CBB

ih

INSTITUTE of HYDROLOGY

No pumping tests.

RB

SUA PAN PROJECT

PHASE III INVESTIGATIONS

INTERIM REPORT ON PROCESS

AND DOMESTIC WATER SUPPLIES

FROM GROUNDWATER SOURCES

Institute of Hydrology
Wallingford
Oxon, UK

May 1984

SUA PAN PROJECT
PHASE III INVESTIGATIONS
INTERIM REPORT ON PROCESS AND
DOMESTIC WATER SUPPLIES FROM GROUNDWATER SOURCES
(MEMORANDUM NO.7)

List of Contents

List of Tables

List of Figures

SUA PAN PROJECT
PROCESS AND DOMESTIC WATER SUPPLIES
FROM GROUNDWATER SOURCES

1. INTRODUCTION

1.1 Water Requirements

Suitable water supplies are required to meet the following demands:

Domestic: 50 m^3/d (0.6 l/s) for the new township

Process Plant: 700 m^3/d (8 l/s) for industrial purposes and containing less than 7000 mg/l dissolved solids. This demand is expected to increase to 1400 m^3/d (16 l/s)

Various alternative means of meeting these demands are being examined, including groundwater sources. This report summarizes the continuing investigations into the potential availability of groundwater supplies.

1.2 Previous Investigations

During 1975/76 Swedish Consulting Group (SWECO) carried out a preliminary evaluation of the groundwater resources around Dukwe[1]. The investigation included a limited programme of drilling and testing.

A faulted depression (graben) was identified at Dukwe containing a thick sedimentary sequence. SWECO concluded that well yields of 10 to 20 l/s could be sustained from the Mea Arkose at Dukwe for at least 15 to 20 years with no recharge. This was based on pumping tests carried out on the three most promising existing boreholes.

[1] Sua Project, Dukwe New Town. Ground Water Study. Inception Report May 1976. SWECO

A particular productive borehole in the Ntane Sandstone, W8/E3 (2981), drilled west of the road junction to Sua Pan for the Francistown - Nata roadline construction, was test pumped for 3 months at 17 l/s.

In the area between Dukwe and Sua Pan hydrogeological information is very limited; the few local groundwater supplies being obtained mainly from shallow sediments of restricted extent and reliability. In 1982 IH brought together the available borehole information in the Sua-Dukwe area[2] as a basis for an exploratory programme of drilling and testing. This programme was undertaken in 1983[3] consisting of six boreholes and associated tests. The results of this initial exploration indicated the following conditions:

* saline groundwater occurs extensively to depth west of the Mosetse Fault
* the sedimentary sequence is at least 200 m thick but consists predominantly of Tlapana Mudstone; only 20 m of Mea Arkose being encountered.
* supplies of very saline water are available in the Ntane Sandstone but the aquifer characteristics of this formation are poor with yields of less than 1 l/s.
* if water was to be abstracted from the Ntane Sandstone, a wellfield of some 10-20 boreholes spaced 1.5 to 2 km apart would be required. As water would be 'mined' from storage the reliability of maintaining long-term supplies was considered doubtful.
* fresh water was encountered at borehole WW7 adjacent to the Mosetse River just east of the Mosetse Fault. However, the well was low yielding obtaining supplies from the junction of the Ntane Sandstone/ Mea Arkose.

[2] Groundwater Supplies for Sua Pan. Proposals for a Drilling Programme. Dec 1982. Institute of Hydrology.

[3] Sua Pan Project. B. Industrial/Fresh Water Supplies. April 1983. Institute of Hydrology

Two areas of further investigation were proposed:

Zone 1. West of the Mosetse Fault as a source of saline water. This supply would be blended with fresher water from elsewhere to achieve a suitable supply for the process plant.

Zone 2. East of the Mosetse Fault between the Mosetse River and the camp acess road as a potential source of fresh water.

In addition, it was also proposed that well W8/E3 could provide a single source of supply to meet both the process and township water demands. However, the high chloride content of this supply exceeds the WHO permissible limits for potable use.

1.3 Phase III Investigation Objectives

Due to the uncertainty regarding the long-term availability of groundwater supplies west of the Mosestse Fault, the investigations during 1984 were undertaken to explore the occurrence of suitable groundwater sources further east, in particular the extent of fresh water along and away from the Mosetse river as a back-up source area to well W8/E3.

2. FIELD PROGRAMME

2.1 Access

Cut lines were prepared by SAB staff in advance of the programme to allow access for the drilling rig:

- a line 6.8 km from existing well WW7 to the Government borehole 3129 along the north bank of the Mosetse river.
- a line of 8.2 km joining the camp access road to a point on the above cut-line 4 km east of well WW7.
- a line of 2 km extending north from well WW7.

The only other track located in the area extends south from Njuutshaa village to existing well MT1. This track was used to site WW15.

2.2 Drilling Programme

The ASTE Rotamec 1302 drilling rig was mobilised on 13 March 1984. Eleven boreholes were drilled by the air-hammer method at eight locations and a total metreage of 996 m was drilled by the end of this phase of the programme. The site locations are shown in Figure 1 and well details in Table 1.

The initial drill sites were selected on the cut-lines to obtain information on the more regional geological and groundwater conditions along and to the north of the Mosetse River. A particular objective was investigated by each borehole; the information gained being used to guide the selection of subsequent sites.

Over much of the area, the low relief and cover of younger sediments combine to mask features, such as fault zones, where an enhanced permeability might allow higher well yields to be obtained. Obviously if such features could be located the number of production wells required would be reduced. However, intersecting such features is unlikely without the support of surface geophysical methods, and, consequently, a wellfield design would have to be based on the more widespread but less productive aquifer characteristics. The sites drilled to investigate the more regional conditions were WW9 to WW12 and WW15.

A wellfield based on the poorer regional aquifer conditions would comprise at least 15 boreholes to meet the total water requirement. As drilling progressed it became apparent that an aquifer of sufficient extent in which such a wellfield could be located was not present within Zone 2 north of the Mosetse river. Although site WW8 was partly 'targeted' at a particular feature, the locations of WW13 and WW14 were selected to investigate further the yield potential of other geological features identified along the river. It was decided also to expand the study further east.

The drilling programme in outline is given below in the order of drilling:

Well No.	Depth (m)	
WW8	108	Sited adjacent to the Mosetse River 4 km east of WW7 as a small diameter exploratory hole into the Mea Arkose. Prior to the drilling programme outcrops of Mea Arkose, which extend upstream of this location, were examined. This indicated the general direction of joint sets and suggested that the river course was partly controlled by structures and/or distribution of these outcrops. Site WW8 was selected to examine one such feature. Fresh water was encountered within weathered flaggy siltstones at 35 m.
WW10	90	Sited 4 km north of WW8. This well encountered a small flow of very saline water at 37 m within maroon highly weathered siltstones and entered Basement Complex gneisses at 74 m.
WW11	60	Located 7 km north of WW8 to explore the area near the camp access road midway between W8/E3 at the Mosetse Fault. Water was not encountered and Basement Complex schists were penetrated at about 43 m.
WW9	108	This site was chosen 1.5 km north of WW8 to further define the extent of fresh water north of the Mosetse River. A low yield of very saline water was encountered at about 43 m.

Well No.	Depth (m)	
WW8/T	78	This larger diameter well for testing purposes was located 26 m north of WW8. It was drilled to a shallower depth in order to allow the opportunity to examine whether yields increase with depth of penetration. Site WW8 could then serve as a piezometer for storage coefficient information.
WW12	60	Sited 2 km north of WW7 just east of the Mosetse Fault to also investigate the northward extent of fresh water along the Mosetse. A low yield of very saline water was encountered at 40 m in light grey mudstones. Basement Complex schists were entered at 52 m.
WW13	72	Located midway between WW7 and WW8 close to the Mosetse River to examine a possible E-W Fault. A small supply of fresh water was obtained near the base of the Mapana mudstones but the well penetrated dolerite at 61 m.
WW14	108	This site was selected from the survey of Mea Arkose outcrops midway between WW8 and 3129. Fresh water of only 350 mS was encountered at 48 m in weathered flaggy siltstones.
WW9/A	108	Sited 16 m south of WW9 and designed to case off the siltstone sequence to assess whether fresher water was present in the Mea Arkose. No significant change in salinity was recorded.
WW8/P	102	In view of the high yield from WW8 a production well was drilled 3 m from WW8. The main supply was encountered at 64 m at the junction of the siltstone - sandstone sequence of the Mea Arkose.

Well No.	Depth (m)	
WW15	102	Following a pumping test at the Mmemo borehole (3.5 km SW of W8/E3), which suggested that the conditions at W8/83 might not be so localized as previously indicated, site WW15 was located approximately midway between these two wells and the site selected to deliverately avoid possible structures. Water of very similar conductivity to both W8/E3 and Mmemo borehole of about 2100 mS was encountered at about 40 m within a sequence of siltstones. Basement Complex gneisses were penetrated at 100 m.

Sample descriptions for each borehole are presented in Appendix A.

2.3 Testing Programme

Pumping tests were undertaken by Pump and Pipe (Botswana) Pty Ltd at four of the new borehole sites (WW8, WW8/P, WW8/T, WW14) together with existing wells W8/E3, 3129 and Mmemo. Tests began on the 21 March 1984 but during the programme the test rig was diverted to brine well W2 to undertake a series of short tests.

The tests carried out to date are summarised in Table 2. They included production (step-drawdown) tests for yield-drawdown characteristics and constant rate tests for aquifer parameters. The results of these tests are summarized in Tables 3 and 4 and the yield-drawdown data plotted in Figures 2 and 3. Only low, constant rate tests were possible at the existing private boreholes. Observation wells were available at sites WW8 and W8/E3.

Shaft-driven Mono pumps were used for the pumping tests:
Type BH 400 for the high rate tests at W8/E3 and type BH 50 for the new wells. The latter pump, which has a capacity of about 3 l/s, was selected on the basis that the new wells in general would have a low yield similar to WW7. In the event the pump capacity proved insufficient to fully test the more productive sites drilled during the 1984 programme. A type BH 200 pump has been installed in well WW8/P for tests at a higher rate.

Tests, or additional tests, are still to be carried out at the following wells: WW15, MT1, MT2, WW8/P, and WW14. These are to be undertaken by WLPU staff and the results presented in a later addendum.

2.4 Water Sampling

Electrical conductivity (EC) measurements were made on water samples collected during drilling and testing to indicate water quality changes with depth or time. The measurements made during drilling are given in Table 1 and those whilst testing are included in Appendix B.

Water samples were also collected for routine chemical analysis. The results are given in Table 4, which also includes chemistry data presented by SWECO (1976) for the Dukwe area. The data are plotted as a trilinear diagram in Figure 4.

3. POTENTIAL AREAS OF GROUNDWATER SUPPLY

3.1 General

The drilling and testing programme enables a more regional view of the groundwater conditions by linking the SWECO investigation of the Dukwe area with our earlier exploration west of the Mosetse Fault. Information, however, is lacking between wells 3129 and WW15.

A preliminary lithostratigraphic interpretation[1] for each new site is given in Appendix A. These have been used to prepare geological profiles, shown as Figures 5 to 8, which, together with lineations identified from 1:50 000 scale map 2026 C2, have provided an interpretation of the geological structure shown in Figure 1.

The broad features of the area east of the Mosetse Fault are as follows:

* In the area of wells WW10, WW11 and WW12, Basement Complex rocks occur at shallow depths of 45 to 55 m (elevation 885-895). This is an upthrown, faulted block (or horst) having the Mosetse Fault as its western boundary and forming a general barrier to the westward flow of groundwater.

* Very saline water, having a Cl/HCO_3 ratio as well as a dissolved solids content similar to sea water, was encountered east of the Mosetse Fault at wells WW9, WW10 and WW12. Site WW9/A suggests that this is not underlain by fresher water.

* The presence of saline water, low yields and well WW11, which was dry, show that the horst and part of its souther block around well WW9 are unsuitable for groundwater development.

* A downthrown block (or graben) with nearly 200 m of sediments occurs between the horst and shallow Basement Complex rocks that outcrop in the south eastern part of the area. Only this eastern graben has any significant potential for groundwater development.

[1] The interpretations will be assisted by the planned geophysical logging of selected wells.

The width and direction of the eastern graben is determined largely by major NE trending faults. However, the structure is complicated faults having a NW trend, some of which are dolerite intruded, parallel to the general dip of the sedimentary sequence and foliation trend of the Basement Complex.

As yet the interconnection between the different blocks along the eastern graben cannot be established: this is likely to be determined largely by a major N-S fault near well W8/E3, NW trending dykes and a major NNW fault east of well 3129. Consequently, we have treated the eastern graben as three separate groundwater areas as follows:

A. The Mosetse downthrown block centred on WW8, investigated during the drilling and testing programme.
B. Northern flank of the eastern graben around well W8/E3, where we have extended the earlier work by SWECO.
C. Dukwe block, previously investigated by SWECO.

