located approximately midway between W8/E3 and the Mmemo well. Although the thickness of the Ntane Sandstone is similar to that recorded at W8/E3, recent pump testing indicates a reliable yield of up to 1 l/s. Recent geophysical logging undertaken in WW15 revealed numerous fractures, generally relating to shale beds. These are likely to be tight, thus accounting for the lower yield recorded during pump testing. The logging confirms Ntane Sandstones and Siltstone to a depth of approximately 49m; between 49m and 79m the recorded activity is indicative of Mea Arkose.

The conclusion is drawn that a pattern of wells intersecting the water bearing Ntane Sandstone would give individual yields of about 1 l/s. These would include WW15 and probably 3106. The apparent interconnection of the Mmemo well with W8/E3 indicates that initial abstractions here could be of the order of 5 l/s. With well W8/E3 providing the major contribution, an arrangement of wells could be designed to meet the industrial demand of 25.5 l/s; this arrangement would be dependent on the build up of demand over the initial years of operation of the project and the monitoring of yields over a prolonged period of abstraction.

Predictions concerning the period over which the demand can be met depend upon the storage capacity of the aquifer, and recharge patterns. Data presently available indicates that recharge is limited to groundwater inflow from the north, via north-south trending faults. Abstraction would thus give rise to permanent depletion of aquifer storage. Further assessment of storage would be possible as a result of monitoring of groundwater levels by means of observation wells, during abstraction. This is discussed further in Section 5.2.

The water from this area generally has a chloride content higher than the 600mg/l recommended by WHO and would necessitate desalination if used for domestic consumption. However, this would not be required for water supplied to the process plant.

### 3.1.4 Dukwe Wellfield

This area is centred on a number of existing wells which provide limited supplies for cattle watering. In view of the remoteness from Sua (via the existing road the distance from Dukwe Camp to Sua is around 50 km) and due to possible abstraction difficulties arising from water rights already in existence, no investigations have been made in this area since SWECO's report in May 1976.

The water bearing formation is the Mea Arkose, being approximately 100m in thickness in the Dukwe Graben. This is overlain by Ntane Sandstone and Tlapana Mudstones which are considered to restrict direct recharge of the Mea Arkose. The extent of the aquifer is approximately 25 $km^2$, being bounded by a major north-east trending fault to the south and possibly a north-west trending fault to the west.

The three most productive wells give test details as follows:

| | | | | |
|---|---|---|---|---|
| 604 | Transmissivity | $412m^2d$ | Specific capacity | 0.99 l/s/m |
| 1239 | Transmissivity | $277m^2d$ | Specific capacity | 0.33 l/s/m |
| 616 | Transmissivity | $371m^2d$ | Specific capacity | 0.94 l/s/m |

There are indications that steady state conditions due to leakage (or interception of a zone of higher transmissivity) occurred during the tests at 1239 and 616 (only 45m apart). Well 604 did not reach a steady state condition at

6 l/s during the test period of approximately 3 hours. Accordingly, it is considered that 604 and 616 could support combined abstraction of 10 l/s, with 1239 sustaining about 5 l/s.

Other boreholes may be equally productive within the same area, but in general yields of up to 2 l/s would be expected, similar to the background values obtained elsewhere in the region.

The water quality in the Dukwe area suggests limited active recharge but a steady decline in storage would nevertheless be anticipated. A reliable estimate of the production life of the aquifer could be made after long term tests were undertaken but our current assessment indicates that a continuous yield of 25.5 l/s could be maintained for 4 years without recharge.

The measured chloride content of the water from wells 604, 616 and 1239 is typically 230 mg/l. This is considerably less than that at W8/E3, and at this level of chlorides desalination would not be regarded as essential for domestic consumption.

On the assumption that difficulties may be encountered in securing water abstraction rights and satisfying requirements of existing users, no further consideration has been given to abstraction from the Dukwe wellfield in meeting the water demand for the Project.

### 3.1.5 Sua Pan Wellfield

The effects of recharge to the brine resource by direct precipitation and river inflows were examined in Memorandum No.11, presented in October 1984.

It was concluded that the recharge process would give rise to an interface between the brines currently stored beneath the Pan surface and overlying relatively fresh water. This fresh water would follow the brines downward as a result of recharge replacement of the brine pumped from storage in the long term.

In the computer model set up to evaluate this effect, and described in Memorandum No.11, a conservative relationship was assumed between the pick up of dissolved salts and the volume of recharge passing through unit depth of the Pan soils, on the basis of laboratory test results. This indicated that the freshwater/brine interface would be drawn down through about 3 to 4m over each five year period of brine abstraction over the wellfield area.

This would suggest that the fresh water stored above the brine could be exploited by a system of shallow wells operating independently from the brine abstraction wells and feeding a separate fresh water supply pipeline supplying the process plant.

It must be borne in mind that conservative assumptions made in relation to salt pick up in the context of brine resource evaluation will be optimistic when applied to the possibility of fresh water supply from the upper strata overlying the brine aquifer.

Furthermore, the brine aquifer model assigns relatively low permeabilities to these upper strata suggesting that shallow freshwater supply wells would have very low yields relative to the brine abstraction wells.

Nevertheless the freshwater demand is relatively very small (26 l/s as against up to 1 000 l/s of brine) and it is understood that a relatively high level of dissolved solids (up to 7 000 mg/l) can be tolerated for process plant water supply. Hence there is a significant possibility that the Sua Pan brine wellfield will constitute a viable source of process water won from shallow depths in the long term.

In view of the uncertainties associated with this possibility it is recommended that it should not be relied upon as a potential source of process water in the project feasibility studies.

The brine wellfield monitoring system will include provision for recording the recharge process, including monitoring of brine concentrations at shallow depths.

If and when the abstraction of brine leads to the indicated specific gravities at 10m depth falling to approximately 1.007, the abstraction of process water from shallow wells could become a viable option to the other sources defined in this Memorandum.

## 3.2 Surface Sources

There are three rivers draining into the Sua Pan from the east, these being the Nata, Mosetse and Mosope. As discussed in Memorandum No.8, investigations have been limited to sources drawing from the Mosetse River only, as this is the nearest to the site and has a mean annual run-off of 26.4 x $10^6$ $m^3$, which is well in excess of the projected annual project demand of 820 000 $m^3$.

3.2.1 Surface Hydrology

The Mosetse River flows westwards to discharge into the Sua Pan south of the Sua Spit. The catchment area is approximately 1 090 $km^2$ and the mean annual run-off (MAR) is 26.4 x $10^6$ $m^3$, both measured close to the point where the Francistown-Maun road crosses the river, at Mosetse Bridge.

Run-off normally occurs between the months of October and April, during which period the flows can be extremely varied in distribution and duration. Maximum run-off is typically experienced in the months of December, January and February.

Daily flow records from the Mosetse Bridge gauge are available for a 14 year period extending from 1969.

Analysis of these river records has been undertaken to assess the reliability of the identified surface water sources, and in gauging the potential for natural recharge of the Mosetse wellfield. To facilitate an appraisal of long term behaviour it was necessary to extend the 14 year period of record using a computer model. This was achieved in two stages. Initially, the rainfall record from Nata, the nearest reliable rainfall station, was used in the computer model to give synthesised river flows which matched the actual river records for the 14 year period as closely as possible. Secondly, using monthly rainfall data extending back to 1932/33 from Plumtree in Zimbabwe, an extrapolation exercise was undertaken on the computer model to give synthesised monthly river flows over the period 1932/33 to 1982/83. The river flows so derived are tabulated in Appendix I.

Neither Nata nor Plumtree lie on the Mosetse catchment and, due to the difficulty in accurately relating the rainfall pattern with river flows over the 14 years of overlapping record, the synthesised river flows obtained are by no means exact. The extremely intermittent and localised nature of the rainfall pattern renders questionable the strict applicability of data from Nata and more especially from Plumtree, where total annual rainfall is on average higher. However, despite these qualifications, the synthesised river flow record obtained from the model is a useful tool in appraising the relative reliability of the various surface sources identified and the application of the computer model for this purpose is considered valid.

The performance of both on-channel and off-channel storage reservoirs is highly sensitive to evaporation losses. For these studies, total annual evaporation losses of 1 890mm per annum, net of rainfall, have been used.

### 3.2.2 Mosetse Dam Sites

An investigation carried out by B.G.A. Lund and Partner in 1972 identified three suitable dam sites along the Mosetse River. The furthest upstream of these sites, near Mosetse Bridge, was further investigated by Sir Alexander Gibb and Partners in 1976.

Our investigations have shown that two of the sites warrant further investigation and these have been designated Dam Site 1 and Dam Site 2 as shown on Fig.1.

Using the input data detailed below, a computer model has been used to predict the performance of storage at each of the two sites:

a) Monthly net evaporation figures giving an annual total of 1 890mm. These figures have been developed from consideration of the Sua Class A Pan results, as originally discussed in Memorandum No.8.

b) Fifty years of synthesised Mosetse River flows (see Section 3.2.1).

c) Continuous abstraction of 26 l/s.

d) Depth-storage and depth-area relationships based on the limited topographical data gathered by the previous investigators and checked for consistency with the subsequent 1 : 50 000 mapping.

<u>Dam Site 1</u>

This dam would consist of an earthfill embankment extending from the steep sided south bank of the river to the relatively flat north bank. The available topographical data from the Lund report indicates that a dam of crest length 3 km and maximum height 7m would have a gross storage capacity of 8M $m^3$. A large open cut service spillway would be constructed on the right bank, together with an emergency spillway to cope with the catastrophic flood.

A limited inspection and survey recently carried out by WLPU site staff has confirmed that assumptions adopted in our appraisal agree with the topographical features of the site, although detailed investigation would be required for further optimisation studies.

