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INSTITUTE of
HYDROLOGY

SUA PAN PROJECT

BRINE SUPPLY

INDUSTRIAL/FRESH WATER SUPPLIES

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SUA PAN PROJECT

A. BRINE SUPPLY

Introduction

During February and March 1983 pumping tests were carried out on two brine test wells W1 and W2 at the western end of Sua Spit and on the northern edge of Sua Pan. Simple production tests were also carried out on two wells SP2 and SP3 adjacent to the trial evaporation lagoons.

It was necessary to repeat the tests at well W1 due to continued mechanical difficulties with the engine, which prevented the planned long-term test. The detailed analysis of the data from the tests is being undertaken by WLPU and to assist their analysis we have examined the data from one such test.

The design of well W1 allows only limited information to be gained from the pumping tests concerning the characteristics and response of the aquifer system. We describe briefly the sedimentary sequence and the well design criteria applicable to the type of sequence. We then discuss the test data in relation to the design of well W1 and outline some recommendations regarding future test sites to gain a better understanding of the aquifer conditions for the design of the proposed wellfield.

The sedimentary sequence at well W2 proved to be very different to that indicated in the area of this site from earlier investigations by others. The aquifer conditions at well W2 are unsuitable for brine extraction due to the occurrence of cemented sandstones. Since the distribution of these sandstones is particularly important to the scheme we present some recommendations for further studies to determine the extent of favourable aquifer conditions for the wellfield location and the potential of the brine resources.

General Hydrogeology

Previous drilling by others across Sua Pan indicates a multi-layered sequence of clays, silts and sands on an uneven surface of Karroo sandstones. The sequence has been divided into an upper, predominantly silt sequence up to

30 m thick and a lower, mainly sand sequence up to 70 m thick. Variably cemented sandstones together with chalcedony bands are distributed to a varying extent within the sequence.

The top few metres of the underlying sandstones are locally weathered and fractured, although the fractures are at least partly infilled with secondary material. The sandstones are extensively faulted and cut by dolerite dykes.

The sedimentary sequence which is probably in overall hydraulic continuity, is almost completely saturated with a concentrated brine and has properties that vary both laterally and vertically. Although the lower part of the sequence appears to form the main aquifer, particular horizons within the sequence, which are better sorted, slightly coarser, contain less clay or silt or are less consolidated, will contribute the major proportion of the yield from a particular well. The resistance of the least permeable horizons to vertical flow will determine whether the sequence more closely resembles a confined or unconfined aquifer. The distribution and occurrence of such horizons will not only affect the volume released from aquifer storage but also the choice of well depth and the position or arrangement of screen(s), although it is not usually possible to predict where such horizons will occur at a given location.

The design of wells W2, SP2 and SP3 follows that normally used for isotropic, water table aquifer conditions where the lower one-third to one-half of the saturated thickness is screened. The upper cased section is used to house the pump; placing the pump within the screen or lowering water levels below the top of the screen can result in sand ingress, a reduction in yield (or increased head) and the risk of corrosion/incrustation of the screen. With this design the available drawdown is the difference between the rest water level and the top of the pump. This will partly determine the well yield, the number of wells needed to meet the total abstraction requirement and the volume of aquifer storage that can be exploited.

A different design was chosen for well W1. At this site the lower part of the sequence was entirely screened with additional screens placed in the upper silt part of the sequence. The pump was set within the lower screen. A stratified aquifer, such as that at Sua Pan, would normally require a well design whereby screens are set against the lower, most permeable parts of the sequence with the pump set in one of the intervening cased sections and the uppermost screen placed below the lowest anticipated pumping water level. The screen positions are selected from the strata log usually in conjunction with geophysical logging. The available drawdown is not controlled by the pump position but by the top of the uppermost screen.

Appropriate well designs must take into account the type of aquifer and its properties together with hydraulic and other criteria. Furthermore, the design of a test well to obtain information for predictions of long term aquifer response is likely to differ from one designed to obtain the maximum yield from the aquifer. For the particular hydrogeological conditions at Sua Pan a test well, and its associated piezometers, should be designed to enable the following information on the aquifer conditions to be obtained:

- the occurrence, relative contribution and properties of the various permeable horizons; minor sedimentalogical differences within these horizons in both the upper and lower parts of the sequence could determine which part of the sequence has the highest transmissivity.

- the ability of the sequence, particularly the upper part, to release water from storage. This will depend largely on the hydraulic connection within the sequence, especially the occurrence and effects of clays, cemented sandstones and chalcedony layers on vertical leakage.

This information will enable the relevant design criteria to be selected for the production wells and subsequently for the wellfield.