As groundwater abstraction already takes place in the Dukwe area (although the annual abstraction is probably small), this area might be less readily available as a source of groundwater supply for the refinery. Nevertheless, since a regional view should be taken concerning the long-term use of groundwater supplies, we have included a brief review of the SWECO results reported in 1976.

3.2 Mosetse Downthrown Block

The recent drilling along the Mosetse between wells WW7 and 3129 has identified a narrow downthrown block beneath the cover of alluvium with at least 100 m of Mea Arkose and Dwyka sediments.

The width of alluvial deposits, about 1 km, is thought to coincide with the Mosetse block, although no drilling has yet been undertaken south of the river. The direction of the river suggests that the major NE fault forming the southern boundary of the Dukwe graben extends into this area. Other parallel faults hidden beneath alluvium between WW8 and WW9 are suggested by the marked change in salinity.

Lineation features, which can be distinguished south of the river due to the thin calcretes and absence of the Ntane Sandstone, indicate a complex fault pattern with WNW and NW faults, some of which may be dolerite intruded.

The axis of the eastern graben may be offset by a major fault trending NW just east of well 3129 and downthrowing to the west. This fault has a downthrow of at least 170 m. Basement Complex rocks occur on the upthrow side of the fault and about 3 km south of well 3129 within a triangular, fault-bounded area.

Well WW13 encountered Tlapana Mudstones intruded by a dolerite sill (?) at 60 m. This area may represent the centre of the downthrown block and extend for 1.5 km upstream of well WW13.

Scattered outcrops of Mea Arkose occur for 3 kms either side of WW14 along the Mosetse river, the course of which appears to be partly controlled by these outcrops. Inspection of these exposures showed minor asymmetric folding superimposed on a regional dip of 7° at N300°E. Dip and strike joints, whilst fairly common, are nonetheless rather widely spaced in general.

The thick calcretes (with silcretes in the lower part) which are present at wells WW13 and WW9, decrease in thickness eastwards. The alluvium is generally only a few metres thick and the sand bed of the river channel rests on calcretes or Mea Arkose. This provides favourable conditions for recharge to occur from the river along 5 km of channel upstream of about WW8.

Water is encountered at about 35 m in micaceous siltstones which are about 15 m in thickness. These occur near the top of the Mea Arkose sequence but were not observed at well WW7. The saline water to the north was also encountered in this sequence but at a greater depth, about 43 m.

The high mica content of the siltstone sequence is thought to give rise to a higher density of bedding planes than the more massive underlying sandstone sequence. At well WW8/P the main supply was encountered at 63 m beneath the siltstone/sandstone junction.

Lower well yields seem to occur where the siltstone sequence is absent, such as at well WW7. However, a low yield was also obtained at well 3129 but where this sequence should also be present. Both wells have similar specific capacities, about 0.1 l/s/m, and transmissivities, about 3 m^2d, which perhaps represent the more regional aquifer characteristics.

Siltstones are present at well WW14. The specific capacity of this 'targeted' site is about 1 l/s/m with a transmissivity of about 600 m^2d. These values, which are similar to the highest yielding group of wells (604, 616, 1239) at Dukwe, may represent conditions where the permeability of the sequence as a whole is increased by the presence of the siltstones.

The potential for obtaining high yields where fractures occur is indicated by site WW8, which has a transmissivity of about 1400 m^2d. However, the localized occurrence of such zones is shown by the specific capacities of the three wells at this site:

	Specific Capacity (l/s/m)	Depth (m)	Distance from WW8 (m)
WW8/T	0.45	78	26
WW8/P	4.81	102	3
WW8	14.1	108	-

These results could also suggest an increase in yield with depth. However, a grey mudstone band which occurs at this site suggests faulting between WW8/T and WW8. Thin maroon mudstones (as well as altered cystalline material (? dolerite dykes)) occurs within the sequence below 75 m and may represent the Dwyka Formation. Semi-confined conditions are indicated by a storativity of about 2 x 10^{-3} obtained from the test at this site.

Potable groundwater containing low dissolved solids and of a mixed cationic-HCO_3 composition and low dissolved solids occurs in the Mosetse Block and indicates active recharge. No deterioration in quality occurred during the short-term tests.

Although water level elevations are similar at wells WW8 and WW9 (1.5 km north), the dissolved solids content are very different: 640 mg/l at WW8 and

41080 mg/l at WW9. This suggests lack of connection with the area to the north.

Continuity from WW8 to 3129 is suggested by the similarity in water level elevation and water chemistries but the higher water level at WW7 indicates isolation of this site from the WW8 area. The direction of groundwater flow cannot be determined reliably from the available data.

3.3 W8/E3 Area

Ten wells have been drilled on the northern flank of the eastern graben around well W8/E3, of which three (MT2, 3106 and Mmemo) are in use.

SWECO attributed the high yield of well W8/E3 to the presence of a conglomeratic facies at the base of the Ntane Sandstone deposited in a buried valley trending southwestwards. Large amounts of sand were initially produced during the recent tests and the well could not be cleaned below about 55 m. This would suggest a possible inflow zone at this level, which is in open connection with the adjacent well E7, and that the Ntane Sandstone is only weakly cemented at this site.

The Ntane Sandstone is 40 m thick at well W8/E3 and the Tlapana Mudstone is absent. A similar thickness of Ntane Sandstone is present at well 3106 (2.5 km north), which has a reported yield of 2.0 l/s, but at this site overlies Tlapana Mudstone. Since the base of the Ntane Sandstone is 870 to 880 m in this area the shallower Basement Complex of the horst to the west encountered at well WW11 could act as a barrier to groundwater flow.

A description of the pumping tests carried out at W8/E3 is given in Appendix B. Early time-drawdown data suggests transmissivities of 400 - 500 m^2/d at W8/E3 and E1 and 1500 m^2/d at E7. Recovery data indicate transmissivities of about 3000 m^2/d but the specific capacity of 3 l/s/m (at 17 l/s) suggests the transmissivity values from the early drawdown data may be more representative. Leakage effects or a recharge boundary as well as the close proximity (2.4 m) of the observation wells rather limit the application of conventional analytical techniques.

The particular aquifer conditions at W8/E3 may extend over a wider area since a short, low rate test on the Mmemo well (3.5 km south) gave a specific capacity of 12.8 l/s/m, over four times that of W8/E3. Unfortunately, no well details are available. Site WW15 was drilled midway between these wells to obtain more information but has yet to be tested. All three wells have a similar conductivity of 2200 to 2300 mS also suggesting interconnection.

The conductivity of well 3106 is 3600 to 4000 mS, the chloride content increasing from 439 mg/l at 37.5 m to 848 mg/l at 180 m depth. Well MT2 (2 km NE of W8/E3) has a conductivity of only 860 mS and a rather different water composition which may be related to a shallow source. No well details are available and the pumping test has yet to be carried out on this site.

The eastern boundary of this area, whilst forming part of the eastern graben, is related to the presence of Tlapana Mudstone, which is faulted against the Ntane Sandstone between W8/E3 and 3098 (see Figures 7 and 8). Favourable aquifer conditions may occur over an area of about 10 km^2 as shown in Figure 1. Direct recharge from precipitation may occur through the calcrete sequence (although silcretes are present in the lower part) which is thick and extensive in this area, but groundwater is more likely to be draining from the north into the area through N–S faults.

The high chloride content of the waters in this area may be due to relatively recent contamination from a saline lake; the 940 m contour marking an old shoreline.

The main supply zone is probably at 50 – 60 m depth and, whilst this would give available drawdowns of about 40 m, the aquifer is perhaps of limited thickness and semi-confined.

3.4 Dukwe Block

SWECO defined an area at Dukwe of some 25 km^2 where favourable conditions for groundwater development were thought to occur. This area contains at least 150 m of Tlapana Mudstone and Mea Arkose bounded by a major NE trending fault to the south, and possibly a NW trending dyke or fault on the west at the main road. The Semowane river crosses the area about 15 km north-east of the road.

No further investigations of this area are believed to have been undertaken since those by SWECO in 1976. Their findings may be summarized as follows:

* Coarse facies in the upper half of the Mea Arkose were considered to form the main aquifer. The groundwater potential would be reduced where this sequence had been eroded, such as on the south-eastern flank of the graben.
* Pumping tests on the three most productive wells gave the following estimates of transmissivity (T) and storage co-efficient (S):

Well Number	T (m^2/d)	S	Specific Capacity (l/s/m)
604	412	-	0.99
616	371	-	0.88
1239	277	-	0.33
	553	2.6×10^{-4}	
	443	2.8×10^{-4}	

(Sites 616 and 1239 are only 45 m apart and penetrate 13 and 18 m respectively into the Mea Arkose. Well 604 penetrates only the Tlapana Mudstone.)

* These test results were used to make long-term predictions of drawdown from which it was concluded that wells 616 and 1239 could sustain yields of 20 and 8 l/s respectively (particularly if deepened to fully penetrate the Mea Arkose) for at least 15 years without any recharge.
* Reported test yields of wells 2165, 2146, 2157 and 2117 suggested relatively high yields of acceptable quality could perhaps be obtained towards the Semowane River.
* The southern boundary fault zone may offer the best prospect of locating high yielding wells.

The full data on which these conclusions are based are not presented in the SWECO Report. However, some general comments on their findings are as follows:

* The Mea Arkose is well cemented. Yields are more likely to be related to the development of a secondary permeability, in joint or bedding planes for example, than to grain size.
* The main supply horizons are not recorded but the highest yielding well, 604, derives a supply from the Tlapana Mudstone and not the Mea Arkose. It is likely that the main supply is related to bedding planes or the less competent nature of the Tlapana Mudstone (sills have preferentially intruded this sequence) but perhaps also to the junction of the two formations. If this is the case yields will not increase significantly with penetration into the Mea Arkose.
* Reported yields of tests undertaken on completion of drilling often relate to pump capacity and are not usually a very reliable indication. Even so, no dry wells are recorded in this area and six of the nine wells drilled in this particular area had yields of 0.6 to 2.5 l/s (excluding those given above).
* A relatively thin aquifer at about 80 m depth of limited storage is indicated with available drawdowns of 15 to 25 m. Specific capacity data is lacking but predicted drawdowns of 7 to 10 m at 20 l/s would occur at a well of 150 mm diameter on the basis of their estimates of aquifer characteristics.
* Tests were undertaken at only three wells within a small area at rates of 4.2 to 6 l/s for up to 72 hours. More extensive tests would be required over a wider area to assess whether the tested sites are typical. The sustained yield predictions seem optimistic on the basis of such limited tests.

3.5 Recharge

3.5.1 Precipitation

Shallow perched aquifers within the calcretes or Ntane Sandstone overlying Tlapana Mudstone are recharged by precipitation. The water composition at MT1 appears to be representative of these conditions (although the details of this site are unavailable). Elsewhere, the widespread distribution of mudstones and siltstones, such as those of the Tlapana Mudstone sequence, must restrict local recharge from precipitation, to areas where these are absent, such as on the southern flank of the eastern graben or along the Mosetse River.

The area and even the source of recharge, which may be distant from a particular well or differ for particular faulted blocks, cannot be defined, since groundwater is likely to follow a complex path through fractures and horizontal zones of higher permeability.

The average annual rainfall in the Dukwe area is 450 mm with a seasonal variability of 45%. The average number of days on which rain occurs (based on the Gaberone record, 500 mm/year average annual rainfall, for 1957 to 1983) is as follows:

J	F	M	A	M	J	J	A	S	O	N	D
11	9	7	6	0	0	0	1	2	6	9	9

The sodium and chloride content of most of the groundwaters would suggest limited recharge from rainfall. In order to estimate recharge from this source regular or continuous water level measurements would be necessary.

3.5.2 River Flows

Our experience elsewhere in Botswana suggests that significant recharge generally occurs only where rainfall is concentrated as river flow. The water quality in the Mosetse Block confirms this general observation. Further recharge may enter this area as underflow from the area upstream along the Basement Complex surface.

Monthly flows on the Mosetse are given in Table 6. The amount of recharge from this source cannot be quantified without water level hydrograph records but the volume required to abstract the annual water requirement entirely from the Mosetse block can be compared to the flow on the Mosetse. This ranges from 0.5 to 21% of the total annual flow. However, as the flow distribution is highly skewed (Figure 8), which is common for rivers in Botswana, the median flow of 13.5 million m^3/year is more representative of the flow likely to occur in any one year. In this case the total water demand represents 3.7% of the median annual flow. This would not seem unreasonable but would depend on flow residence times and other factors.

Flow occurs typically for short periods and is very seasonal, there being no flow between April and October. The rainfall record given above shows that rain can occur for about 30% of the month between November and February inclusive suggesting flow might also occur continuously during these months.

4. CONCLUSIONS

The eastern graben contains at least three areas which offer potential for development as groundwater sources. These areas are of relatively limited extent but high yields can be obtained from structural zones.

So far only short term tests have been undertaken. However, the recent field programme provides a more optimistic picture of the potential role of groundwater supplies for the refinery, either used independently or in conjunction with alternative supply sources under consideration by WLPU and SEL.