<u>Dam Site 2</u>

This site was considered in Memorandum No.8. It features fairly steep abutment slopes, formed by the river channel as it passes through the Kgwana Hills at this point.

As for Site 1, the dam would consist of an earthfill embankment, of indicated crest length 650m and maximum crest height 12m. A large spillway would be routed either north or south of the dam, along the valleys between the hills. The indicated gross storage for this dam is 40M $m^3$.

Each dam would incorporate a low level outlet to permit drawdown of the reservoir under emergency conditions, for silt scouring, and to provide compensation flows downstream if required. With careful sizing and routing the pipeline from either reservoir would permit supply of water to Sua under gravity.

Analysis of data on sediment yield of rivers in Southern Africa* gives an approximate figure of 2.5M $m^3$ of silt deposited in a reservoir on the Mosetse River over a 25 year period. This figure has been allowed for in analysis of the reliability of the options.

The results of the computer runs show that both dams give a reliability of approx. 90%, i.e. some 65 months of deficit over the 50 years of record.

*"Surface Water Resources of South Africa" by W.V. Pitman and D.C. Midgley (1981), Water Research Commission, University of Witwatersrand

### 3.2.3 Mosetse Off-Channel Storage

Construction of an off-channel storage reservoir has several advantages over the valley storage options; the major ones being reduced losses due to evaporation and the absence of a major and expensive spillway structure to pass the extreme floods which are very high relative to mean annual flows.

The reservoir would comprise an earthfill confining embankment constructed on the relatively flat ground adjacent to the Mosetse river near wellfield WW8. The floor and internal faces of the embankments would be sealed with a bentonite based sealant or synthetic membrane to limit losses due to seepage. A reinforced concrete silt trap structure would be required around the inlet pipe at its point of discharge into the reservoir from the river pumping station. A substantial perimeter fence would be required to prevent damage to the embankments and contamination by livestock and wildlife in the area.

The river intake structure would require careful design so as to limit silt intake to the reservoir. Large pumps in the river would deliver a maximum of $0.5m^3/s$ along a rising main to the reservoir. For the computer analyses we have assumed that abstraction from the river would not take place until river flow exceeded $0.5m^3/s$, so as to limit silt intake by positioning the intake invert above the level of the bed load moving by saltation.

Computer analyses have been carried out to determine the reliability of the off-channel storage reservoir option. Two sizes of reservoir were considered; 250m x 250m and 500m x 500m in plan, with a maximum water depth of 5m.

The following input data were used for the model:

a) Monthly net evaporation figures (as described in Section 3.2.2).
b) Fifty years of synthesised Mosetse River flows.
c) Pumped inflows fixed at 0.5 $m^3/s$, above a threshold flow of $0.5m^3/s$ in the river.
d) Continuous abstraction of 26 l/s.

The results of the computer runs are given in Figs.2, 2A, 3 and 3A. The reliability of the 250m x 250m reservoir is calculated at approximately 48%, and the 500m x 500m reservoir reliability is approximately 90%.

## 4. CONJUNCTIVE USE SCHEMES

The investigations into the reliability of the various sources of supply have shown that no one source will prove capable of supplying the expected total demand of 26 l/s for the anticipated 25 year life of the Project. A combination of sources can, however, meet the demand with long term reliability.

After consideration of each individual source the following conjunctive use options, shown in Fig.1, have been identified for further investigation:

Option 1 - Dam Site 1 plus W8/E3 and Mosetse Wellfields

This option consists of an earthfill dam constructed on the Mosetse River at Site 1, with a gravity pipeline connecting to the Mosetse wellfield and then on to the process plant and township. A separate pipeline would connect the W8/E3 wellfield into the main pipeline to the process plant.

Option 2 - Dam Site 2 plus W8/E3 and Mosetse Wellfields

Similar to the first option, this consists of an earthfill dam at Site 2 connected to the W8/E3 wellfield with a gravity pipeline and then on to the process plant and township. A separate gravity line would connect the Mosetse wellfield to the township.

Option 3 - Off-Channel Storage Reservoir plus W8/E3 and Mosetse Wellfields

This scheme consists of an off-channel storage reservoir and associated river inlet works situated adjacent to the Mosetse wellfield. A gravity pipeline connects the reservoir and wellfield to the main line running from the W8/E3 wellfield.

In finalising the detailed pipeline configuration for any of the above options, consideration should be given to separating the domestic water supplied from the Mosetse wellfield from the process water, to ensure that the 0.5 l/s domestic demand can be met without interruption and without requiring expensive desalination.

The reliability of both 250m x 250m and 500m x 500m reservoirs, when used individually, was discussed in Section 3.2.3. Even when used conjunctively with Mosetse and W8/E3 wellfields, it is concluded that the reliability of the 250m x 250m is so low as to render it non-viable as a source option. We have therefore restricted further analysis to the 500m x 500m reservoir only.

## 5. RECOMMENDED EXPLOITATION STRATEGY

In assessment of a programme for development of potential sources to meet the demand for the Project, consideration should be given to the following:

) Reliability of source - both individually and when used conjunctively with other sources.

ii) Capital cost of source development, together with operating and maintenance costs for the duration of the Project.

iii) Design and construction period required to bring the source "on stream".

iv) Anticipated construction period for Sua Pan brine wellfield, process plant and township, together with rate at which demand will increase up to anticipated peak of 26 l/s.

v) Means of meeting potable and construction water demands during the construction period of the Project.

Detailed consideration of costs and programming of the Project are beyond the scope of this report, but it has nevertheless been necessary to take account of their significance in the discussion which follows.

Budgetary costs have been estimated as follows, at 1984 prices:

| Option No. | Capital Cost (Million Pula) |
|---|---|
| 1 | 17 |
| 2 | 18 |
| 3 | 12.5 |

The exploitation of sources to meet the demand has been considered in two stages, viz. firstly, development to cover an initial demand development period and secondly, subsequent enhancement to meet the demand on a long term basis.

## 5.1 Initial Scheme

Section 4 of this report discussed three options, each utilising conjunctive use of separate sources.

Each of these options includes development and abstraction from wellfields near the Mosetse and in the W8/E3 area, with the balance of the demand being met from either one of the two identified dam sites, or from an off-channel storage reservoir. The reliability of the supply from either dam or off-channel reservoir has been estimated to be approximately 90%, with abstraction from the Mosetse wellfield necessary to ensure 100% reliability of supply of domestic water, and abstraction from W8/E3 wellfield necessary to guarantee 100% reliability of process water supply over the 25 year life of the Project.

Whereas our appraisal indicates that both wellfields are adequately reliable to provide water over a 25 year period in the manner described, i.e. as a back-up source to meet domestic or process water demand for approximately 10% of the time, insufficient data is presently available to accurately predict drawdown or recharge patterns, or to assess whether higher yields could, in fact, be sustained in the long term.

Also, budgetary cost estimates show that due to the high capital cost of dam construction, Option 3, using an off-channel storage reservoir with Mosetse and W8/E3 wellfields,is significantly the cheapest in terms of capital cost. However, when accout is taken of higher operating costs associated with river abstraction, particularly pumping to fill the off-channel reservoir, it is apparent that the cost advantage held by Option 3 will be narrowed.

Construction of the process plant, associated production wells, infrastructure, etc., has been assumed to take a minimum of 2 years. During this period water of a quality suitable for domestic consumption (with minimal treatment) will be required. Thereafter, it has been assumed that it will take up to 2 years to develop full production, by which time the full 25.5 l/s will be required for the process plant, plus 0.5 l/s for domestic consumption.

During the 2 year period (say) required for construction, it is recommended that the Mosetse wellfield be exploited to provide water of potable quality. The supply pipeline from the Mosetse wellfield will be routed to Sua via the existing road (see Fig.1) in order that a branch can conveniently be extended to the W8/E3 wellfield at a later date.

Whilst abstraction continues during this period, it will be necessary to extend the collection of data on the behaviour of the Mosetse and W8/E3 wellfields, and to undertake further investigation of the two identified dam sites, and of the off-channel storage reservoir and associated river intake, in order to assist detailed appraisal of these potential sources for long term development. Proposals for monitoring wellfield performance are outlined in Section 5.2, and longer term source development is discussed in Section 5.3.

## 5.2 Wellfield Monitoring

Abstraction from the Mosetse wellfield during the construction period, and from the W8/E3 wellfield later, may need to be modified as large scale abstraction reveals features of the groundwater system that cannot be identified from small scale testing. Such features include increased drawdown from barrier boundaries or dewatering of aquifer horizons and changes in water quality.

It will be necessary to predict unacceptable changes as far in advance as possible. Sustained, regular and frequent monitoring will provide the required information on which to base water supply management decisions. Furthermore, Government may have to be satisfied that the groundwater scheme will be properly monitored before issuing an abstraction licence.

A monitoring network should comprise two parts; each of which has slightly different objectives, frequency of readings and equipment requirements:

) Baseline or Hydrological Network.

ii) Management Network.

In outline these networks would be as follows:

A. Baseline (Hydrological) Network

The objectives of this network are to obtain information on natural changes in the groundwater system, such as recharge, but also to examine the aquifer response to abstraction on a wider scale. It should include:

new river gauging station in the area of a proposed off-channel reservoir, or upstream of a proposed storage dam (together with rating curve information)

rainfall station in the W8/E3 area

monitoring wells, preferably fitted with chart recorders but alternatively having at least weekly water level measurements by water level dipper at five sites distributed between the two wellfields:

a) Mosetse Wellfield

One north and one south of the Mosetse River, sited away from pumped wells to assess water level changes resulting from river recharge. Monitoring should also be undertaken at WW7. Wells should be 100mm nominal diameter to 70m depth.

b) W8/E3 Wellfield

? One near to W8/E3 and another at WW15.