Brine Test Well W1

Well W1 is 51 m deep, fully penetrates the sedimentary sequence and has three screened intervals. Twenty-three piezometers were drilled in three arrays at different depths at distances of 7 to 200 m from the test well. Details of the sequence, test well and piezometers are given in Appendix A. A general summary of the site conditions is as follows:

Screen position	Piezometer group (depth)	Sequence
1 m	1 m	0-3 m Sand (with water level at about 1 m)
3-9 m, upper screen (against silt horizons)		3-30 m Silt, soft sandstone and sands. About 87% silts, 17% sands
15-21 m, middle screen	15-20 m	
27-51 m, lower screen comprising 16 m against sands and 8 m against silts (part of sandstones)	50 m	30-50 m Sand with sandstones and silts About 22% silts, 78% sands
		50 m+ Sandstone

The upper screen has been placed too high and was dewatered at the pumping rates used for the tests. More importantly, the screen positions also allow water to be abstracted from both the upper and lower parts of the sequence causing horizontal flow induced by pumping to dominate vertical leakage. Consequently, the interconnection within the sequence cannot be properly established from the test data.

Erroneously high values for the aquifer characteristics would be obtained if the pumping rate were to be used for the appropriate calculations. If the pumping rate is proportioned according to the lengths of the middle and lower screens, values of 110 m^2/d and 3×10^{-4} for transmissivity (T) and storage coefficient (S) are obtained for both the upper and lower piezometers at P5 (50 m NW of the test well). However, these results are inconsistent with the strata log which suggests that the lower part of the sequence should have a higher transmissivity than the upper part of the sequence. It was not possible to employ higher pumping rates to dewater the middle screen to thereby indicate the contribution from the lower screened horizons and, due to the absence of a log at wells SP2 and SP3, the results from these sites cannot be used to assist the analysis of data from well W1.

Only piezometer P5/1L was set within the main aquifer sequence. The late date suggests leakage occurs but cannot be reliably analysed for the above reasons. Water levels in the shallowest piezometers (1 m depth) were unaffected by pumping during the test period indicating limited connection between the water table in the top sands and the underlying sequence. This would suggest that perched aquifers may develop a result of abstraction reducing the amount of storage that can be developed.

Drawdowns in the upper piezometers (15 to 25 m depth), all within the upper silt sequence, are relatively large and conform to a Theis confined type curve. This is considered to be due to the well design rather than vertical leakage effects. The lower piezometers (50 m depth) were unaffected by pumping during the test period and appear to be placed within silts separating the main aquifer from the sandstones. Piezometer P11/1L, only 7 m from the test well and apparently set within the sandstones, did not respond to pumping suggesting little or no connection between the main aquifer and the underlying sandstones.

In effect, well W1 is of a design that, whilst increasing the yield from the well, does not enable a reliable, full assessment of the aquifer behaviour for predictive purposes. Nevertheless, the data from site W1 indicate the following aquifer conditions: a leaky, confined aquifer (with storage release from the overlying silts) a storage coefficient of (S) about 3×10^{-4} and a transmissivity (T) of 100 to 150 m^2/d. These values are lower than those obtained from earlier investigations on the nearby well R2[1], but have been used for the initial design of the wellfield.

Recommendations for Brine Test Wells

It has not been possible to determine whether the aquifer is semi-confined or semi-unconfined. Since the water table was unaffected by pumping it is more likely that the aquifer is semi-confined and since the hydraulic resistance of the clays, cemented sandstone or chalcedony layers is likely to be high there may be more than one semi-confined aquifer present. Analysis of test data under these conditions is complex but several analytical methods are now available to determine the hydraulic properties of the aquifer. The future test well and the number and depth of piezometers should be planned carefully so as to allow the most appropriate methods to be applied. In outline we would recommend the following:

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(1) Jacob method	:	T	395 m^2/d	S	.001	Permeability	18.8 m/d
De Glee "	:	T	333 "	S	.001	"	15.8 "

Aquifer thickness 21 m, aquitard thickness 31 m.

*perform a double pumping test in the upper and in the lower parts of the sequence with complete recovery between each test. This is best carried out as paired test wells, say 10 to 15 m apart, one pentrating the upper silts only and the other with screen(s) set only in the lower parts of the sequence. Each test well should be properly developed and subject to a step-drawdown test to assist in planning the aquifer test.

*a line of four double piezometers between 20 and 100 m from the deep test well. The upper set should have a short screened interval half the length of the upper test well screen with the piezometer screen midpoint at a depth equal to the midpoint of the upper test well screen (subject to geophysical logging results). These would be completely isolated from the lower set having the same arrangement but in relation to the lower test well screen. Each test well would provide an additional observation point during the test on the other well. We would also suggest three drive-point piezometers with 0.5 m screened tips penetrating about 0.5 to 1 m below the water table. The total number of observation points would then be 13, including the test wells.