The use of groundwater supplies alone depends on certain aspects, such as specific yields or aquifer extent, which can be evaluated only from long-term hydrological data and more detailed geological information.

Reliable predictions of the sustained yield of each of the potential groundwater development areas are extremely difficult due to the complex hydrogeological conditions. However, some tentative estimates of the groundwater in storage are as follows:

Area		Storage (million m^3)	Expected duration (years)	
			Low demand	High demand
			1/s	16 1/s
Mosetse	3 km^2	0.75(plus recharge)	(3)	(1.5)
W8/E3	10 km^2	1	4	2
Dukwe	25 km^2	2.5	10	5

(These assume a specific yield of 0.1% and aquifer thickness of 10 m for the W8/E3 and Dukwe areas and 1% and 25 m for the Mosetse valley).

These estimates suggest that consideration should be given to exploiting each area for a short period rather than relying on a single area for the supply requirement duration of 25 years. Furthermore, due to the complex, compartmented nature of the eastern graben the degree of hydraulic continuity or water quality changes can only be studied after long term abstraction begins. Monitoring of water levels and quality to predict if and when another area would need to be brought into supply (as well as to assess the effects of abstraction on other users) will be essential and sources within each area should be identified in advance to ensure continuity of supply.

The type of groundwater scheme, and thus developments costs, will rely on whether supplies can be sustained from a few, irregularly spaced high-yielding wells penetrating zones of high permeability, or a larger number of lower-yielding wells located to develop aquifer storage over a wide area. Some combination of both types is likely. Suitable target sites would need to be selected with the assistance of surface geophysical surveys.

4.1 Mosetse Valley

High quality potable groundwater occurs in a narrow zone perhaps 1 km wide of complex faulting beneath the alluvial valley of the Mosetse for some 6 km west of well 3129. The most favourable conditions for development occur along a 3 km stretch downstream of this well.

The main supply to derived from or at the base of a silstone sequence in the Mea Arkose at depths of about 60 m. Short term tests indicate specific capacities from 0.1 to 10 l/s/m, the highest yields being associated with structural zones.

Three to five wells targeted onto structural features in this area could supply the total requirement. This would include WW8 and WW14, subject to the longer term tests to be undertaken shortly. However, there are a number of constraints which may limit the long-term use of this area as a supply for the refinery:

* The total water demand represents a recharge requirement of 3.7% of the median annual flow of the Mosetse river. The water quality shows that active recharge occurs. However, for part of the year and during drought years abstraction may need to draw upon aquifer storage. The long-term test to be undertaken at WW8/P may provide information on the specific yield of the sequence.
* Hydraulic interconnection between different downfaulted blocks may be mainly restricted to fault zones producing a complex pattern of groundwater movement. The net result of such conditions on sustaining well yields may not become apparent until after larger scale abstraction has commenced.
* Very saline water is present on the northern boundary of the area. We cannot assess the hydraulic connection between the fresh and saline waters, which both occur in the same siltstone sequence. Water quality would need to be monitored regularly to indicate an unacceptable deterioration in the quality of the supply.

* The aquifer extent has not been defined fully, in particular south of the river.

Development of this area would require only a single pipeline and a small wellfield. However, further investigation of the above constraints is required.

It is likely that a potable supply could be abstracted for a long period from this area using existing wells WW8P or WW14, which, if necessary, could be supported by developing the area around well WW7.

We would recommend that the Mosetse Valley area is retained for long term potable supplies for the new township in view of the scarcity of good potable water in the region generally.

4.2 Supplies from the W8/E3 Area

The Ntane Sandstone forms the main aquifer in this area. Structural features, however, which affect the underlying sequence, are masked by a thick cover of calcretes. There are several other possible constraints on development.

* Existing private wells (MT2, Mmemo and 3106) abstract groundwater for cattle watering in the same area. Their total abstraction is unlikely to exceed 20,000 m^3/year. However, these could be included in an overall abstraction scheme.
* Although the water quality is suitable for the refinery, the chloride content exceeds WHO limits and an independent supply of drinking water would be preferable.
* Barrier boundaries (including those formed by the horst to the west and Tlapana Mudstone to the east) may not become apparent until large scale abstraction begins.
* Recharge is limited and abstraction may need to be maintained largely by depletion of aquifer storage.

Nonetheless, well W8/E3 could be used as a supply for the refinery but we cannot predict whether this could be maintained for 25 years. A standby site would be needed in the event of pump failure and this could be a new well at the same site or perhaps the Mmemo well (subject to further testing and negotiation with the owner).

In addition, a short test at MT2 suggests that this private well could supply at least the initial potable water demands. This would depend on negotiation with the owner but could be incorporated more economically than wells in the Mosetse Valley. We would, however, expect the water quality to deteriorate with long-term abstraction.

4.3 Dukwe Area

The Dukwe Block appears to be more extensive than the other two potential supply areas, and therefore perhaps more capable of maintaining long-term supplies. The main aquifer appears to be the lower part of the Tlapana Mudstone or its junction with the Mea Arkose.

However, the following constraints may apply:

* The water quality is marginal in terms of chloride content.
* Abstraction already occurs. SWECO identified ten boreholes in the area, which could have a total abstraction of perhaps 70,000 m^3/year.
* Structural zones would be difficult to locate and a larger number of low yielding wells would probably be required. Since also this area is a further 5 to 10 km further east of W8/E3, the costs of developing supplies would be greater.
* The extensive occurrence of Tlapana Mudstone limits direct recharge. Some recharge may occur via fracture zones from distant sources such as the Semowane River or off the southern flanks of the graben. Storage would be depleted to maintain long-term supplies.

Nonetheless, this area could provide an additional source of supply, although the groundwater potential suggested by SWECO is considered optimistic. Further investigations would be required to establish the availability and role of groundwater supplies from this area.

5. FURTHER INVESTIGATIONS

5.1 Drilling

Further drilling at this stage will not necessarily provide much more information on the groundwater conditions. The accent is rather more on obtaining longer-term hydrological data. However in order to take advantage of the presence on site of the ASTE rig additional drilling would be desirable at the locations shown in Figure 1:

WW16 : to examine the connection between WW8 and WW7 near the edge of the alluvium (80 m depth)

WW17 : to obtain geolgical information between Mmemo and MT1 since no information is available in this general area (100 m)

WW18 : near the edge of the calcrete sequence along the camp access road on the fault passing close to MT2 (100 m, or Basement Complex)

A short cut line may be required for WW16 but the other sites are easily accessible.

The type of scheme may depend on the reliability of intersecting zones of high permeability. It would be useful to undertake trial surface geophysical surveys over a selected area, such as around W8/E3, to study the geological structure on a wider scale to thereby indicate the potential aquifer extent and prescence of structural zones. Exploratory wells could then be drilled at favourable locations before the rig leaves site.

5.2 Logging

BPBI will be on site to undertake geophysical logging for other aspects of the Sua Project. It would assist correlation between sites and possibly identify inflow zones if logging could be carried out at the following sites:

- any of the wells at W8/E3 site (these may be blocked at about 95 m)
- WW15 in the W8/E3 area
- WW8 and WW9 in the Mosetse valley.

Logs of WW17 and WW18 if drilled in time would also be most useful but alternatively, if time allows, WW14 and WW11. The BPBI combination sonde (caliper, gamma and neutron density) is generally sufficient but if differential temperature logs are included an indication of the type of flow (intergranular or fissure) and aquifer thickness would assist estimates of aquifer storage. However, it would be preferable to log as many boreholes as possible with the combination sonde than to log only a few boreholes in detail.

5.3 Testing

Certain outstanding tests to complete the current fieldwork were outlined in Memorandum 4 (April 1984). The results of these tests will be included in Memorandum 7A as an addendum to this report. In addition to these planned tests we would recommend a high rate pumping test at 10 l/s with the SAB pump BH 200 at the Mmemo well, if permission is granted by the owner, in order to assess this site as a back-up source to W8/E3.

Table 1

DRILLING PROGRAMME - DETAILS OF EXPLORATORY WELLS

Well Reference	WW8	WW8/T	WW8/P	WW9	WW9/A	WW10	WW11	WW12	WW13	WW14	WW15
Grid Ref. (UTM) E :	43150	43150	43150	43140	43140	43130	43100	42875	43020	43280	43560
N	77199	77199	77199	77213	77213	77227	77264	77198	77184	77203	77295
Elevation (m) (Estimated)	942	942	942	942	942	941	935	939	940	944	938
Date drilled	13.3.84	15.3.84	5.4.84	16-18.3.84	6.4.84	14.3.84	15.3.84	16.3.84	17.3.84	19.3.84	6.4.84
Drilled depth (m)	108	78	102	108	108	90	60	60	72	108	102
Casing : Length (m)	2	4,7	11	3	2,5 6,1	3	3,5	3,5	6	6	4
Dia. (ins)	6	7	7	7	7 6	7	6	7	6	7	6
Open Hole dia. (ins)	5,25	6,5	6,5	6,5 (0-66) 5,25 (66-108)	5,25	6,5	5,25	6,5	6,5	6,5	5,25
Rest Water Level (m below casing top)	30,16	30,16	30,31	34,10	33,70	31,23	Dry	28,80	NR*	32,95	15,59
Conductivity (Micro Siemens per cm	760	740 -	755 (77 m)	35300 (66 m)	35200 (60 m) 34300 (90 m)	40500 (Approx) 34000 (100 m)	-	28000	1700	335	2100 (72m) 2210 (90m)

*Hole blocked at 13 m.

Table 2

PUMPING TEST PROGRAMME:
SUMMARY OF TESTS

Well Number	Date	Type and Duration (minutes)		Rate (1/s)	Remarks
W8/E3 (2981)	22.3.84	S	4 x 120	8.26 to 25.9	E7, E1 monitored
	23.3.84	C	1680	22.8	"
		R	360	-	"
WW8	3.4.84	C	360	2.95	WW8/T monitored
WW8/T	25.3.84	S	4 x 60	0.57 to 2.73	WW8 "
	26.3.84	C	1440	3.70	"
WW8/~~8~~l	5.4.84	C	60	8.40	Initial test
		R	30	-	
WW14	29.3.84	S	3 x 120	0.64 to 3.30	Extended step test
		(4th step to 1680)			
		R	510		
3129	30.3.84	C	106	1.2	Existing pump
Mmemo	4.4.84	C	120	0.64	"

S : step (production) test without intervening recovery

C : constant rate test

R : recovery

Table 3

PUMPING TEST RESULTS:

SPECIFIC CAPACITIES

Well Number	Pumping Rate (l/s)	Drawdown* (m)	Specific Capacity (l/s/m)	Rest water** level (m)	EC (mS)
W8/E3 [2981]	8.27	2.263	3.62	14.69	2150
	13.5	4.090	3.30		
	21.5	7.515	2.86		
	26	9.235	2.81		2250
WW8	2.97	0.211	14.1	30.450	760
WW8/T	0.57	0.765	0.74	30.313	740-815
	0.97	1.462	0.66		
	1.67	3.025	0.55		
	2.73	6.05	0.45		
WW8/P	8.04	1.671	4.81	30.50	755
WW14	0.69	0.35	1.97	32.950	330
	1.15	0.66	1.74		
	1.99	1.48	1.34		
	3.33	4.18	0.80		
3129	1.2	13.24	0.09	34.62	620
Mmemo	0.64	0.05	12.8	23.133	2420
[WW7	1.5	12.5 (t30)	0.12	20	820-650]
		34.3 (t440)	0.04		

* At elapsed time of about 100 minutes

** Below measuring datum

Table 4

PUMPING TESTS: AQUIFER PARAMETERS

Well Number	Transmissivity (m^2/d)	Storativity	Remarks
WW8	Jacob 2120	3.5×10^{-3})	WW8/T as observation
	Theis 1450	1.8×10^{-3})	well r/B 0.2
WW8/T	Jacob 2250	1×10^{-3})	WW8 as observation
	Theis 1340 ($t < 30$)	1.1×10^{-3})	well r/B 0.2
	Jacob 2930	-	Recovery at WW8/T
	" 150	-	Step 1 WW8/T
WW8/P	Jacob 705 ($t < 12$)	-	
	" 1415 ($t > 12$)	-	
	" 2544 (early data)	)	Recovery
	" 4710 (late data)	)	
WW14	Jacob 645	-)	Step 1
	Chow 635	-)	
	Jacob 595	-	Recovery from extended step 4 (unweighted)
3129	Jacob 2.4 ($t < 40$)	-	
	3.2 ($t > 40$)	-	
	Jacob 3.8 (late data)	-	Recovery
	Theis 2.2	-	

Memo

CHEMICAL ANALYSES (mg/l where applicable)