Even though abstraction from the wellfields may be undertaken in a staged manner, the five observation wells should be installed as soon as possible, to facilitate the appraisal of water levels, natural recharge and groundwater flow patterns over an extended period of time, to assist in predictions of long term yields.

B. Management Network

The data from this network would be used to examine how the individual pumped wells, together with the system as a whole, are responding to larger scale abstraction. It should comprise:

pumping rate, water levels, pumping duration and water quality measurements at all project pumping wells

water level recovery during non-pumping periods (recorded via monitoring wells)

In addition, the Government may require regular water level measurements to be taken in any existing wells likely to be affected by abstraction in the W8/E3 area.

## 5.3 Notional Long Term Strategy

Following from the recommendation given in Section 5.1 that the Mosetse wellfield be used to meet the demand during the construction period, one or other of the identified conjunctive use options will be implemented, together with development of the W8/E3 wellfield, for the long term requirements of the Project.

Clearly, decisions regarding such development will need to be taken as early as possible, certainly well before the process plant is commissioned, thus allowing sufficient lead time for design and construction of the second phase works. Before detailed design can be commenced, the following information should be to hand:

i) Results of monitoring of water levels and water quality gathered during the period of abstraction under the initial scheme from the Mosetse wellfield.

ii) Results of monitoring undertaken at the W8/E3 wellfield.

iii) Report on site investigation, feasibility and optimisation of either of identified dam options, or the proposed off-channel storage reservoir.

It is considered essential, therefore, that the recommended wellfield monitoring proposals, (see Section 5.2) and the dam/reservoir studies be implemented as early as possible. Detailed terms of reference for the latter should include, inter alia, dam and river basin surveys, availability and properties of suitable construction materials, depth, soundness and permeability of rock at dam and spillway sites, and further investigation on hydrology and sedimentation. Both field investigations and desk studies would be required, including cost optimisation studies embracing operating and maintenance costs, as well as capital costs.

The size of off-channel storage reservoir necessary to give performance comparable with the dam options is very large relative to structures of this type constructed elsewhere and its development would require careful appraisal of seepage control, intake design and desilting measures. The dam options entail a more conventional design approach and hence their technical optimisation can be approached with greater confidence.

Monitoring of brine concentrations at shallow depths in the Sua Pan wellfield will indicate whether relatively fresh water overlying the receding brines in the progressively depleted aquitard can be regarded as a viable option for process water supply in the long term.

Without the benefit of the data from these further studies, selection of the long term source cannot be made at this stage with any authority. Purely on the basis of information prepared for this Memorandum, however, it appears that a dam at Site 1, used conjunctively with abstraction from Mosetse and W8/E3 wellfields, is likely to prove attractive. The size of the dam and reservoir would be determined by updated assessments of the reliable yield from the wellfields and from improved definition of the depth/area and depth/storage characteristics of the proposed site. As mentioned previously, the apparently higher capital cost is likely to be offset by reduced operating and maintenance costs, and certainly draw-off from this dam and its conjunctive use with wellfield abstraction will prove more convenient from an operational and management viewpoint. The overall cost of such a scheme is likely to be of the order of P17 Million at constant 1984 prices. The phasing of this capital expenditure is likely to be an important factor in the DCF analysis of the Project and this will depend in part on the emergence of firmer demand estimates and the development of demand over the early years.

## 6. CONCLUSIONS

The following potential sources of supply have been identified to meet the process and domestic water supply demands of the Project:

a) Groundwater sources:
   Mosetse Wellfield
   W8/E3 Wellfield
   Dukwe Wellfield
   Sua Pan Wellfield

b) Surface Sources:
   Mosetse River - Dam Site 1
   Mosetse River - Dam Site 2
   Mosetse River - Off-channel Storage

The Dukwe wellfield is discounted on the grounds of distance from the Project site and current abstractions by other users.

The Sua Pan wellfield could prove attractive in the long term as a source of process water drawn from shallow depths. However, insufficient data is currently available for this option to be regarded with confidence as a viable option.

It has been established that the W8/E3 and Mosetse wellfields could together meet the total demands of the Project in the short term. However, storage depeletion is anticipated under long term abstraction and the complex hydrogeology of the wellfield areas precludes reliable prediction at this stage of the available storage which may be called upon.

Nevertheless, it is conservatively estimated that the Mosetse wellfield would meet the predicted demand for potable water over the life of the Project and that the W8/E3 wellfield would meet the full estimated process demand for up to 5 years.

Each of the identified surface sources would supply the full project demand with a reliability of about 90% in the long term, with the extremely variable annual flow pattern as indicated by 50 years of synthesised monthly flows in the Mosetse leading to shortfalls in prolonged drought periods.

An assessment of the potential yield and long term reliability of the viable alternative sources may be summarised in tabular form as follows:

| Source | Yield | Reliability Assessment |
|---|---|---|
| Mosetse Wellfield | 0.5 l/s Domestic Supply | Continuous for 25 years |
| W8/E3 Wellfield | 25.5 l/s Process Supply | Continuous for up to 5 years |
| Mosetse - Dam Site 1 | Domestic and Process Supply | 90% over life of Project |
| Mosetse - Dam Site 2 | Domestic and Process Supply | 90% over life of Project |
| Mosetse - Off-Channel Storage | Domestic and Process Supply | 90% over life of Project |

Arising from the above appraisal of the available source options considered individually, a progressive exploitation strategy is advocated based on conjunctive use of groundwater and surface sources to provide complete long term reliability of supply.

Initially, it is recommended that construction phase demands should be met by closely monitored abstractions from the Mosetse wellfield, leading to a firm assessment of the long term performance of this source.

Based on this assessment, coupled with concurrent further study of the W8/E3 wellfield and Mosetse storage options it is recommended that a long term exploitation strategy should be progressively evolved.

In the current phase of project feasibility studies, preliminary design and costing should be deferred until firm demand estimates have been arrived at, including demands over the construction period and the phasing of process demand build up in the early years of operation.

Once this stage is reached it will be possible to prepare estimates related to the Project development programme of the phased expenditure necessary to implement a conjunctive use scheme. It is likely that three phases of resource development will emerge as follows:

Phase I: A scheme to meet construction demands from the Mosetse wellfield with concurrent design studies of the W8/E3 wellfield and surface supply options, concentrated on Dam Site 1 and the 500 x 500 x 5m off-channel storage reservoir.

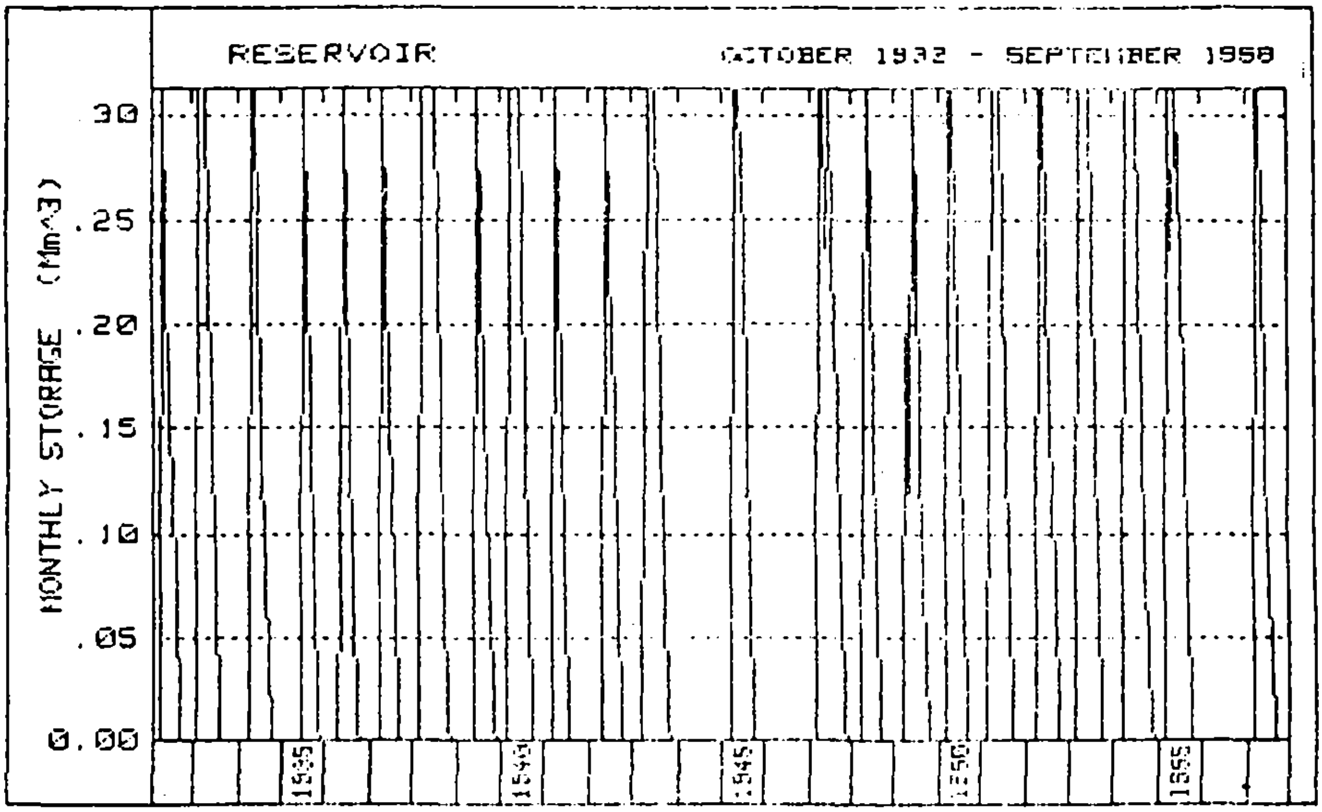
Phase II: Development and linking in of the W8/E3 wellfield to meet the initial process demand.