This site arrangement allows application of the Bruggeman (1966) method and the Neuman and Witherspoon (1969) method, which provides information on the overlying aquitard properties with greater reliability than the type-curve solutions. The analysis is simplified by continuing the tests until approximate steady state is achieved. Numerical radial flow models could also be applied, although these do not always provide unique solutions.

Brine Test Well W2

Well W2 is situated about 1 km from existing site R39, which indicated a thick sequence of sediments 101.5 m thick of which the lower 72.5 m were considered a potential aquifer. A yield could not be obtained from R39 test well, which was considered to be due to lack of development or wall-smear. A cored hole drilled to 91 m at site W2 encountered hard, greenish, generally silty cemented and fractured sandstones (with thin intervining silty fine sands) below a depth of 5 m. A very hard, grey sandstone at 77.75 m was taken as the base of the potential aquifer sequence and the test well W2 was drilled subsequently to 72 m with the lower 39 m screened. Water was struck at 5 m and the well was initially flowing.

The first step of the production test at about 1.38 l/s produced drawdowns in well W2 of m after 4 hours. Only the lower piezometers responded to pumping. A transmissivity of about 3 m^2/d was computed from the test results.

The strata differ considerably from those reported at R39, as well as W1, by the extensive occurrence of sandstones. This would account for the low transmissivity, which is also similar to results from the exploratory drilling in the Ntane (Cave) sandstone to the east. The results must cast some doubts on the log interpretations of the earlier drilling unless the strata at well W2 are localised or relate to faulting. Examination of the log descriptions from the earlier investigations suggest that sandstones may be more common in the northern part of Sua Pan. This area includes the greatest thickness of deposits indicated by the earlier drilling.

Recommendations for Further Investigation

Since doubts have been raised over the reliability of the results from earlier investigations, the area of potential aquifer and exploitable resources may not be so extensive as previously indicated. Further investigations are required to establish the aquifer extent and we would recommend the following studies:

*The distribution of sediments where thick sandstones are absent and topographic variation in the base of the sedimentary sequence. Surface geophysical methods would be applicable but we would suggest that exploratory drilling and logging should be undertaken first. However, regional aeromagnetic and gravity maps are available and should be examined for broad structural patterns. The exploratory holes should be fully penetrating, small diameter holes which should be geophysically logged and fitted with slotted intervals wrapped with synthetic pack material. A record should be kept of penetration rate. Cores and/or drive samples should be obtained where possible and particularly in the lower part of the sequence below 30 m, since it will be essential to obtain as much information on the variation in sediment grain size distribution for the wellfield borehole slot sizes and gravel pack designs. Simple input or other suitable tests should be used at each exploratory hole to provide an indication of transmissivity.

We suggest that firstly one exploratory site is drilled, logged and tested at sites W1, W2 and W3 to provide control points. Secondly, a line of exploratory sites should be constructed at 4 km intervals from W1 to W2 and extending 4 km south of W1 and then four sites at the same separation on a roughly E-W line eastwards from a point 4 km west of site W3. An additional two or three boreholes should be included as infill sites whose locations would be selected from the results of the two lines of exploratory boreholes. The programme would then comprise a total of 15 or 16 exploratory boreholes.

The results of the exploratory drilling would be used to select three sites for the paired test wells described above, which would be located at the particular exploratory site so that this could be incorporated into the test site as one of the pizometers.