TAPLE 5

WELL NUMBER

	WW/8T	WW8/T	WW14	WW14	WW9A	MT2	W8/E3*	W8/E3	W8/E3	W8/E3	604*	3067*	616*	1239*	3106*	3106*
Date	25.3 S4	27.3	19.3 72m	29.3	6.4	13.4	20.2	22.3 S3	23.3 C/R	24.3 C/R	10.3	8.11	22.1	31.1	11.12 37.5 m	11.2 180 m
Conductivity (mS @ 25°C)	925	945	533	400	41110	1020	3300	2660	2710	2790	1700	960	1600	1650	3600	4000
T.D.S.	640	660	416	316	41080	876	1604	1748	1724	1722	868	688	988	900	2136	2620
Total Hardness $CaCO_3$	364	417	77	148	12584			405	416	472						
Total Alkalinity $CaCO_3$	386	384	160	164	196	485		534	530	528						
Calcium Ca	71.22	71	15.94	31.97	2051.8	80	106	93.54	95.54	97	105	91	74	26	9	89
Magnesium Mg	45.15	58	8.66	16.41	1812.3	72	54	41.74	42.90	55	60	41	37	53	11	58
Sodium Na	72.06	70	88.67	29.75	8740.4	28	579	455.64	481.86	486	216	52	263	293	892	920
Potassium K	1.4	0.1	4.2	1.8	28.2	42	8	6.6	7.6	3.0	4	5	5	5	26	22
Bicarbonate HCO_3	470	468	195	200	239	384	655	651	646	644	576	472	524	472	1468	1153
Carbonate CO_3	Nil	Nil	Nil	Nil	Nil	101	Nil	Nil	Nil	Nil	Nil	52	Nil	39	Nil	90
Chloride Cl	79.8	88	65.1	31.5	19635	38	735	510	529	577	233	64	233	225	439	848
Sulphate SO_4	17	20	13	10.5	2811	1	161	125	125	137	112	14	98	112	91	121
Nitrate NO_3	0.1	0.8	-0.1	-0.1	-0.1	45		0.2	0.2	7.3	1.5	-0.1				
Fluoride F	0.5	1.0	0.6	0.5	0.7	0.2	0.7	1.0	1.0	1.5	1.0	1.0	0.2	0.1	0.3	1.2
Silica SiO_2	70.2	69	61.5	70.4	33.0	106		77.8	79.8	79						
Iron Fe	0.02	0.04	0.06	0.01	10.8	0.05		0.02	0.03	0.03	0.1					
pH	7.35	7.35	7.8	6.9	7.25	8.65	8.15	7.25	7.25	7.15	6.9	7.5	7.7	7.7	7.6	8.0

* From SWECO Report May 1976 Table 4.1

\- Indicates less than value shown

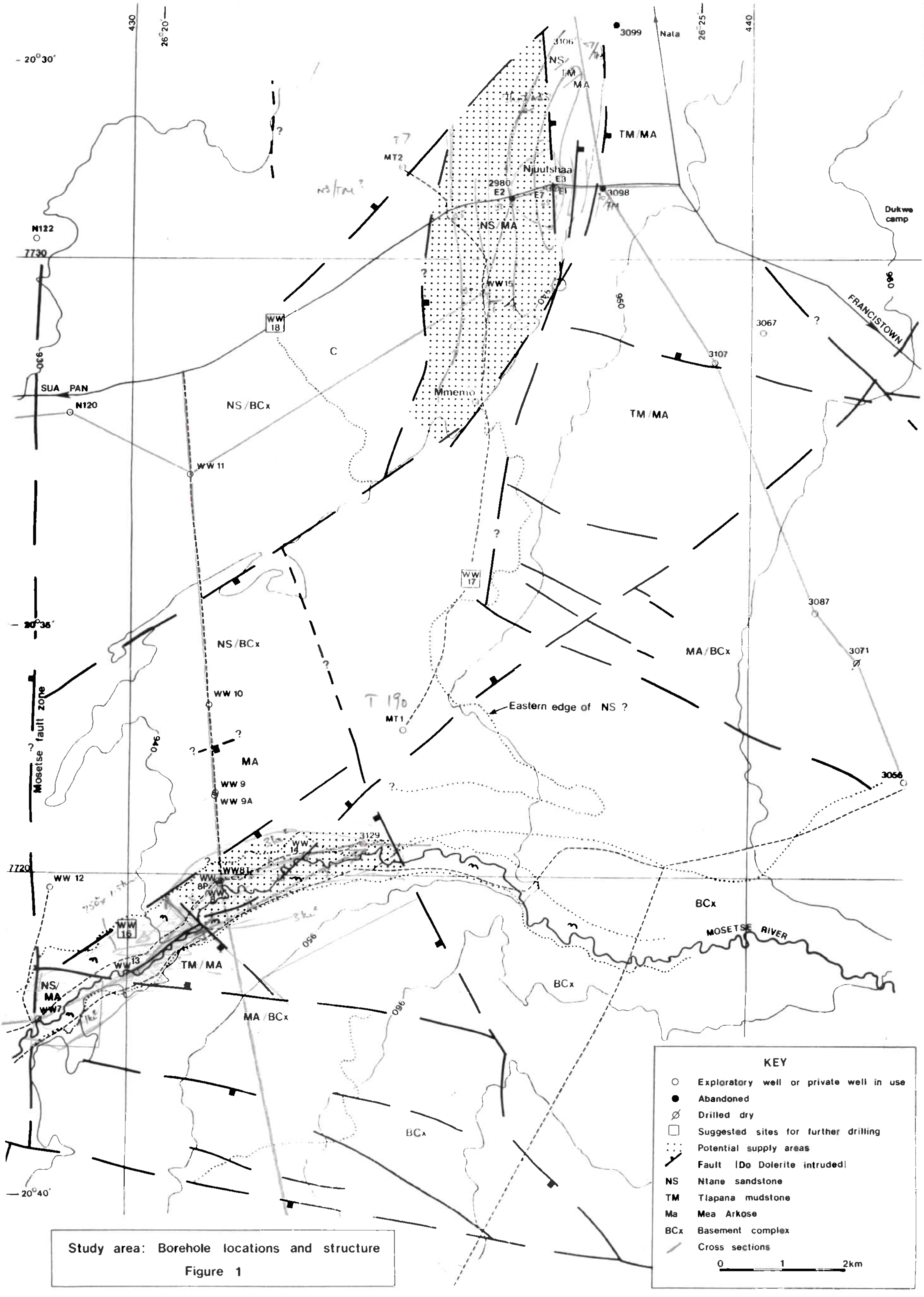
STATION: MOSETSE

Table 6

MONTHLY AND ANNUAL FLOWS IN M^3 10^6, 1970 - 1982

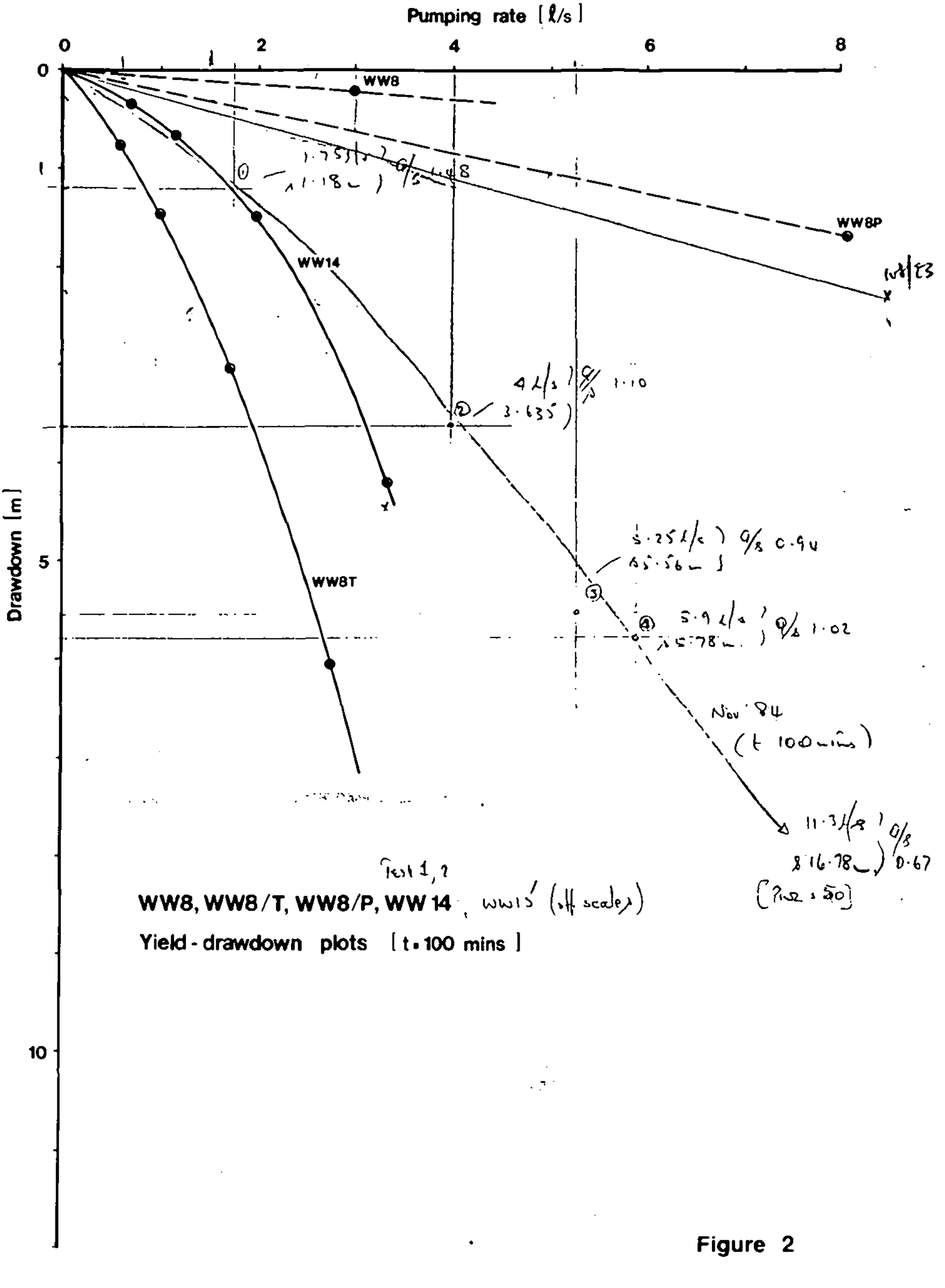
Catchment area 1090 km^2

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual Total
1969-70	0.008	0.002	1.597	0	9.029	0.636	0	0	0	0	0	0	11.272
1970-71	0	0.372	8.204	29.12	0.19	0	0	0	0	0	0	0	37.886
1971-72	0	0.35	0.34	95.91	0.10	1.08	0	0	0	0	0	0	97.78
1972-73	0	0	0	1.105	0.447	0.88	0	0	0	0	0	0	2.432
1973-74	0	1.785	27.793	33.136	3.054	0.967	0	0	0	0	0	0	66.735
1974-75	0	0.28	0.285	0.265	5.827	1.21	0	0	0	0	0	0	7.867
1975-76	0	0	0	0.40	3.535	4.99	0	0	0	0	0	0	8.925
1976-77	0	0	0	0.80	3.81	10.67	0	0	0	0	0	0	15.28
1977-78	0	0.267	11.254	50.242	0	0	0	0	0	0	0	0	61.763
1978-79	0	0	1.632	1.264	0.004	8.776	0	0	0	0	0	0	11.676
1979-80	0	0	0.423	0.963	3.04	0.009	0	0	0	0	0	0	4.435
1980-81	0	2.152	1.908	18.544	11.495	3.703	0	0	0	0	0	0	37.802