Phase III: Construction and interconnection of the favoured surface supply option emerging from Phases I and II to provide security of supply in the long term.

The overall capital cost of this three phase water resource development programme is currently estimated to lie in the range P12.5 to 18.0 Million at constant 1984 prices.


FIGURE 1
MOSETSE VALLEY SHOWING
LOCATION OF BOREHOLES
& CONJUNCTIVE USE OPTIONS
Notes Contours are at 10m intervals
2 1 0 5 10 km
N
NATA
FRANCISTOWN
SUA PAN
PROCESS PLANT
SUA
SUA VILLAGE
NXAKATO
NJUUTSHAA
W8/E3 WELLFIELD
DUKWE
MOSETSE WELLFIELD
RESERVOIR
DAM SITE 1
DAM SITE 2
KGWANA HILLS
MOSETSE
MALELEJWE
CONJUNCTIVE USE OPTIONS
OPTION PIPELINE ROUTES
1 I + II + III + IV
2 I + II + III + V
3 I + II + III

FIGURE 2
OFF-CHANNEL STORAGE 250 x 250 x 5 m
SIMULATED PERFORMANCE
1932 - 1958



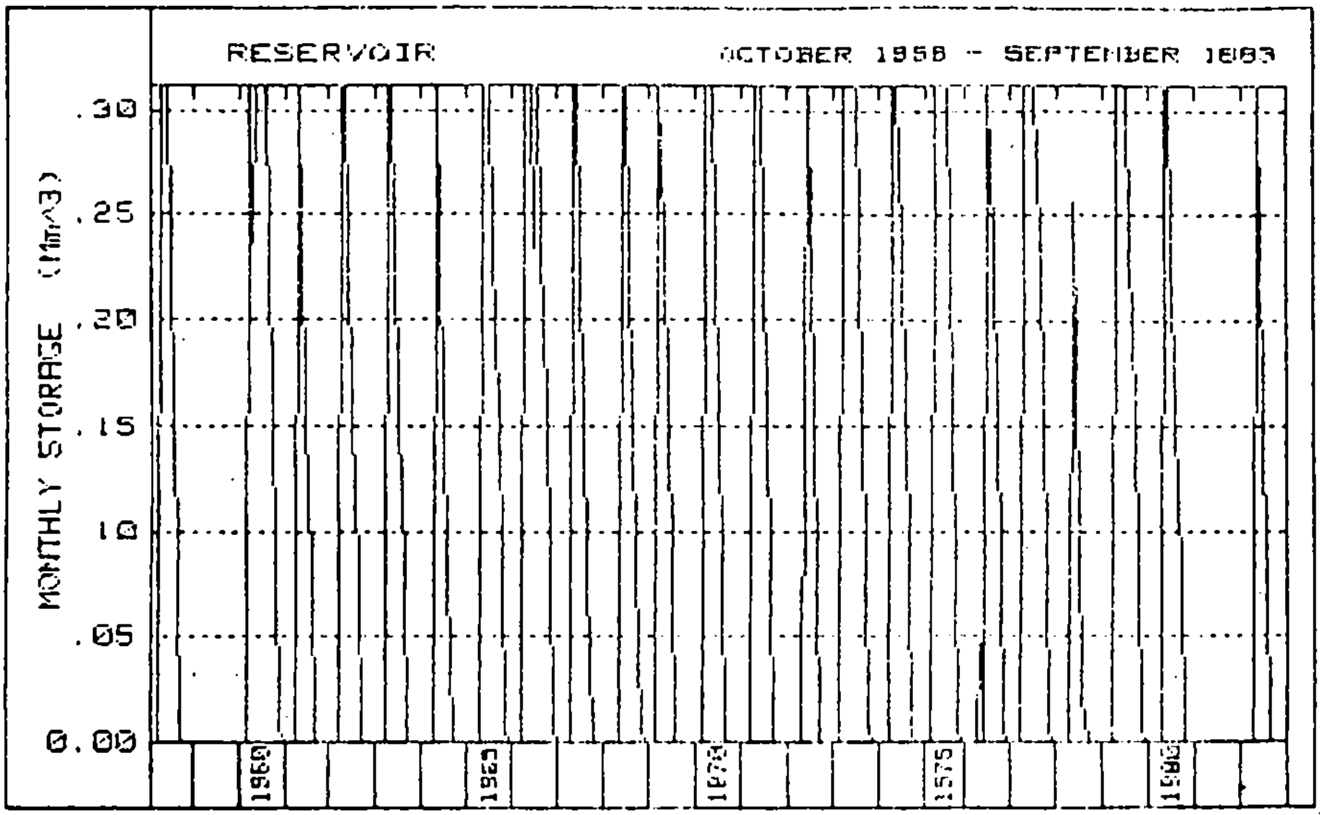

RESERVOIR ROUTING     Length = 250   Width = 250   Depth   5.0

DEMAND =   .068     CAPACITY =   .312   INIT. =  0.000

THRESHOLD FLOW IN RIVER (IN M^3/s)          =   .50
MAX. ABSTRACTION RATE FROM RIVER (IN M^3/s) =   .50

Volumes, Flows etc are in 10^6 * M^3

FIGURE 2A
OFF-CHANNEL STORAGE 250 x 250 x 5m
SIMULATED PERFORMANCE
1958-1983



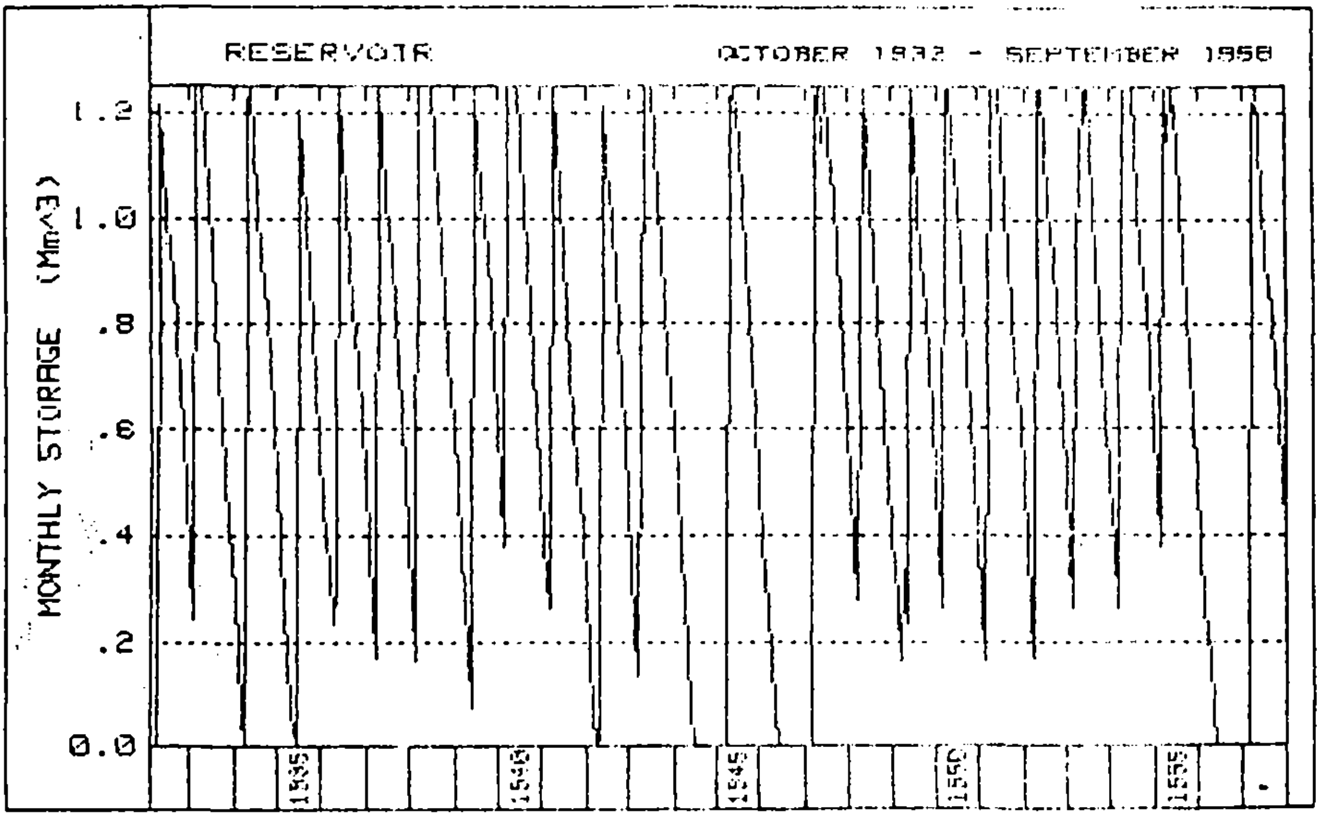

RESERVOIR ROUTING    Length = 250  Width = 250  Depth = 5.0

DEMAND = .068    CAPACITY = .312  INIT. = 0.000

THRESHOLD FLOW IN RIVER (IN M^3/s) = .50
MAX. ABSTRACTION RATE FROM RIVER (IN M^3/s)= .50

Volumes, Flows etc are in 10^6 * M^3

FIGURE 3
OFF-CHANNEL STORAGE 500 x 500 x 5m
SIMULATED PERFORMANCE
1932-1958



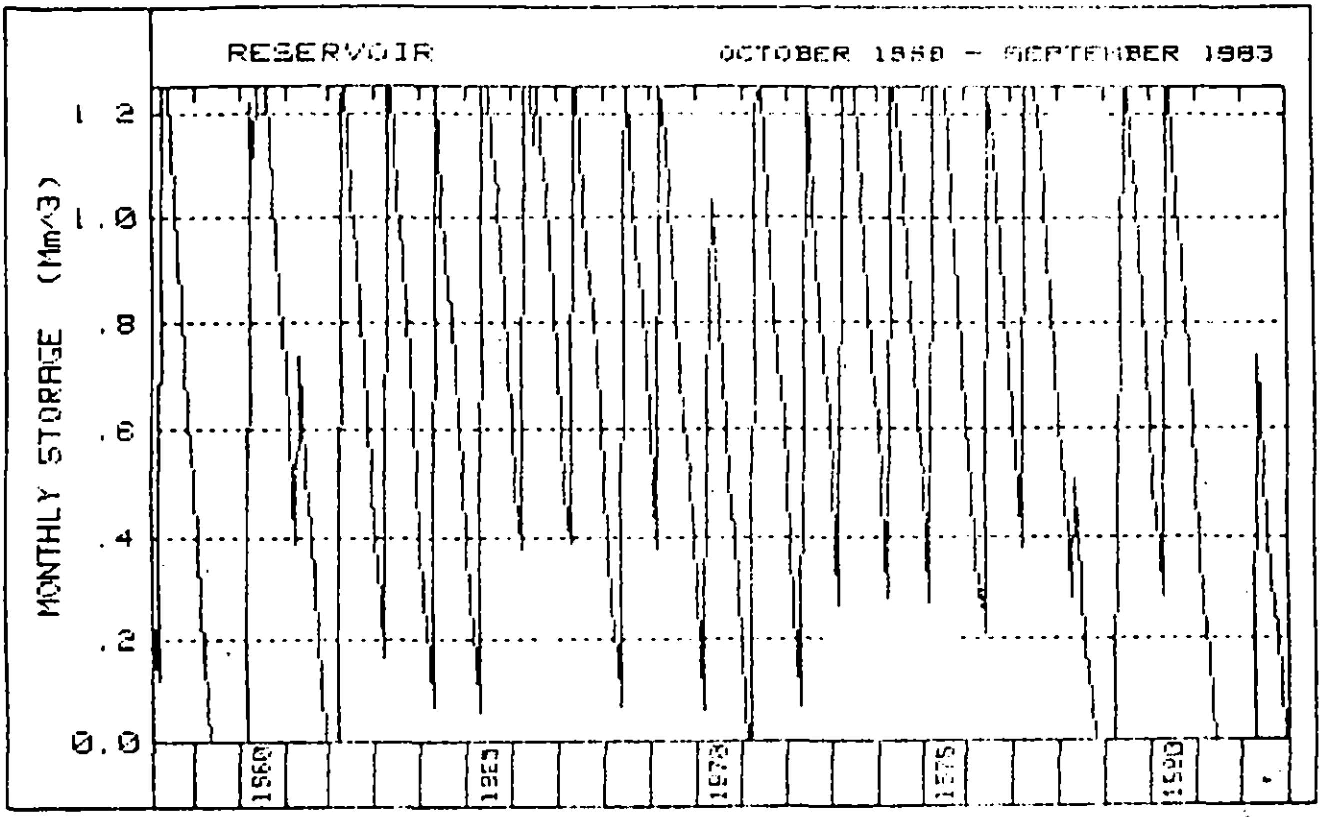

RESERVOIR ROUTING      Length = 500   Width = 500   Depth =   5.0

DEMAND =   .068        CAPACITY =  1.250  INIT. =  0.000

THRESHOLD FLOW IN RIVER (IN M^3/s)          =   .50
MAX. ABSTRACTION RATE FROM RIVER (IN M^3/s)=   .50

Volumes, Flows etc are in 10^6 * M^3

# FIGURE 3A
# OFF-CHANNEL STORAGE 500 x 500 x 5m
# SIMULATED PERFORMANCE
# 1958-1983



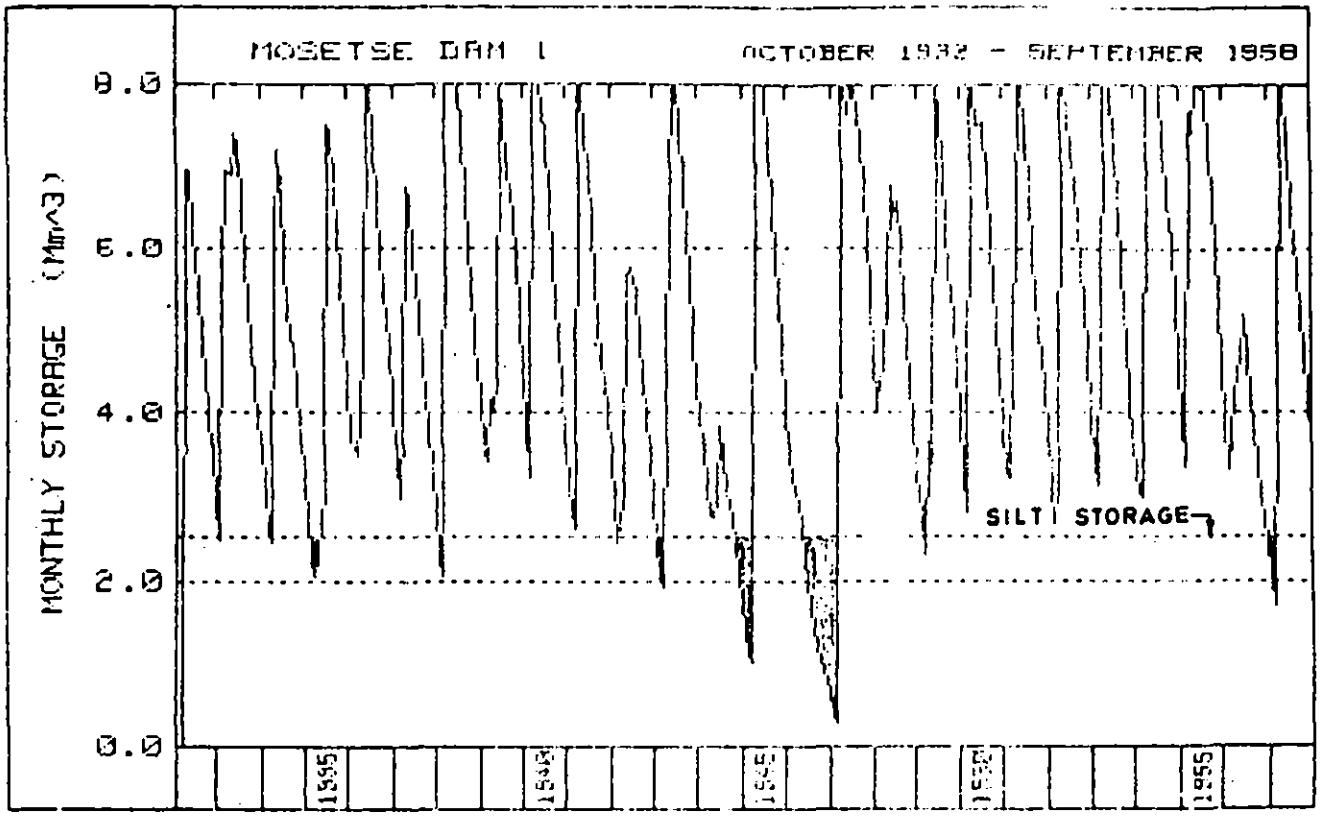

RESERVOIR ROUTING      Length = 500   Width = 500   Depth =   5.0

DEMAND =   .068      CAPACITY =  1.250   INIT. =   .399

THRESHOLD FLOW IN RIVER (IN M^3/s)         =   .50
MAX. ABSTRACTION RATE FROM RIVER (IN M^3/s) =   .50

Volumes, Flows etc are in 10^6 * M^3

FIGURE 4
MOSETSE DAM SITE 1
CAPACITY 8M $m^3$
SIMULATED PERFORMANCE