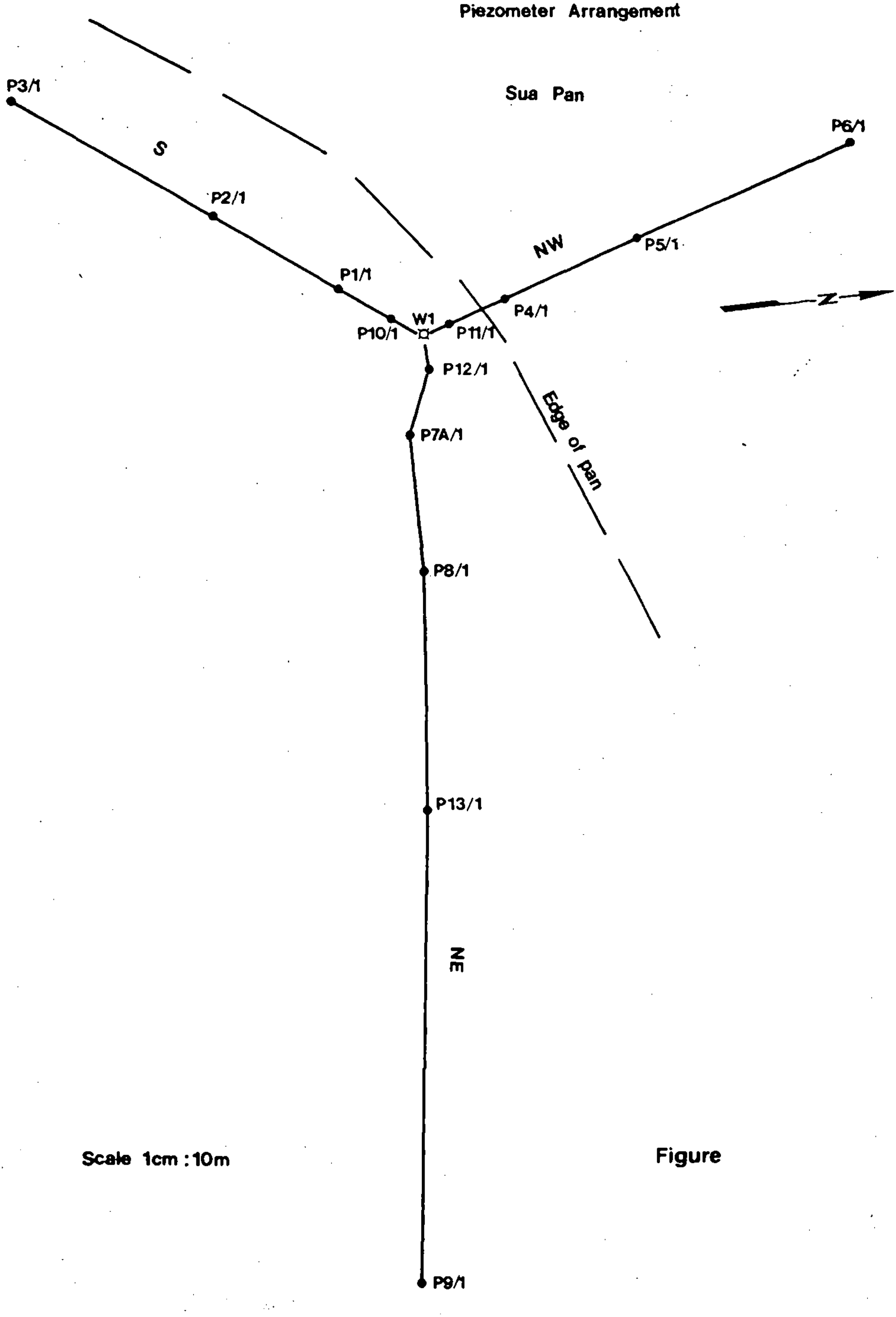
*We recommend that geological information relating to the Sua Pan area is collated to develop a geological history of the pan and underlying deposits, since we believe that this will assist in locating favourable areas for brine extraction. The origin and stratigraphy of the sedimentary sequence, particularly the cemented sandstones, is not yet properly understood. Petrographic analysis of recent cored material from wells W1 and W2 suggests that the basal sandstones may not be the Ntane (Cave) Sandstone, which underlies the area to the east, as originally supposed.