Study area: Borehole locations and structure

Figure 1

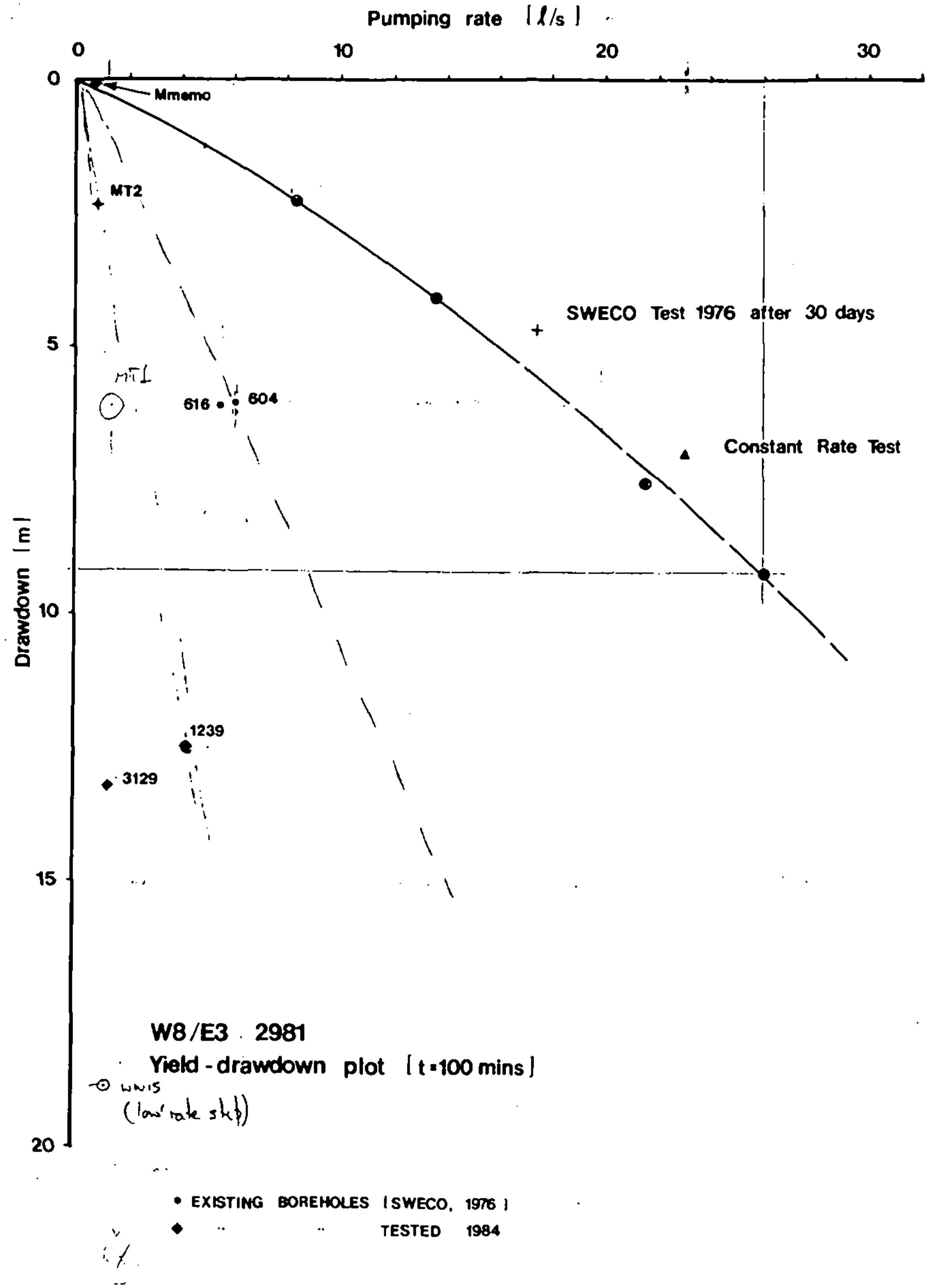


Test 1, 2

WW8, WW8/T, WW8/P, WW 14 , WW15 (off scale)

Yield - drawdown plots [t = 100 mins]

Figure 2



Pumping rate [l/s]
0
10
20
30
Mmemo
MT2
SWECO Test 1976 after 30 days
5
MT1
616
604
Constant Rate Test
Drawdown [m]
10
1239
3129
15
W8/E3 2981
Yield - drawdown plot [t=100 mins]
wwis
(low rate step)
20
• EXISTING BOREHOLES (SWECO, 1976)
◆ " " TESTED 1984