1932-1958



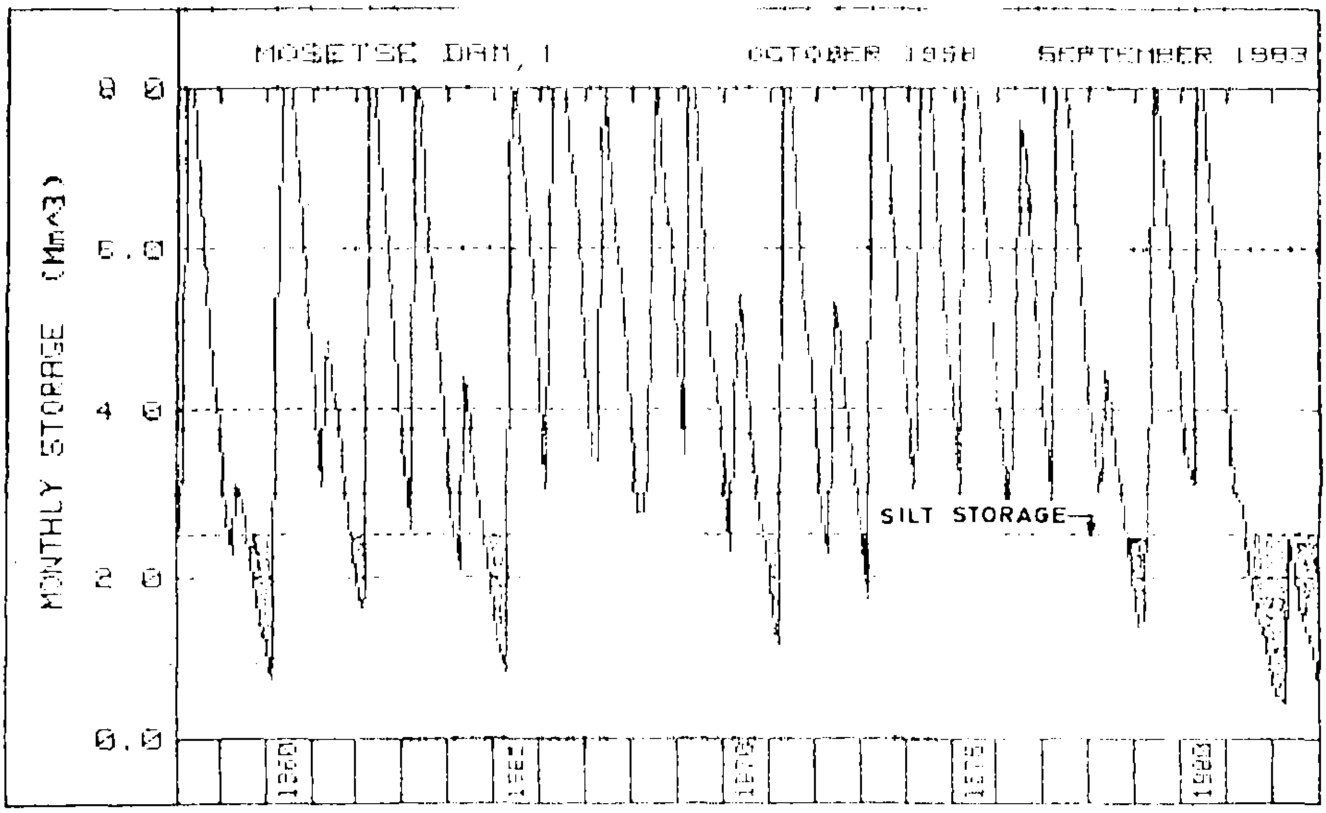

RESERVOIR ROUTING    CAPACITY =    8.00  INIT.    0.00

Constant Monthly Demand =    .068

Volumes, Flows etc. are given in 10^6 * M^3

SHORTFALL PERIODS

FIGURE 4 A
MOSETSE DAM SITE 1
CAPACITY 8 M $m^3$
SIMULATED PERFORMANCE
1958-1983



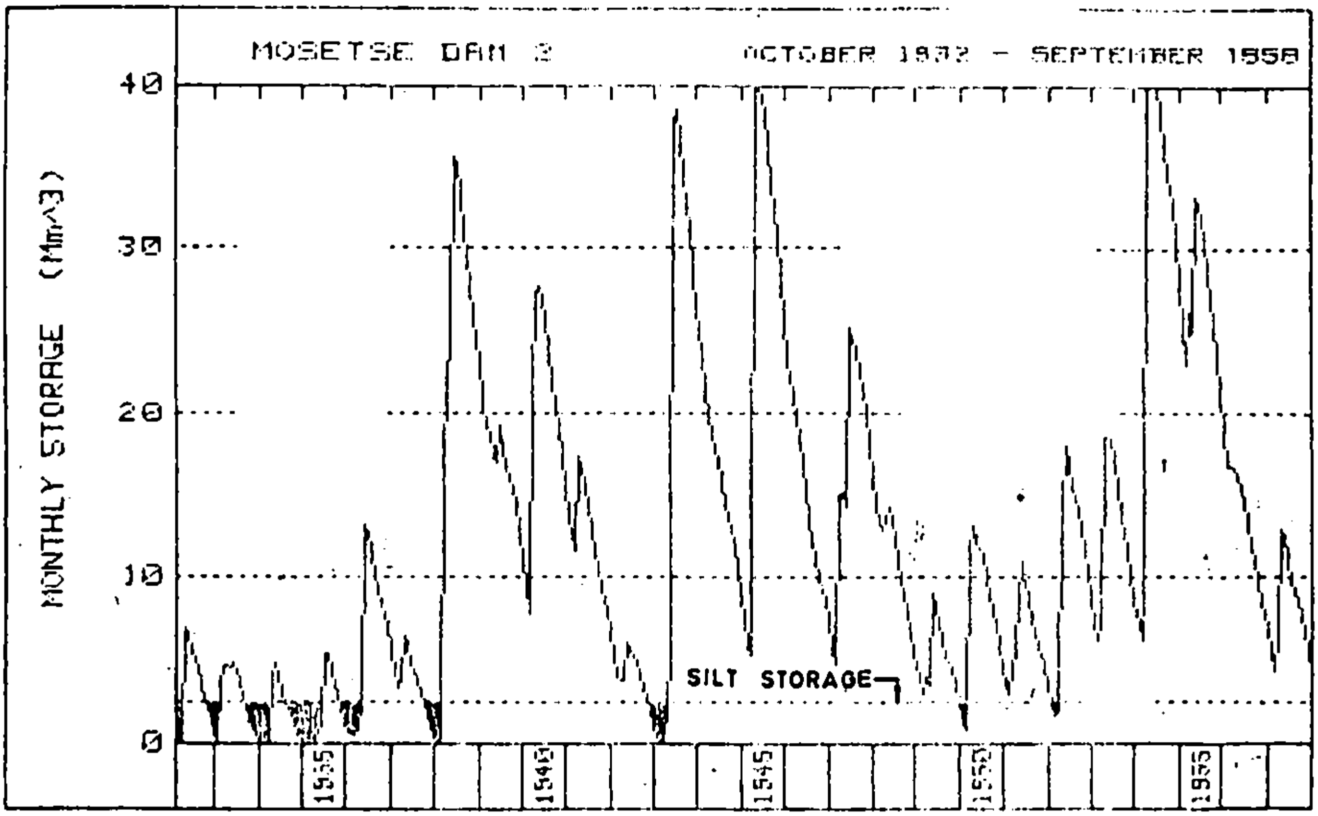

RESERVOIR ROUTING CAPACITY 8.00 INIT. 3.60

Constant Monthly Demand .068

Volumes, Flows etc. are given in 10^6 * M^3

SHORTFALL PERIODS

FIGURE 5
MOSETSE DAM SITE 2
CAPACITY 40 $Mm^3$
SIMULATED PERFORMANCE
1932-1958



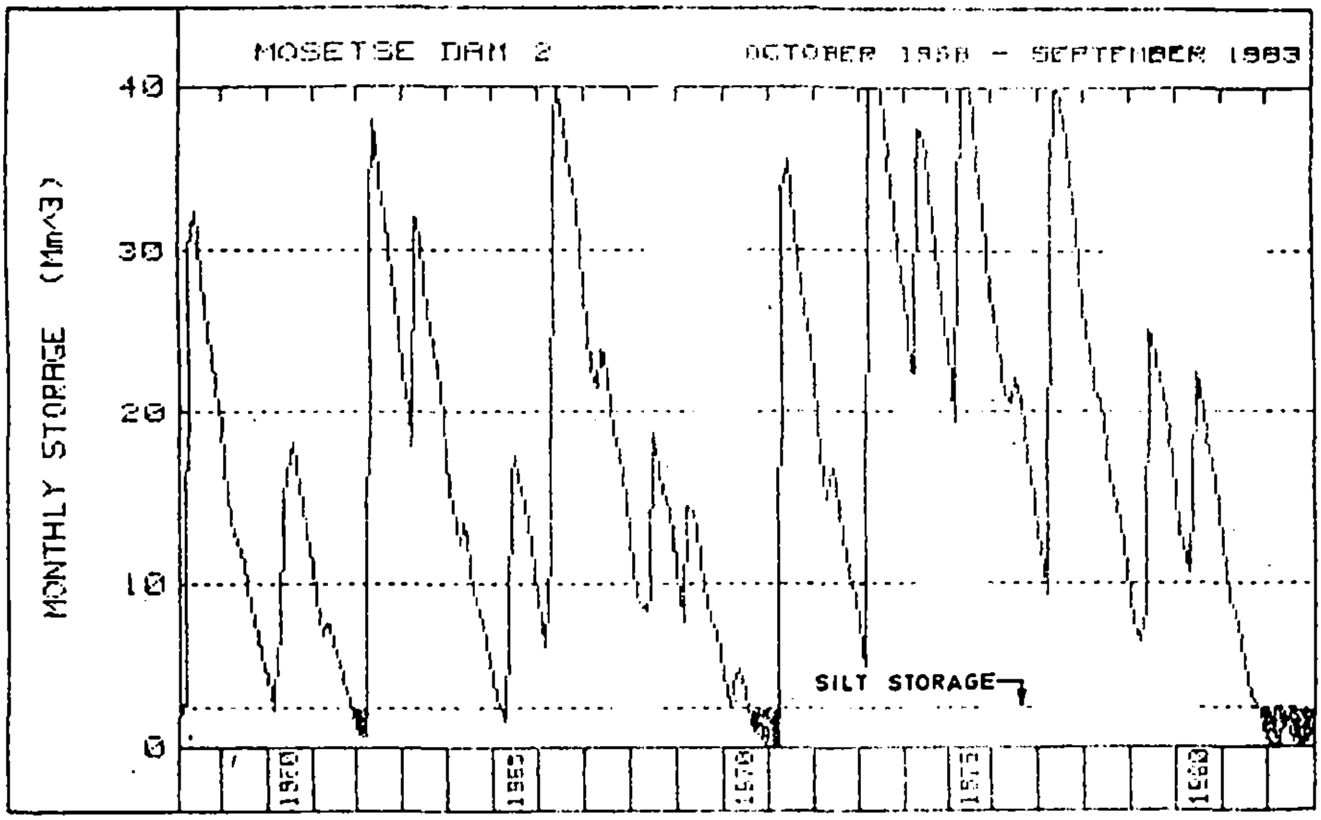

RESERVOIR ROUTING CAPACITY = 40.00 INIT. = 0.00

Constant Monthly Demand = .068

Volumes, Flows etc. are given in 10^6 * M^3

SHORTFALL PERIODS

## FIGURE 5A
## MOSETSE DAM SITE 2
## CAPACITY 40 M $m^3$
## SIMULATED PERFORMANCE
## 1958-1983




RESERVOIR ROUTING    CAPACITY =   40.00   INIT.   4.30

Constant Monthly Demand =   .068

Volumes, Flows etc. are given in 10^6 * M^3

[ ] SHORTFALL PERIODS

# APPENDIX I

## MONTHLY RUN-OFF DATA

MOSETSE RIVER - SYNTHESISED MONTHLY FLOWS (in m^3 x 10^6) YEARS 1932 TO 1956

| Year | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Annual Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1932-33 | 0.00 | 0.00 | .12 | 6.97 | .70 | .07 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 7.87 |
| 1933-34 | 0.00 | 3.53 | 1.86 | .58 | 1.24 | .64 | .11 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 7.97 |
| 1934-35 | 0.00 | .01 | .14 | 3.97 | 1.75 | .20 | .02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 6.09 |
| 1935-36 | 0.00 | 0.00 | .06 | .51 | 1.14 | 4.85 | .72 | .13 | .01 | 0.00 | 0.00 | 0.00 | 7.42 |
| 1936-37 | 0.00 | .36 | .81 | 1.48 | 11.84 | 1.21 | .12 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 15.83 |
| 1937-38 | 0.00 | 0.00 | 1.31 | 3.23 | .52 | .06 | .02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5.14 |
| 1938-39 | 0.00 | .13 | 17.70 | 9.04 | 12.19 | 2.05 | .21 | .02 | 0.00 | 0.00 | 0.00 | 0.00 | 41.34 |
| 1939-40 | 0.00 | .39 | 1.14 | .30 | .80 | 4.28 | .49 | .05 | .09 | .01 | 0.00 | 0.00 | 7.55 |
| 1940-41 | 0.00 | 0.00 | 14.59 | 7.52 | 2.38 | .24 | .02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 24.75 |
| 1941-42 | 0.00 | 0.00 | 6.92 | .92 | .09 | .52 | .05 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 8.51 |