Appendix A

Details of Brine Test Well Site W1

Brine Test Well W1

Piezometer Arrangement



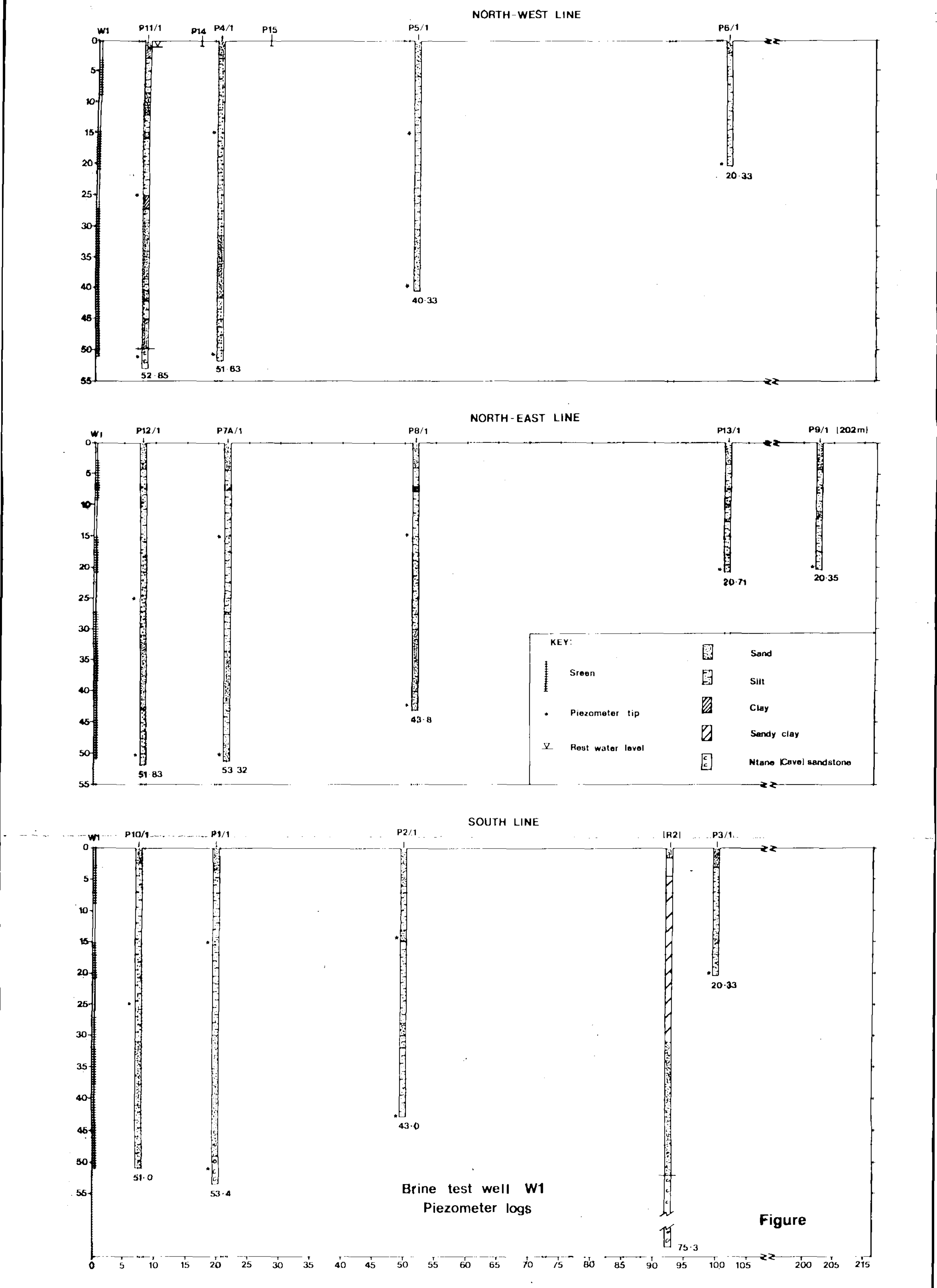
Scale 1cm : 10m

Figure

BRINE TEST SITE W1 : PIEZOMETER DATA

ARRAY	NUMBER	Elevation top of standpipe (m)	Distance from W1 (m)	Depth of tip (m)	Rest Water Level below top standpipe (m)	10/3/83 Elevation (m)	Zone
NORTH-WEST							
	11/1 U	902.74	7	25.0	2.297	900.443	B
	(BH1 SUA) L			51.0	2.531	900.209	D?
	4/1 U	902.15	20	15.0	1.732	900.418	B
	L			50.6	1.505	900.645	D
	5/1 U	902.02	50	15.0	1.598	900.422	B
	L			39.6	1.085	900.935	C
	6/1	902.16	100	20.0	1.577	900.583	B
NORTH-EAST							
	12/1 U	902.94	8	25.0	2.451	900.489	B
	L			50.[illegible]3	2.131	900.809	D
	7A/1 U	902.85	21	15.0	2.496	900.354	B
	L			50.2	3.341	899.509	D?
	8/1 U	902.70	50	14.8	2.342	900.358	B
	L			42.3	2.589	900.111	D?
	13/1	903.39	100	20.4	3.482	899.908	B
	9/1	903.52	200	19.5	(7.642)	(895.878)	B
SOUTH							
	10/1 U	902.78	7.5	25.0	2.274	900.503	B
	L			50.0	2.422	900.358	D
	1/1 U	902.78	20	15.0	2.364	900.416	B
	L			51.4	2.438	900.342	D
	2/1 U	903.06	42	14.84	2.703	900.357	B
	L			42.65	2.459	900.601	D?
	(R2)	-	92	20.00	2.172	- (ref point 0.20m a.g.l.)	
	3/1	902.85	100	(slotted)	2.474	900.376	B
W1					1.562		
	14/NW	-	17	1	1.831	Top of standpipe 1.02 agl	A
	15/NW	-	28	1	1.379	Top of standpipe 1.055 agl	A

Zone:
- A - Surface sands
- B - Upper aquitard
- C - Main aquifer
- D - Lower aquiclude/Cave Sandstone



Brine test well W1
Piezometer logs

Figure

SUA PAN PROJECT

B. INDUSTRIAL AND FRESH WATER SUPPLIES: RESULTS OF DRILLING PROGRAMME

Introduction

The Sua Pan Project will require suitable supplies of water to meet the following requirements:

- a supply for industrial purposes, initially of 8 l/s (700 m^3/d) increasing to 16 l/s (1400 m^3/d) and containing less than 7000 mg/l dissolved solids.

- a small potable supply of about 0.6 l/s (50 m^3/d) for the new township.