Figure 3

Sua Pan Project, Botswana

Trilinear plot of chemical analyses

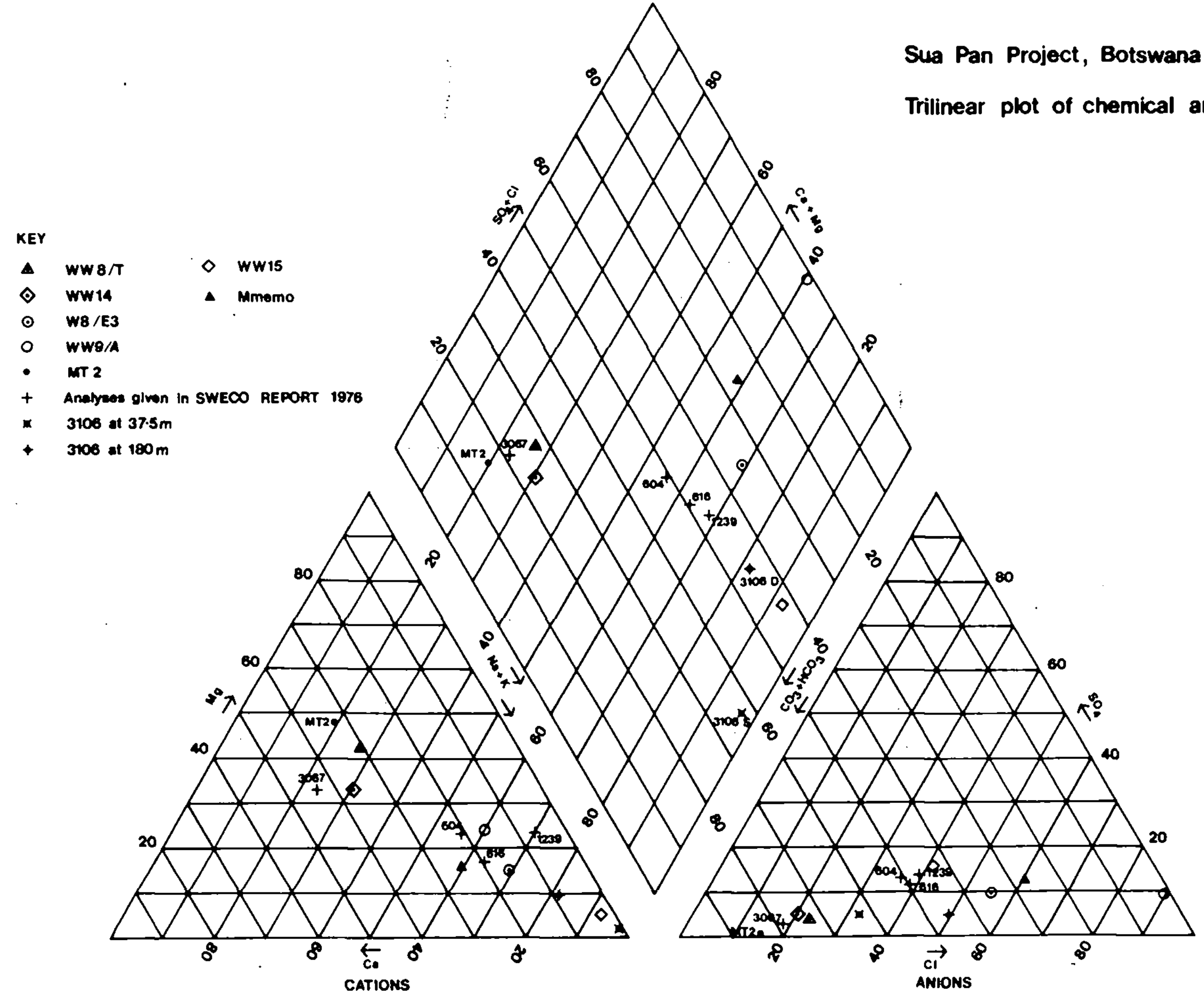


Figure 4

Profile W–E cut line along Mosetse river

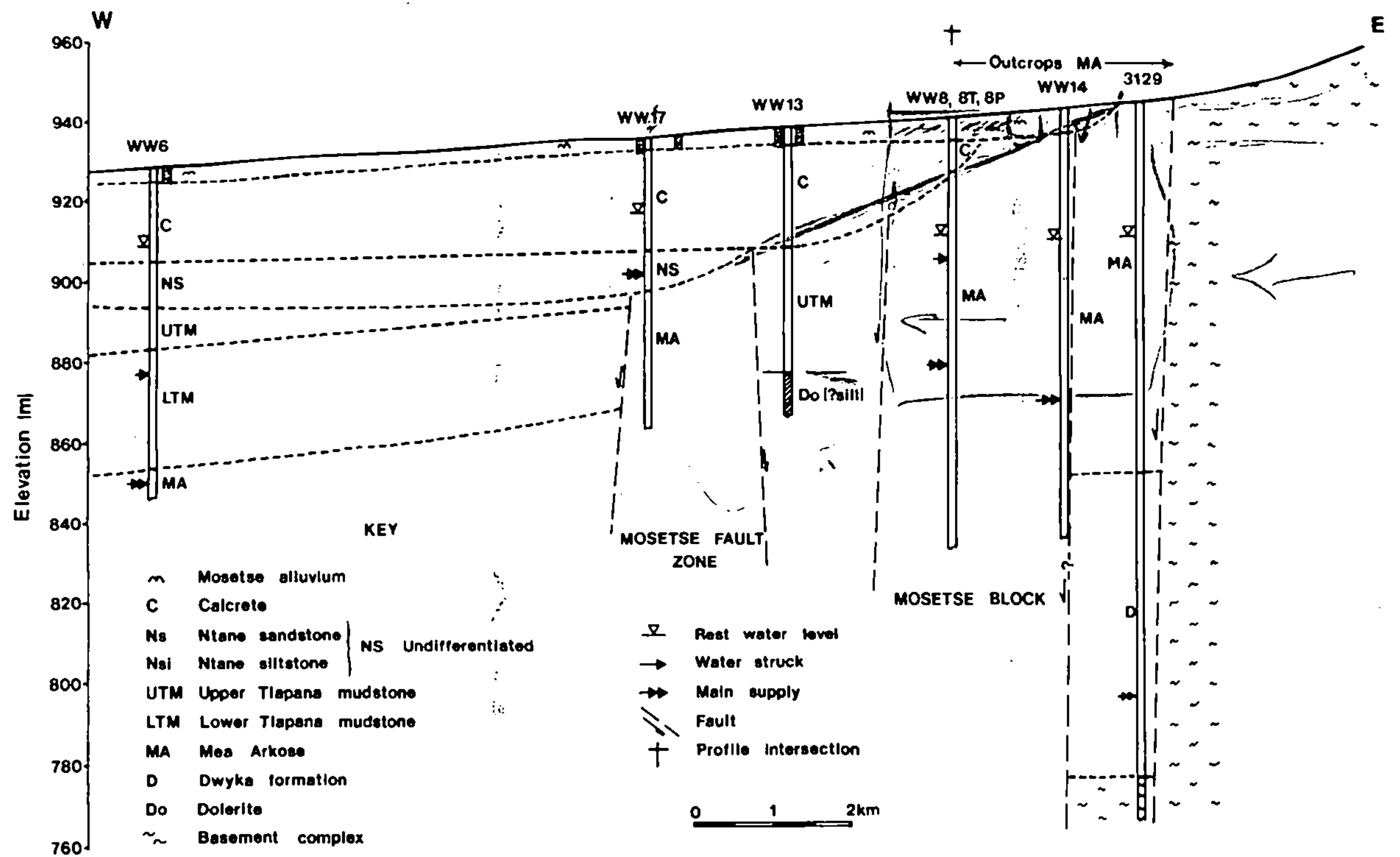


Figure 5

Profile N-S cut line

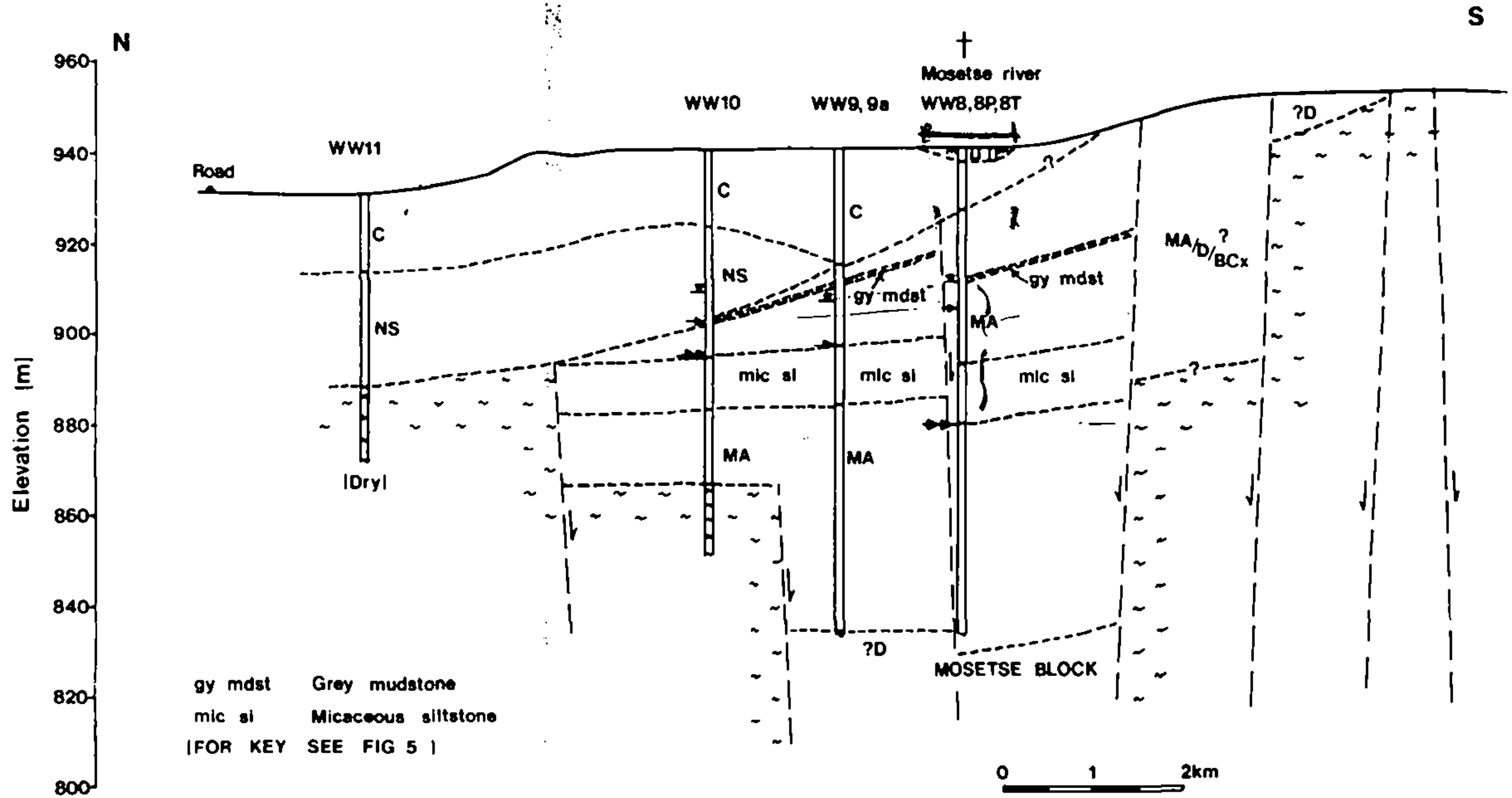


Figure 6

Profile W-E Sua Pan access road

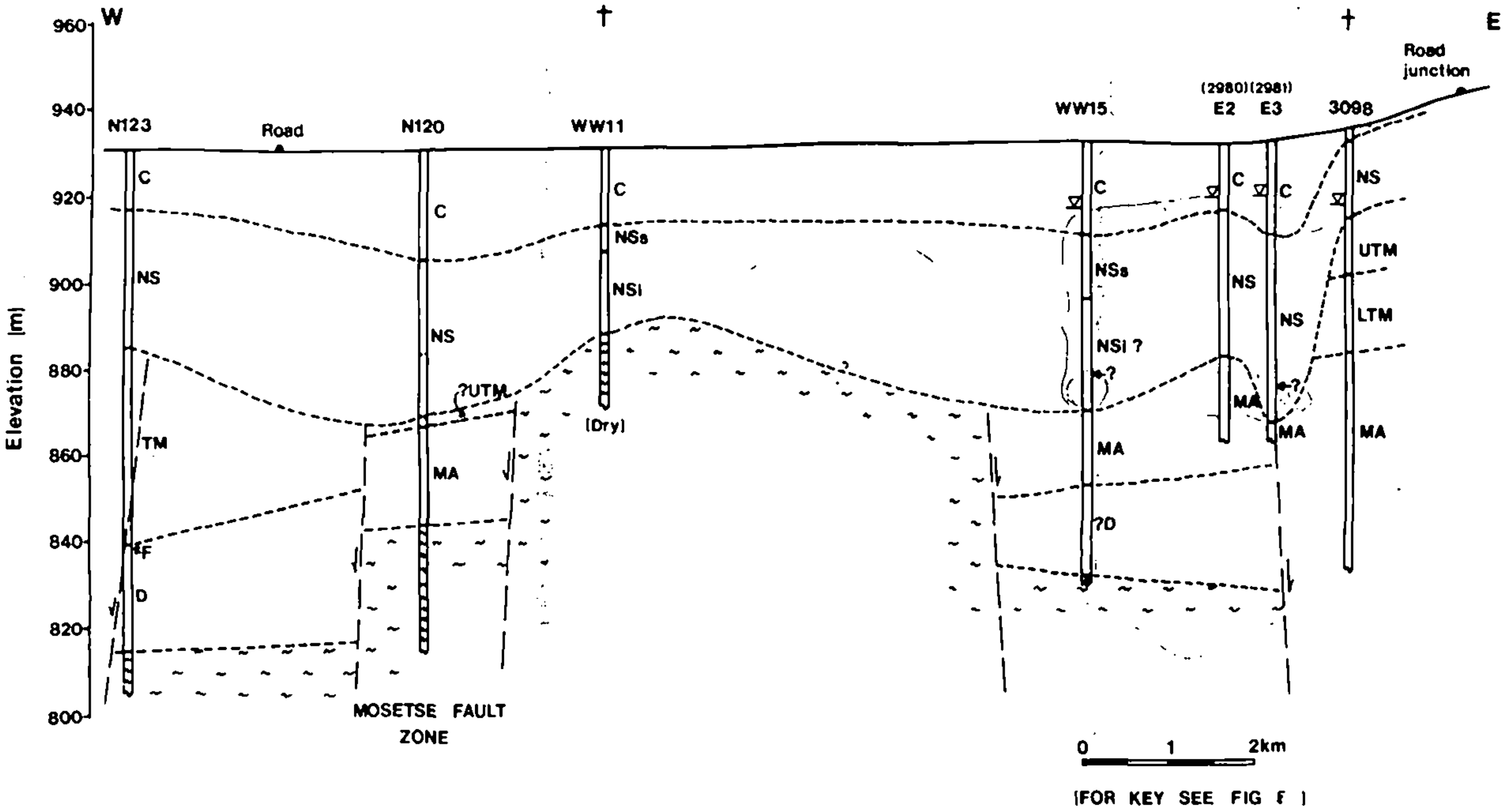


Figure 7

Profile NNW-SSE Dukwe Graben

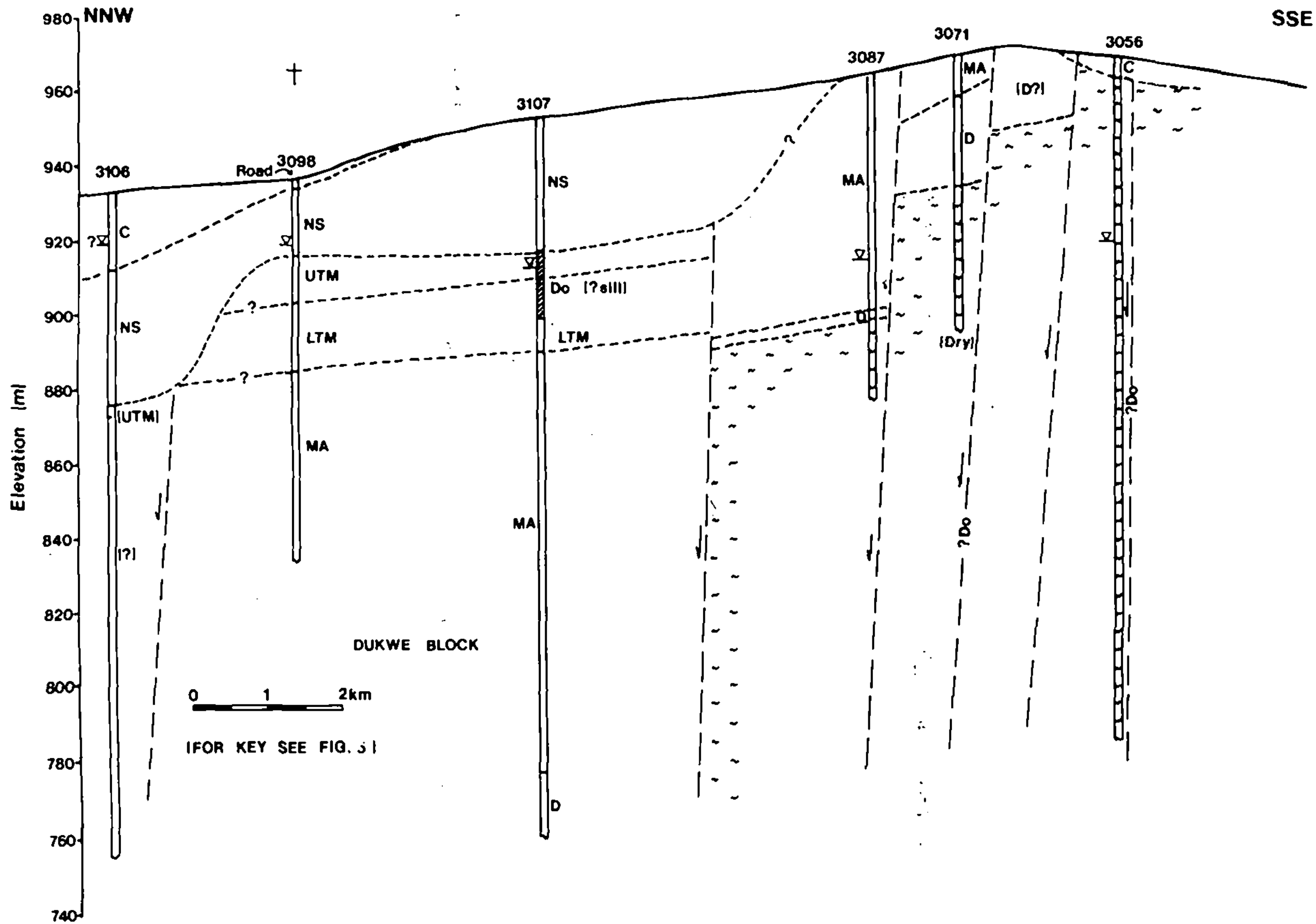


Figure 8

Distribution of flows at Mosetse

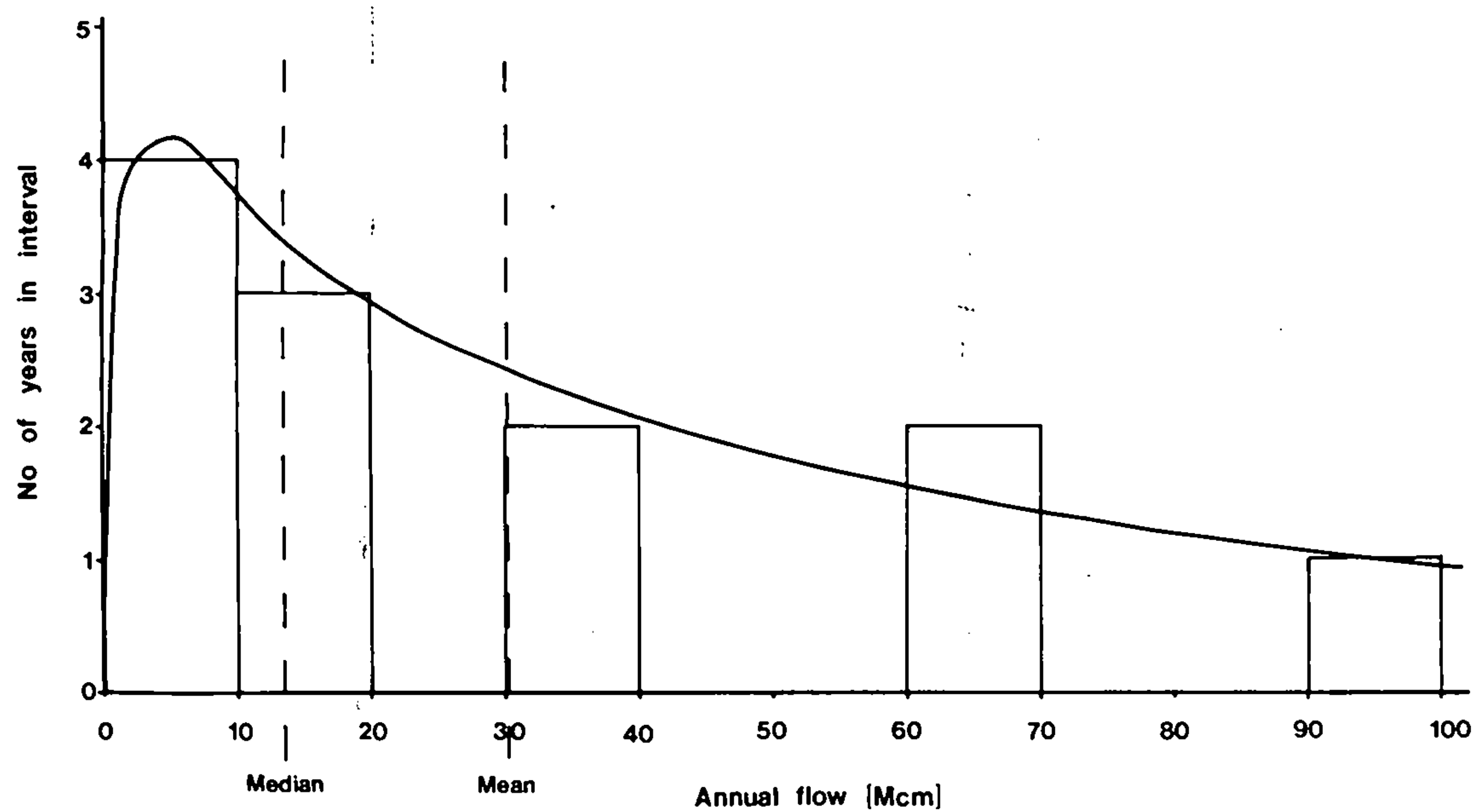


Figure 9

APPENDIX A

Sample Descriptions

Table A1

DRILLING PROGRAMME: LITHOSTRATIGRAPHIC INTERPRETATIONS

Well Number (prefix WW)