| 1942-43 | 0.00 | 0.00 | .49 | .64 | 3.08 | .80 | .34 | .03 | 0.00 | 0.00 | 0.00 | 0.00 | 5.38 |
| 1943-44 | 0.00 | 0.00 | .11 | 5.03 | 33.65 | 3.37 | .34 | .03 | 0.00 | 0.00 | 0.00 | 0.00 | 42.53 |
| 1944-45 | 0.00 | 0.00 | .01 | .30 | .64 | 1.28 | .13 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 2.37 |
| 1945-46 | 0.00 | 0.00 | .08 | 45.50 | 8.81 | .88 | .10 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 55.38 |
| 1946-47 | 0.00 | .10 | .24 | .03 | 0.00 | .05 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | .43 |
| 1947-48 | 0.00 | 0.00 | 11.33 | 1.45 | .40 | 12.83 | 1.29 | .13 | .01 | 0.00 | 0.00 | 0.00 | 27.44 |
| 1948-49 | .03 | 1.02 | .47 | 2.76 | .38 | .93 | .09 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 5.69 |
| 1949-50 | 0.00 | .01 | 1.59 | .18 | 6.33 | .64 | .07 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 8.83 |
| 1950-51 | 0.00 | 0.00 | 11.37 | 2.55 | .26 | .91 | .10 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 15.20 |
| 1951-52 | .01 | .47 | 3.52 | 3.69 | 3.58 | .36 | .04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 11.67 |
| 1952-53 | 0.00 | 0.00 | .69 | 12.76 | 5.59 | .66 | .18 | .02 | 0.00 | 0.00 | 0.00 | 0.00 | 19.90 |
| 1953-54 | 0.00 | .26 | 2.09 | 12.35 | 1.57 | .16 | .02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 16.45 |
| 1954-55 | 0.00 | .44 | 36.51 | 10.89 | 33.86 | 7.78 | .80 | .08 | .01 | 0.00 | 0.00 | 0.00 | 90.37 |
| 1955-56 | 0.00 | 0.00 | 4.65 | .47 | 10.00 | 1.20 | .75 | .08 | .01 | 0.00 | 0.00 | 0.00 | 17.16 |
| 1956-57 | 0.00 | 0.00 | 1.18 | .83 | .64 | 1.14 | .11 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 3.91 |

MOSETSE RIVER - SYNTHESISED MONTHLY FLOWS (in m^3 x 10^6) YEARS - 1957 TO 1983

| Year | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Annual Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1957-58 | 0.00 | 0.00 | 2.61 | 7.75 | .94 | .11 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 11.42 |
| 1958-59 | .01 | .01 | 1.37 | 27.70 | 4.34 | .43 | .04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 33.90 |
| 1959-60 | 0.00 | 0.00 | .09 | .11 | 1.16 | .24 | .04 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 1.65 |
| 1960-61 | 0.00 | .06 | 4.53 | 1.03 | 9.61 | 4.40 | 2.29 | .23 | .02 | 0.00 | 0.00 | 0.00 | 22.17 |
| 1961-62 | 0.00 | 0.00 | 0.00 | 1.77 | .86 | .09 | .07 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 2.80 |