The Karroo sedimentary sequence at Dukwe, some 40 km east of the development site at Sua Pan, contains exploitable reserves of good quality groundwater. The same formations extend to Sua Pan and consequently suitable supplies could occur closer to the development site.

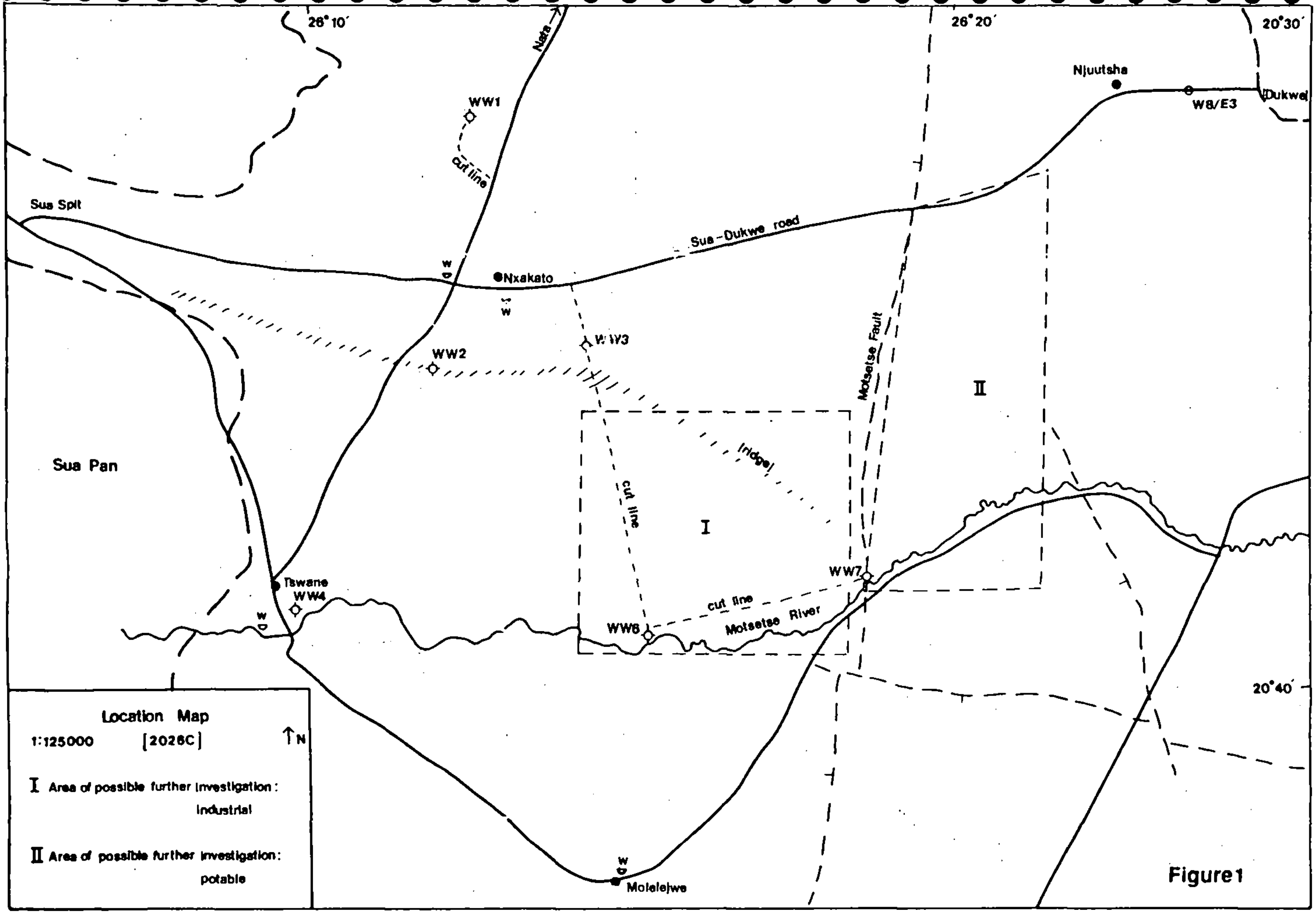
However, the Karroo east of Sua Pan is structurally complex and masked beneath a cover of younger deposits. It has not been previously investigated for groundwater supplies and little hydrogeological information is available.

Our desk study of December 1982 [(1)] brought together the available information from different sources into a broad, regional hydrogeological model. From this model we were able to make proposals for an exploration programme of drilling and testing.