	8	9	10	11	12	13	14	15
Alluvium or Recent deposits	0-5 6-14	0-14 15-26	0-12 13-17	0-9 10-18	0-6 7-20	0-5 6-30	0-6) 6-7)	?0-21 ?
Ntane Sandstone	-	-	18-36	19-42	21-39	-	-	22-36
Tlapana Mudstone	-	-	-	-	40-51	31-60	-	-
Mea Arkose	15-108 EOH	27-106	37-73	-	-	-	8-75	37-79
Dwyka Formation	-	107-108 EOH	-	-	-		76-108 EOH	80-100
Basement Complex	-	-	74-85 EOH	44-60 EOH	52-60 EOH	-		101-102 EOH
Dolerite						61-72 EOH		

Go Pur

Borehole WW8 : Sample Descriptions

Depth (m)	
0-2	Grey silty-sand clay
3-9	Light green return, weathered calcrete with orange (iron) stained fine to coarse-grained, sub-rounded quartz.
10-13	White return, calcrete with abundant orange-stained quartz, some silcrete at 12 m.
14-26	Yellowish sand returns of light grey calcareous sandstone, with clear quartz, iron speckling, variably weathered.
27-31	Light grey mudstone in yellow brown returns.
32-38	As 14-26 m (Slurry return at 36-38).
39-40	Light grey mudstone in non-slurry, sandy return.
41-42	Buff return, mainly medium grained sandstone, grey quartz.
43-51	Slurry returns (? siltstone).
52	Slurry return with flatter returns of micaceous siltstone.
53-56	Yellow-buff returns, with quartz-felspathic sandstone, grey quartz.
57-60	Sand returns with more abundant brown, micaceous siltstone and dark brown ironstone chippings.
61-108 EOH	Buff returns grey quartz-felspathic sandstone, occasional micaceous siltstones and felspars yellow stained. Dark red crystalline material at 75, 96, 100-101 and 103-108 in slightly maroonish-grey returns.

Borehole WW8/T : Sample Descriptions

Depth (m)	
0-5	Grey sandy-silty clay
6-10	Light green, silty clay becoming more sandy at 10 m with orange (iron) stained, sub-rounded quartz.
11-14	White returns calcrete, some silcrete with varying amounts of poorly sorted, sub-rounded iron stained quartz.
15-27	Light grey, medium grained, loosely cemented calcareous sandstone with clear quartz. More weathered at 21-24 m.
28	Weathered micaceous siltstone in light brown return.
29-30	As 15-27 m but coarser grained.
31	Slightly pinkish return, light grey mudstone.
32-36	Yellowish felspathic coarse grained sand returns weathered brown at 36 m with very hard, crystalline angular chippings.
37-39	Partial slurry returns.
40-42	Drier sandier returns? micaceous siltstone.
43-54	Slurry returns (some light grey mudstone at 50, 51 m).
55-59	Flat returns, brown micaceous siltstone, weathered and with abundant rounded grey quartz at 55 m.
60-78	Pale yellow returns of light grey quartz-felapathic sandstone, with flat returns of brown micaceous silstone at 75, 76 m in brown return with purplish mudstone (? crystalline).

Borehole WW8/P : Sample Descriptions

Depth (m)	
0-10	Soil and alluvium (casing to 10 m, mixed samples).
11	White angular chippings of calcrete.
12-13	White powdered returns, calcrete.
14-15	Flat returns brown micaceous siltstone in yellowish return.
16	Light yellow return of light grey sandstone, loosely cemented, moderately well sorted, calcareous matrix.
17-28	Light grey returns, grey quartz scathed in calcareous matrix. At 20 m medium-coarse grained, predominantly coarse at 22 m, weathered and iron-stained at 24-25 m, coarse grey quartz at 28 m.
29-32	Yellowish-brown mudstone, some light grey mudstone.
33-35	Light yellow sand returns of weathered light grey, iron stained, medium grained grey quartz sandstone.
36-47	Yellowish, sandy returns (Damp). Coarse grained, sub-rounded grey quartz, occasional light grey-pinkish hard mudstone and some flatter returns of fine grained sandstone-siltstone.
48-61	Flat, coarse returns of brown to maroon micaceous siltstone with relatively little grey quartz sand but some crystalline, purpose fragments.
62-74	(Main supply 62-63 m). Yellowish sand returns with cross-bedded, quartz-felspathic sandstone, poorly sorted, with grey quartz. Iron stained.
75-76	As 62-74 but with dark brown, crystalline material.
77-89	As 62-74
90-92	As 62-74 but more maroon return with dark red crystalline material, occasional banded jasper.

Borehole WW8 : Sample Descriptions

Depth (m)	
0-2	Grey silty-sand clay
3-9	Light green return, weathered calcrete with orange (iron) stained fine to coarse-grained, sub-rounded quartz.
10-13	White return, calcrete with abundant orange-stained quartz, some silcrete at 12 m.
14-26	Yellowish sand returns of light grey calcareous sandstone, with clear quartz, iron speckling, variably weathered.
27-31	Light grey mudstone in yellow brown returns.
32-38	As 14-26 m (Slurry return at 36-38).
39-40	Light grey mudstone in non-slurry, sandy return.
41-42	Buff return, mainly medium grained sandstone, grey quartz.
43-51	Slurry returns (? siltstone).
52	Slurry return with flatter returns of micaceous siltstone.
53-56	Yellow-buff returns, with quartz-felspathic sandstone, grey quartz.
57-60	Sand returns with more abundant brown, micaceous siltstone and dark brown ironstone chippings.
61-108 BOH	Buff returns grey quartz-felspathic sandstone, occasional micaceous siltstones and felspars yellow stained. Dark red crystalline material at 75, 96, 100-101 and 103-108 in slightly maroonish-grey returns.

Borehole WW9 : Sample Descriptions

Depth (m)	
0-4	Green-brown silty clay to clayey sands.
5-14	Light green sand return with sub-rounded, poorly sorted orange (iron) stained quartz.
15-24	Light yellow soft calcrete with orange stained quartz.
25-26	White return, harder calcrete.
27-42	Yellowish sand returns with light grey - slightly pinkish sub-rounded quartz (weahered from 31-36 m), sandstone with light grey mudstone at 29-30 and red crystalline material at 40-41 m.
43-59	(Water struck at 43 m) Brown to purpose/light grey micaceous silstone as flat returns. Very weathered.
60- $\frac{108}{\text{EOH}}$	Pinkish, becoming yellowish quartz-felspathic sandstone with grey quartz, brown ironstone, fine to coarse grained (plus calcrete contamination). Dark red-brown fragments (? dyke) at 103-105 m.
	At WW9/A brown, laminated siltstones 43-53 m with coarse, grey sand returns from 54 m in washed samples. Dark grey water flow at 107-108 m with dark green shale or mudstone and calcite veining (as agate).

Borehole WW10 : Sample Descriptions

Depth (m)	
0-3	Sandy clays, greenish-grey.
4	Pale olive quartz sand.
5-6	Light green sandy clay.
7-9	Light grey sandy clay.
10-12	Light yellow silty sand.
13-17	White return, calcrete with orange-stained, sub-rounded quartz at 14 m and silcrete at 15 m.
18-23	White-pinkish returns weathered, weakly cemented light grey, mainly fine to medium grained sandstone with calcareous matrix.
24-25	Brick red-maroon, coarse hard returns of ? dyke material.
26-35	White to yellowish returns with light grey to light yellow fine grained weakly cemented sandstone and micaceous siltstone. Weathered.
36	Chocolate brown return, clayey very decomposed sandstone
37-38	(Water struck at 37 m, slurry return at 38 m). Light grey mudstone.
39-41	Very micaceous, fine grained sandstone to siltstone in light brown return.
42	Maroon return (? siltstone).
43-44	Red-brown very weathered soft sandstone.
45	? Light grey mudstone
46-85	Light brown to slightly pink returns (as slurry), becoming sandy at 57 m. Sequence 46-56 decomposed silstone?- and sandstone from 57 m.
86-90 EOH	Brown samples, weathered schist and gneiss fragments.

Borehole WW11 : Sample Descriptions

Depth (m)	
0-1	Brown, clayey soil.
2-9	Light to light green weathered calcrete with fine to medium grained orange-stained quartz.
10-19	White to pinkish calcrete and silcrete.
19-23	Moderately hard, poorly sorted, calcareous 'granular' sandstone, weakly cemented.
24	Dark red hard shale.
25-34	Pink, powdered return with large cuttings of mainly light grey fine grained sandstone, reddish-orange speckling.
35-43	Slightly greyish, silty return of laminated, micaceous light grey silstone with red speckling, soft but becoming coarser and more sandy at 38.
44-60	~~That~~ brown-maroon returns of weathered micaceous schist in brown silty returns.

Borehole WW12 : Sample descriptions

Depth (m)	
0-6	Pale green, poorly sorted fine to coarse grained unconsolidated, sub-rounded quartz sand.
7-12	Pale green, weathered, soft calcrete with sub-rounded orange (iron) stained quartz grains (up to 1 cm).
13-18	Light to slightly yellow fresh calcrete. Light grey calcareous matrix with abundant, sub-rounded orange (iron) stained quartz.
19-20	Coarse, light orange returns with orange (iron) stained quartz and organe-brown silcrete.
21	White return (pale green wet) of light grey fine-medium grained sandstone of clear quartz in calcareous matrix.
22-26	Pale green (green wet) sandstone of clear, mainly medium grained quartz in calcareous matrix with ? chlorite.
27-	Pink-yellow (brown wet) decomposed fine to coarse grained sandstone with brown iron-staining. Clear quartz grains.
28-30	Light yellow (buff wet) fine to coarse grained sandstone predominantly sub-angular clear to greyish quartz with iron-staining, in calcareous matrix.
31-33	Light pink (brownish wet) fine to coarse grained quartz (clear and with pink staining), granular texture, loosely cemented in calcareous matrix.
34	Light brown (chocolate brown wet) decomposed calcareous sandstone with abundant hard, dark brown ironstone.
35-39	Light brown (greyish wet) return of hard light grey sandstone with calcareous matrix.
40-43	Light grey mudstone in light brown slurry return (damp at 39 m, water struck at 40 m).
44-46	Orange-brown sandy return.
47-48	Light grey to purplish mudstone.
49-51	Brown, soft weathered flaggy micaceous siltstone.
52-56	Coarser returns, angular ≈ 1 cm, brown-yellow. Maroon schist at 54 m, iron stained quartz present.
57-60 EOH	Maroon returns of red brown-black mica schist.

Borehole WW13 - Sample Descriptions

Depth (m)	
0-5	Buff-orange, poorly sorted, fine to coarse grained, unconsolidated, sub-rounded quartz sand. Slightly greenish at 4 - 5 m.
6-10	Light green, soft decomposed calcrete with orange (iron) stained quartz.
11-16	Light yellow to white or slightly greenish, calcrete with iron stained, rounded quarz.
17	Buff return with light grey, hard silcrete.
18-21	Light grey returns, calcrete.
22-30	Pinkish returns, coarse, angular silcrete bands in calcrete.
31	Pinkish mudstone.
32	Light-dark brown mudstone.
33-35	Brick-red mudstone.
36	Light-dark grey mudstone.
37-40	Grey-yellow brown mudstone.
41-45	Grey-pink mudstone.
46-51	Dark grey mudstone.
52-60	Grey, finer returns mudstone. Water struck at 58 m.
61-$\frac{72}{\text{EOH}}$	Moderately fresh (brown neath surfaces), ? dolerite (possibly fractured).

Borehole WW14 : Sample Descriptions

Depth (m)	
0-6	Clayey, unconsolidated, poorly sorted fine to coarse grained, iron-stained, sub-rounded quartz sands.
7-	Light green, very weathered, soft light grey fine to coarse grained calcareous sandstone.
8-13	White to light yellow or grey returns of soft, light grey fine to coarse grained calcareous sandstone with grey quartz.
14	Light brown-yellow return of light grey mudstone with very weathered brown, micaceous silstone.
15-19	Pale returns of light grey calcareous sandstone with yellow-brown speckling and grey quartz, coarser at 18, 19 m.
20	White return of slightly micaceous light grey sandstone and few light grey mudstone framents.
21-31	Buff to light yellow returns of poorly sorted, calcareous sandstone with grey quartz and moderately soft.
32	As 21-31 with dark red crystalline fragments in brown return.
33	As 21-31 grey return with brown, very weathered sandstone.
34-35	Brown-yellow return of light grey mudstone and brown very soft micaceous siltstone.
36-37	Brownish return, flatter returns of micaceous light grey siltstone, moderately soft.
38-40	As 36-37 in pinkish-brown return, very weahtered at 38, 39 m and abundant grey quartz at 40 m.
41	Grey sand return of grey sandstone with abundant grey quartz.
42-43	As 41 with some black mudstone and weathered brown micaceous silstone.
44-45	As 41 with micaceous siltstone.
46	White return, slightly coarser light grey sandstone.
47-53	Brown to pinkish returns with micaceous siltstone, laminated (slurry returns from 49 m, drier more sandy at 51-53 m).
54-55	Light to dark grey mudstone in pink return.
56-72	Slurried returns with , flat returns weathered brown, micaceous siltstone from 65.
73-75	Light yellow, sand returns (as 56-72).