| 1962-63 | 0.00 | .55 | 31.56 | 8.01 | .87 | .13 | .07 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 41.20 |
| 1963-64 | 0.00 | 0.00 | 15.43 | 1.83 | .43 | .04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 17.73 |
| 1964-65 | 0.00 | 0.00 | .03 | 2.60 | .32 | .03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.98 |
| 1965-66 | 0.00 | 0.00 | .01 | 6.07 | 9.98 | 3.18 | .32 | .03 | 0.00 | 0.00 | 0.00 | 0.00 | 19.59 |
| 1966-67 | 0.00 | 0.00 | 6.33 | 27.32 | 9.99 | 1.01 | 1.85 | .18 | .02 | 0.00 | 0.00 | 0.00 | 46.70 |
| 1967-68 | 0.00 | 0.00 | .29 | 4.07 | 1.65 | .21 | .36 | .04 | 0.00 | 0.00 | 0.00 | 0.00 | 6.62 |
| 1968-69 | 0.00 | 0.00 | .32 | .86 | 2.45 | 10.51 | 1.07 | .11 | .01 | 0.00 | 0.00 | 0.00 | 15.33 |
| 1969-70 | .05 | .01 | 7.82 | .98 | .23 | .02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 9.11 |
| 1970-71 | 0.00 | .07 | 2.01 | 1.80 | .18 | .03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.09 |
| 1971-72 | 0.00 | .05 | .01 | 33.49 | 4.25 | .47 | .07 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 38.35 |
| 1972-73 | 0.00 | 0.00 | .10 | .07 | 3.35 | .61 | .06 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 4.20 |
| 1973-74 | 0.00 | 0.00 | 44.39 | 54.56 | 26.72 | 2.67 | .27 | .03 | 0.00 | 0.00 | 0.00 | 0.00 | 128.64 |
| 1974-75 | 0.00 | .01 | 1.20 | 16.82 | 1.96 | 1.32 | .18 | .02 | 0.00 | 0.00 | 0.00 | 0.00 | 21.51 |
| 1975-76 | 0.00 | 0.00 | 13.08 | 10.66 | 3.18 | 2.70 | .27 | .03 | 0.00 | 0.00 | 0.00 | 0.00 | 29.92 |
| 1976-77 | 0.00 | 0.00 | 0.00 | 1.44 | 1.33 | 3.49 | .35 | .03 | 0.00 | 0.00 | 0.00 | 0.00 | 6.64 |
| 1977-78 | 0.00 | 0.00 | 25.66 | 64.01 | 8.69 | 1.58 | .16 | .03 | .03 | .02 | 0.00 | 0.00 | 100.18 |
| 1978-79 | 0.00 | .01 | .53 | 1.65 | .29 | .21 | .02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.71 |
| 1979-80 | .01 | .35 | 1.91 | 1.76 | 18.12 | 1.81 | .18 | .02 | 0.00 | 0.00 | 0.00 | 0.00 | 24.16 |
| 1980-81 | 0.00 | .23 | .25 | 5.36 | 9.12 | 1.11 | .32 | .03 | 0.00 | 0.00 | 0.00 | 0.00 | 16.42 |
| 1981-82 | 0.00 | 0.00 | .18 | .26 | .05 | .01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | .50 |
| 1982-83 | .02 | .16 | .02 | 2.16 | .22 | .03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.61 |

# APPENDIX II

# SUMMARY OF PUMPING TEST RESULTS

New results'