Drilling Strategy

Our conceptual model showed a salinity gradient in the Karroo sequence to the west towards Sua Pan, the direction of regional groundwater flow. Moderately high salinities of 2000 to 5000 mg/l, which would still be acceptable for the

1. *Groundwater Supplies for Sua: Proposals for Drilling Programme. Institute of Hydrology, December 1982.*



26°10'
26°20'
20°30'
20°40'
Nata
Njuutsha
W8/E3
Dukwe
WW1
cut line
Sua Spit
Sua-Dukwe road
Nxakato
W
WW2
WW3
Motsetse Fault
II
Sua Pan
ridge
cut line
I
Tswane
WW4
WW7
cut line
WW6
Motsetse River
Location Map
1:125000 [2026C]
N
I Area of possible further investigation: industrial
II Area of possible further investigation: potable
Molelejwe

Figure 1

industrial water supply, were expected in the Ntane (Cave) Sandstone with the possibility of similar or better quality waters in the deeper Mea Arkose, depending on the distance from fresh water which occurs in this formation at Dukwe.

A drilling strategy was adopted to confirm the predicted water quality in the area closest to the development site. If suitable supplies were not encountered, exploration would then extend eastwards, particularly to locate potable supplies.

The following target areas were chosen for six exploration boreholes to prove the occurrence and quality of groundwater:

- just east of the development site for industrial water supplies, firstly testing the Ntane Sandstone and then the Mea Arkose (borehole WW1).

- a marked topographic feature, that continues into the present Sua Spit for shallow potable supplies (boreholes WW2, WW3).

- along the Motsetse river, a potential source of recharge, firstly for shallow supplies around Tswane, then into deeper formations upstream as far as the Motsetse Fault (boreholes WW4, WW6, WW7).

The locations of these sites are shown in Figure 1 . The drilling and testing programme was undertaken during February and March 1983 and the results are presented in Appendix B, with a summary of each borehole given in Table 1 .

Summary of Groundwater Occurrence and Quality from Drilling Results

The strata sequence after SWECO (1976)[1] and based on lithostratigraphy is given in Table 2 . Geological descriptions are given in our earlier report of December 1982.

Strata sample descriptions for each exploration borehole are given in Appendix B; the down-the-hole (DTH) air-hammer method was used to drill these holes. A stratigraphic interpretation of the samples is given in Table 3 and shown diagrammatically in Figure 2 .

Basement Complex gneisses were encountered at only WW1 and WW3, at 217 and about 125 m depth respectively. Boreholes WW6 and WW7 could not be continued to the Basement Complex due to the risk of hole collapse at the

(1) *From SWECO May 1976 Sua Project: Dukwe New Town*

surface.

The Dwyka sequence was not encountered in any of the boreholes, or at least could not be identified from the strata samples.

Mea Arkose. The Mea Arkose, the main aquifer at Dukwe, was encountered at WW1, 3, 6 and 7, although the full thickness was not penetrated at WW6 or WW7. At WW7 it is at least 35 m thick overlain directly by the Ntane Sandstone, and occurs at a shallow depth, about 38 m but the thickness decreases west of the Mosetse Fault to 16 or 17 m. Westerly throwing faults, associated with the flank of the Dukwe horst structure, give rise to an increase in the depth to the top of the Mea Arkose from 74 m at WW6 to 200 m at WW1. Faults with throws of at least 35m between WW7 and WW3 or WW6 and of about 100m between WW3 and WW1 are indicated.

Only WW6 obtains its supply from the Mea Arkose; no significant increase in supply was observed during drilling in the Mea Arkose at the other sites. However, the supply at WW6 appears to come from near the top of this formation and the supply at WW7 may be derived from the junction of the Mea Arkose and Ntane Sandstone. Potential supplies from the Mea Arkose may be restricted to local zones where the permeability has been enhanced by solution or fracturing, but their extent and even occurrence cannot be predicted at specific locations.

Pumping tests at WW3 and WW6 indicate that the Mea Arkose does not contribute significantly to the yield of these sites and, unfortunately, planned tests of the Mea Arkose at WW1 and WW3 could not be carried out due to drilling problems. Early drawdown and recovery data give transmissivities of 25 to 40 m^2/d at this site (Table 4) but the rate of drawdown increases with time, either due to depletion in storage or a lateral change in transmissivity.

A chemical analysis of a water sample from the Mea Arkose of WW6 is given in Table 5 . This water is very saline with a total dissolved solids content of 16160 mg/l. No change in conductivity was observed whilst drilling through the Mea Arkose.

Tlapana Mudstone. The upper, non-carbonaceous mudstone sequence is similar lithologically to the lower part of the Cave Sandstone, such as at

Serowe. This sequence was encountered at WW1, 3, 4 and 6. The lower, carbonaceous sequence occurs at WW1 and WW3 (and possibly at WW6) and thickens possibly to the north-west from 28m at WW3 to 106m at WW1, where it is particularly carbonaceous. Minor coarser deposits within this sequence seem infrequent.