Depth (m)

76-92	Reddish-grey returns of pinkish siltstone with iron stained quartz (contamination ?), black carbonaceous mudstone at 90 m and light grey mudstone at 91 m.
93-94	Greyer returns, predominantly fine to coarse grained felspathic sandstone with grey quartz.
95-96	Dark grey to maroon return (rust coloured water) with maroon-grey mudstone in grey quartz-felspathic sandstone.
97-101	Grey sand return, quartz-felspathic sandstone.
102	As 95-96.
103-104	Light grey as 97-101 m.
105-108 EOH	Maroon-grey returns with hard maroon mudstone in quartz-felspathic sandstone.

Borehole WW15 : Sample Descriptions

Depth (m)	
0-21	White mainly coarse angular returns of calcrete, becoming reddish with silcrete from 17 m.
22-24	Light orange sand returns of light grey, weakly cemented mainly medium grained clear quartz with red iron staining.
25-26	Brown-orange coarser grained poorly sorted sand return with moderately soft light grey sandstone with abundant bronw iron staining.
27	Fine grained orange return of light grey mudstone.
28-29	Fine grained, pinkish return with mixed purplish fine grained sandstone, soft and light grey/brown mudstone. Sandier return at 29 m.
30-33	Light grey to buff return of light grey, weakly cemented sandstone.
34-35	Grey-olive grey sand return, predominantly medium grained ? sandstone, sub-rounded, abundant felspar.
36	Light brown clayey sand return.
37-38	Light grey mudstone in very fine powdered return.
39	Yellowish sand return? light grey sandstone.
40	Light grey sand return.
41-61	[Clayey returns, slurried 54-61 m. Identification difficult, probably sandstone - siltstone].
62	Brown, flaggy, micaceous siltstone.
63-67	Sand returns, slightly yellow, quartz-felspathic sandstone.
68	Maroon sand return of brown and maroon micaceous siltstone.
69-77	Yellowish brown, coarse grained quartz-felspathic sandstone.
78	Buff-light yellow, predominantly coarse grained grey quartz, sub-rounded with grey mudstone.
79	As 69-77.
80-100	Light grey (buff-yellow wet) as 69-77, becoming greyer from 85 m with black shale fragments at 85 m and dark grey micaceous siltstone at 90 m.
101	Sand return, grey fresh hornblende gneiss.
102 / EOH	Dark grey sand return, hornblende gneiss chippings.

APPENDIX B

Pumping Test Data Plots

B1 Pumping Test Results: W8/E3 [2981]

Well W8/E3 was drilled by the Tona Earth REsources Association (Pty) Ltd for the Francistown - Nata road construction. It is situated along the camp access road 2 km from the main road.

The site consists of W8/E3 (2981) and two observation wells, E1(2979) 2.4 m east and E7, 2.4 m west (both drilled by SWECO). All three wells are believed to be 70 m deep. An additional well E2 (2980) drilled 570 m west by SWECO, and used as part of their testing programme, is now infilled.

A long-term test was carried out by SWECO in 1976 at the following rates: 11.3 l/s (976 m^3/d) for 25 days with a short recovery followed by 13.5 l/s (1166 m^3/d) for 5 days and then 17.4 l/s (1503 m^3/d) for 64 days. A plot of their data is given in Figure B.1.1 (from SWECO 1976).

A series of short tests were undertaken as part of the 1984 testing programme (see Table 2) to confirm the earlier tests by SWECO.

Step Test

Yield-drawdown data up to a test rate of 26 l/s (2246 m^3/d) are plotted in Figure 3. A reduction in specific capacity of 22%, from 3.62 to 2.81 l/s/m, occurred over the range of test rates of 8 to 26 l/s.

Fine sand was pumped from the well during the third and 4th steps of the test, i.e. at rates higher than tested previously. Sand was present in the well below 52 m (test pump depth was 46 m) prior to the test and 49 m after the tests. Some development of the well took place at the higher pumping rates. The slightly smaller drawdowns given by SWECO for the same rate of pumping may partly reflect development but are more likely to be due to the differences in rest water levels used to compute drawdowns.

Attempts to clean the well with the drilling rig were stopped when water emerged at the surface from well E7 since there was a risk of caving. It would be desirable to clean the well by bailing but an acceptable sand content and reduced pump wear can be achieved using a continuous operating regime and a pump depth of 30 - 36 m to meet the refinery demands.

Pumping water level predictions at 8 l/s and 16 l/s are approximately 17 and 20 m respectively. The well efficiency at 8 l/s is 87%. Each well is now capped.

Aquifer Test

Analysis of the constant rate test data is limited by the very close proximity of each observation well and fluctuations produced by rapid recovery with small changes in pumping rate.

Wells E7 and E3 show a similar drawdown response indicating close connection between these wells. A much smaller drawdown was recorded even though E1 is of similar depth and spacing to E7. The data from E1 are more suitable for conventional analysis. However, this well may not be representative or a narrow fracture zone (rather than a coarser facies of the Ntane Sandstone suggested by SWECO) occurs through W8/E3 and E7. If this is so, then it may be difficult to reproduce the same yield as W8/E3 by drilling a new standby well at this location. Well E7 could perhaps be reamed out to form a standby well but a higher yield will not be obtained by pumping W8/E3 and E7 together.

Estimates of aquifer parameters are given in Table B.1. Recovery data suggest a high transmissivity (T) of about 3000 m^2d and the late drawdown data at well E1 gives a similar value of 2775 m^2d. However, the form of the data plots suggests leaky confined conditions and these values reflect leakage rather than a high transmissivity. Early data (less than 10 minutes elapsed time) from well E1 gives a lower, probably more representative transmissivity value of 400 to 450 m^2d from the Chow or Theis methods. However, the high storage co-efficient values of about 0.10 are incompatible with this phase of the drawdown or anticipated aquifer conditions; a value of 10^{-3} to 10^{-4} would be more likely.

Sua. Sweco data

No.	% Reported yields l/s/m	l/s			No	
* 604	1.0	·6	TM	0	5	all to w of road
* 616	0.94	3.8	TM/MA 13	<1	5	
* ~~600~~ 1239	0.33	4.2	TM/MA 18	1-2	4	
1756	?	2.5	Ca + Gn	>2.3	~~7~~4	(<2.5)
1872	?	1.2	Sch	3-4	1	
E 2008		0.1	Sch	4-5	1	604-1239
* 2016		1.1	TM/MA 25	5-6	1	
E 2017		2.5	MA/Gn			
(*) 2028		0.6	TM/MA 28			
E 2037		0 Dry	MA/Gn *			Run these @ Dukene 10 wells *
* 2117		1.9	TM/MA 19	MA-kau		(9 tests)
* 2146		2.5	TM/MA 26		0	-
* 2157		2.5	TM/MA 21	23/33 0-1	2	
* 2165		1.0	TM/MA 33	25/19 1.1-2	2	
S 3056		-	Gn *	26/21 2.1-3	2	
E 3066		0 Dry	Gn *	13 3.1-4	1	616
SE 3067		0.8	TM/MA 103	8 4.1-5	1	1239
S 3071		0	Gn *	0 5.1-6	1	604
E 3074		N/R	D/Gn *			
S 3087		0	D/Gn *			
W 3098	(0.0027)	0.16	TM/MA 51			
W 3099		0	(TM 48)			
W 3106	(0.014)	2.0	TM/?MA			
SE 3107		N/R	TM/MA 113/D			
* 3112		N/R	TM + Do			
E 2982 (W/EU)			MA/D			
E 1662		0.5	Gn			
	Σ 27					

8 in W.

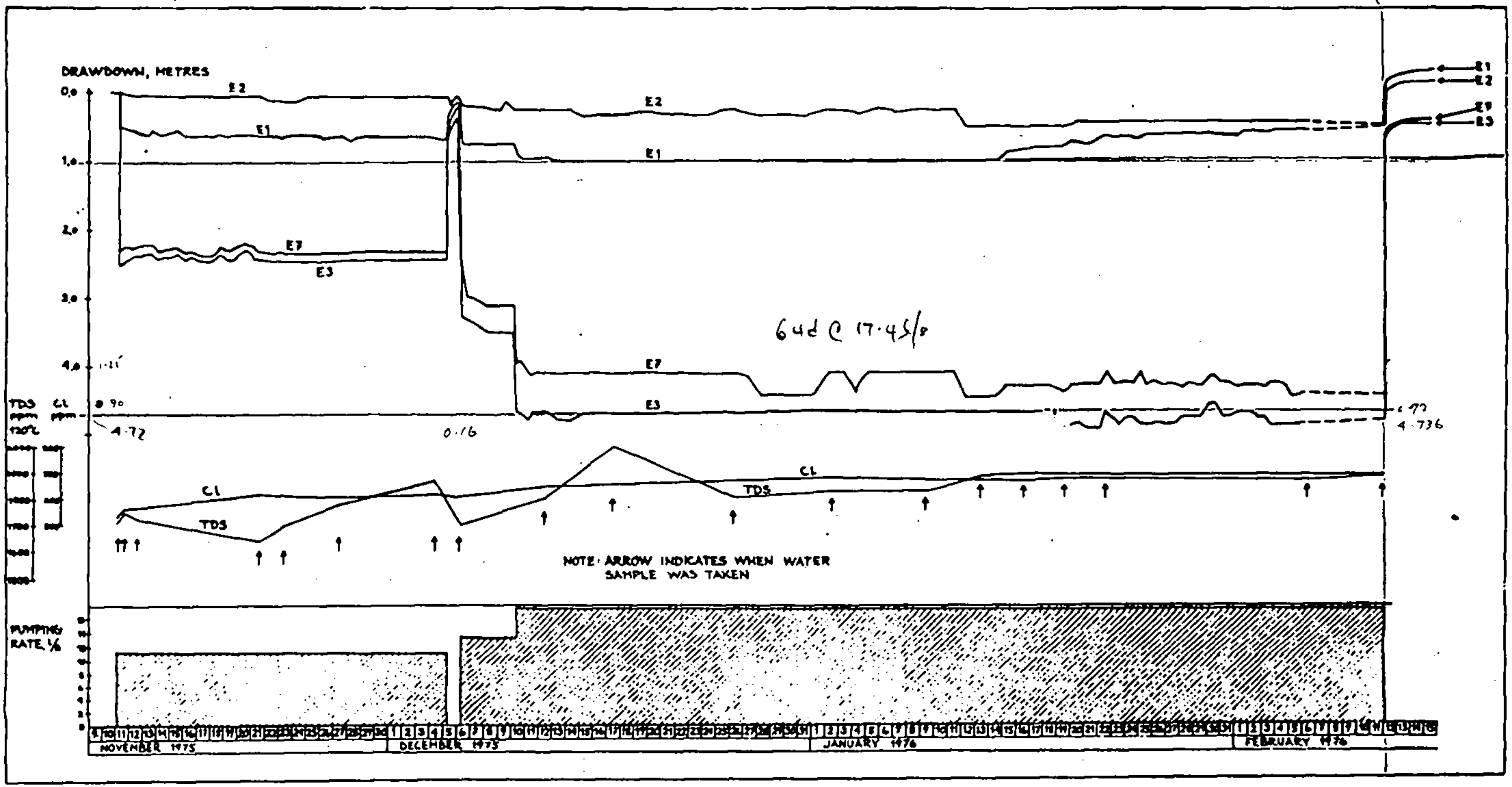


Figure B 1.1

Long term test pumping in well-field 8 borehole E3. Drawdown, water quality and pumping rate

SWECO May 1976

Table B.1.1

W8/E3 (2981): PUMPING TEST RESULTS

Well	Method	Transmissivity m^2d		Storativity
W8/E3 (Pumped)	Jacob	350		Step 1. Data less than 10 minutes.
		565		Constant Rate, minutes
	" recovery	3000		
E7	Jacob	935		Step 1 Early data
		1500		Constant Rate data
	" recovery	3000		
E1	Jacob	580		Step 1 Early data
		515	0.08	Constant Rate "
	Chow	410	0.11	Constant Rate "
	Jacob	2775		Constant Rate Late data
	Theis	435	0.10	Constant Rate Early data
	Jacob recovery	3275		

GEOLOGICAL SURVEY OF BOTSWANA

DUKWE

QUARTER DEG

"Bele 1 Kcl.
1:125000