# PUMPING TEST PROGRAMME : SUMMARY OF TESTS AND RESULTS

| Well No. | Date Tested | Test Type & Duration (mins) | Pumping Rate (l/s) | Drawdown (m) | Specific Capacity (l/s/m) | Transmissivity ($m^2$/d) Jacob | Transmissivity ($m^2$/d) Theis | Remarks |
|---|---|---|---|---|---|---|---|---|
| W8/E3 | 22-3-84 | S | 8.27 | 8.27 | 3.62 | | | E7, E1 monitored |
| | | S 4 x 120 | 13.5 | 4.090 | 3.30 | | | |
| | | S | 21.5 | 7.515 | 2.86 | | | |
| | | S | 26.0 | 9.235 | 2.81 | | | |
| | 23-3-84 | 1 680 | 22.8 | | | | | E7, E1 monitored |
| | 23-3-84 | 360 | | | | | | E7, E1 monitored |
| WW8 | 3-4-84 | 360 | 2.95 | 0.211 | 14.1 | 2 120 | 1 450 | WW8/T monitored - Storativity: Jacob 3.5 x $10^{-3}$, Theis 1.8 x $10^{-3}$ |
| WW8/T | 25-3-84 | S | 0.57 | 0.765 | 0.74 | 2 250 | 1 340 (t ≤ 30) | WW8 monitored - Storativity: Jacob 1.0 x $10^{-3}$, Theis 1.1 x $10^{-3}$ |
| | | S | 0.97 | 1.462 | 0.66 | | | |
| | | S 4 x 60 | 1.67 | 3.025 | 0.55 | 2 930 | | Recovery at WW8/T |
| | | S | 2.73 | 6.05 | 0.45 | 150 | | Step 1 WW8/T |
| | 26-3-84 | C 1 440 | 3.70 | | | | | WW8 monitored |
| WW8/P | 5-4-84 | C 60 | 8.40 | 1.671 | 4.81 | 705 (t ≤ 12) | | Initial test |
| | 5-4-84 | R 30 | - | | | 1 415 (t ≥ 12) | | |
| | | | | | | 2 544 (early data) | | Recovery |
| | | | | | | 4 710 (late data) | | |
| WW14 | 29-3-84 | S | 0.69 | 0.35 | 1.97 | 645 | | Step 1 |
| | | S 3 x 120 | 1.15 | 0.66 | 1.74 | | | |
| | | S | 1.99 | 1.48 | 1.34 | 595 | | Recovery from extended Step 4 |
| | | S up to 1 680 | 3.33 | 4.18 | 0.80 | | | |
| | | 510 | | | | | | |
| WW14P | 7-11-84 | 3 932 | 9.1 | 12.947 | 0.70 | 240 | | WW14 monitored |
| | 7-11-84 | 425 | - | | | | 576 | WW14 monitored |
| WW15 | 6-11-84 | | 1.22 | 28.37 | 0.04 | | | |
| | | | 0.85 | 27.20 | 0.03 | | | |
| | | | 0.60 | 18.80 | 0.03 | | | |
| | | 100 | 0.80 | 22.612 | 0.04 | < 1.0 | | |
| 3129 | 30-3-84 | 106 | 1.2 | 13.24 | 0.09 | 2.4 (t ≤ 40) | | Existing pump |
| | | | | | | 3.2 (t ≥ 40) | | |
| | | | | | | 3.8 (late data) | 2.2 | Recovery |
| Mmemo | 4-4-84 | 120 | 0.64 | 0.05 | 12.8 | | | Existing pump |
| WW7 | | | 1.5 | 12.5 (t 30) | 0.12 | | | |
| | | | | 34.3 (t440) | 0.04 | | | |

Notes:
S : step (production) test with intervening recovery
C : constant rate test
R : recovery
Drawdown measured at elapsed time of about 100 mins (unless otherwise stated)

# APPENDIX III

## INSTITUTE OF HYDROLOGY
## APPRAISAL OF GEOPHYSICAL LOGS OF WELL Nos.8, 14 and 15

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For the attention of Mr P Garrett

Your ref 7696/2/3

Our ref 33/347

Date 8 November 1984

Dear Sirs

SUA PAN PROJECT
INDUSTRIAL/FRESH WATER SUPPLIES - GEOPHYSICAL LOGS

We have now been able to examine the geophysical logs from WW8-WW14-WW15 to identify inflow zones and to provide a broad geological interpretation.

The analysis has been restricted mainly to the caliper, gamma and neutron logs. Unfortunately, the E-logs and in particular the temperature log were not carried out at a suitably sensitive scale and consequently they are of limited use. The low, very sharp peaks on the BRD log seem spurious and perhaps due to changes in scale during the logging, although the logs are not annotated.

Low peaks on the BRD logs are in the range 1.9~2.0 g/cc. Some of these correlate broadly with increased hole diameter and could thus be due to water-filled collapse zones. Normally, such low values would suggest evaporite or coal beds but we consider this to be unlikely.

The peaks on the caliper logs at WW14 and WW15 have a shape typical of fractures (as bedding planes?). In contrast those at WW8 are of a form that suggests softer perhaps weathered zones which could consequently have a higher porosity and permeability. To some extent the peaks at WW8 correlate with low gamma-high neutron counts suggesting weathered sandstones. However, some peaks are almost certainly due to increases in diameter due to hole cleaning and collapse of mudstone bands.

Features and an interpretation of the logs are given on each chart. The main features are now given in more detail:

<u>WW8</u>

Drill samples indicate that the whole saturated sequence comprises Mea Arkose. The well is situated along the strike direction from WW14.

The gamma log indicates an upper sequence of sandstones with only occasional mudstones separated at 66m from a lower sequence of shales with thin sandstones. We have assigned these to the Upper and Lower Mea Arkose respectively.

..continued..

There are some ten 'collapse' zones from water level to 90m, with major zones at 47-48m (hole cleaning?) and 59m (main supply at WW8/P). Higher resistivities (25~40ohm/m) and neutron counts but low BRD are associated with these zones.

There are slight changes in temperature gradient at 58.5 and 83m; only the higher level can be related to other log features.

Below 89m the BRD log is more 'peaky' suggesting a change in the formation. There are six collapse zones between 90 and 100m, although none seem to correlate with red crystalline material thought to be dyke intrusions and possible inflow zones.

WW14

This well is situated on the outcrop of the Mea Arkose. Government borehole 3129 nearby is reported to penetrate Dwyka at 90m and a colour change at 75m at WW14 suggested possible Dwyka sequence.

There is a change in gamma activity at 63m as shown by WW8. This suggests no intervening faults and the overall similarity indicates that both boreholes may only penetrate Mea Arkose.

Some 20 possible fractures are indicated by the caliper log. These are probably bedding planes and are in general associated with shales or shale/sandstone bedding contacts, particularly from 72 to 75m. Changes in temperature gradient occur at 40, 94 and 98m but these are unrelated to any fracture zones.

There are fewer high peaks on the neutron log than at WW8 and little correlation between both neutron logs below 50m, perhaps suggesting fewer weathered zones at WW14.

WW15

This well is located in the W8/E3 area and was logged for comparison with this borehole.

Low gamma counts are recorded to a depth of 49m, below which mudstones/shales are more frequent. The low activity to 36m indicates Ntane Sandstone and ? Ntane Siltstone from 36~49m. Water was encountered in these siltstones, which are generally softer (? weathered) to 43m.

There are some 20 fracture zones indicated on the caliper log. These are associated mainly with low BRD peaks. The fractures are most common at 50 to 54m and 70 to 78m (similar to WW14) and in general relate to shale beds.

Several changes in temperature gradient occur: 36m (base of Ntane Sandstone, fracture), 44m (no features), 72m (sandstone, general fracture zone), 86.5, 91, 93.5 (all in a thick sandstone layer but no other features).

The neutron log is broadly similar to WW14 for the same depth. Higher porosities are indicated at 36m (base Ntane Sandstone), 45~50m (sandstone in ? Ntane Siltstone), 55m and 63m.

The gamma activity suggests that perhaps the upper part of the Mea Arkose is absent [or is represented by the sequence assigned to the Ntane Siltstone]. Lithologically the sequence below 79m was described as Dwyka Formation. The gamma activity below this depth indicates sandstones to 94m, which may correlate with sandstones at about 100m at WW14. We have now re-assigned the sequence below 79m to the Mea Arkose. The Basement Complex, whilst penetrated by the borehole, could not be logged.

..continued..

## Summary Conclusions

1. Whilst fractures and weathered zones are indicated the inflow zone(s) cannot be identified. A recent test at WW14 suggests that the main supply is deeper than 50m. It is likely that the main horizons occur at the base of the upper Mea Arkose at both WW8 and WW14 at a depth of between 63 and 66m.

2. SWECO have suggested that yields are largely obtained from the upper part of the Mea Arkose associated with coarser grain size. The logs from WW8 suggest that weathered zones are more important, although we cannot establish if such zones develop preferentially in relation to grain size.

3. Fractures (? bedding planes, but also enlargement at shale or shale/ sandstone contacts) are shown at WW14 and WW15 but not at WW8. The lower yields at the former sites suggest that the fractures are 'tight' (also suggested by surface exposures) and perhaps less important than weathered zones. A general zone of fracturing occurs at 70-80m depth in an alternating sandstone-mudstone sequence.

4. On the basis of the gamma logs a general succession for each of the wells logged is as follows:

| | WW8 | WW14 | WW15 |
|---|---|---|---|
| Ntane Sandstone | | | - 36 |
| " Siltstone (?) | - | - | 36-49 |
| Upper Mea Arkose (sandstone) | -66 | -63 | ? |
| Lower Mea Arkose (shales) | 66-(EOL) | 63-75 | 49-60 |
| (sandstone) | - | 75-81 | 60-69 or 83-94 |
| | | 81-(EOL) | 94-(EOL) |

5. It was unfortunate that W8/E3 could not be logged since this is a site of particular importance to the project. In April the depth was measured as 57m (probably just below the main inflow zone) - has this well collapsed further and, if so, was it not possible to log the adjacent wells? It is important that we attempt to establish the main aquifer in this well to predict long term yields.

Our interpretation of the logs has been restricted by limitations of the logging itself, in particular we had hoped that the inflow zones and thus available drawdown would be indicated. Nonetheless, certain patterns emerge from the logs which have assisted us in developing our understanding of the aquifer conditions and stratigraphy. Please do not hesitate to contact us if you have further enquiries.

Yours faithfully

R B Bradford

RBB/SS