No increase in yield was observed whilst drilling through the Tlapana mudstones and they do not appear to contain potential aquifer zones.

Ntane (Cave) Sandstone. The Ntane Sandstone is present at all of the sites except the shallow borehole WW4. The thickness varies from about 10 to 20m, increasing in thickness westwards, and are relatively unaffected by faulting.

Water was encountered in the lower part of the Ntane Sandstone at boreholes WW1, 3 and 7 at depths of between 32 and 48m, but not encountered at WW2 or WW6. Although the water strike may be suppressed by drilling, the Ntane Sandstone appears to be confined with a piezometric surface some 5 to 10m above the base of the overlying Kalahari Beds, and with a shallow gradient to the west.

A pumping test was carried out at WW1 when the borehole had penetrated 19m into the underlying Tlapana Mudstone. Early drawdown and recovery data indicate a transmissivity of only 1 m^2/d (Table 4). The drawdown appears to stabilize with continued pumping (this may, however, be due to a decline in pumping rate) giving a specific capacity (yield per unit drawdown) of 4 m^2/d. The saturated aquifer appears to be from 32 to 48m but no increase in the rate of drawdown occurred when pumping water levels declined below 32m.

Similar transmissivities of 1 to 3 m^2/d were obtained from the tests at WW3 and WW 7 and suggest that the Ntane Sandstone forms the main aquifer at these sites, although the aquifer thickness is only 3m. Steady state conditions were not achieved and both show an accelerating rate of drawdown, at the level at which water was struck, suggesting dewatering of the Ntane Sandstone. Breakaway conditions occur at WW3 indicating little or no contribution from the Tlapane Mudstone and Mea Arkose at this site.

Supplies from the Ntane Sandstone have high conductivities of 20,000 to 30,000 micromhos, west of the Motsetse fault. * However, fresh water

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* Analyses were unavailable at the time of reporting from WW1 and 3. They are thought to have a similar composition to WW6, the analysis of which is given in Table 5 .

with a low conductivity of 825 micromhos, was encountered at WW7, just east of the Motsetse Fault and very close to the Motsetse river. Analyses of samples from WW7 taken on encountering water and during the pumping test are given in Table 5 . The concentration rises slightly on drilling but the maximum dissolved solids is 556 mg/l.

Kalahari Beds and Recent deposits. The Kalahari Beds comprise a sequence of calcretes and silcretes, some 20 to 30m thick. The base has a low westerly slope.

Shallow groundwater is present locally in the Kalahari sequence associated with perched aquifers near sources of recharge such as the Motsetse river and local pans. Only WW4 near Tswane encountered groundwater, as a small inflow, in this sequence. The water had a conductivity of 4300 micromhos.

Supplies are obtained from the Kalahari Beds from the few dug wells in the area of investigation. Four dug wells 5m deep 1.5 km downstream of WW5 and adjacent to the Motsetse river obtain small supplies from blocky calcretes, which occur at the surface in this area, and the conductivity of these supplies is 2200 micromhos. A well 18m deep near Nxakato has a conductivity of 3000 micromhos and a standing water level of 12m depth. Whilst the water level is very similar to WW1, the conductivity is much lower. Water was not encountered in the Kalahari Beds to the south of this well at WW2, reflecting the localized occurrence of water in this sequence.

The strong ridge feature at WW2 comprises unconsolidated sands and has a marked band of tall vegetation. This feature is perhaps an offshore bar. Supplies were not obtained in these sands, although an abandoned shallow well is located in the same feature (or an associated strand line) to the east.

No supplies were encountered in the Motsetse river alluvial deposits at WW6 or WW7. They are only a few metres thick at these locations and consist of poorly sorted sands. The presence of shallow groundwater at Molelejwe, some 6km south of WW6, could suggest that recharge from the Motsetse moves south-west after the river crosses the Motsetse Fault.

Discussion of Drilling Programme Results

Drilling targets were selected partly to examine particular geological structures. However, it proved extremely difficult to locate these structures precisely on the ground, if indeed they have a surface expression. Fault blocks are indicated by the drilling results but the boundaries of these blocks are uncertain.

Nonetheless, the reconnaissance drilling programme, together with other field observations, enable us to draw the following broad conclusions regarding groundwater occurrence in the area of investigation.

1. For the most part, groundwater does not occur in the Kalahari Beds away from local sources of recharge and, consequently, although supplies have a moderately low salinity, they have a limited development potential. The ridge feature extending into the present day Sua Spit does not contain shallow groundwater supplies.

2. The Motsetse Fault forms an important boundary between saline groundwater to the west and fresh water to the east. The saline groundwater has concentrations about twice that acceptable for the industrial water supply and is thought to be associated with connate water in the Tlapana Mudstone.

3. Groundwater supplies were only encountered in the Mea Arkose at WW6, but of a salinity unacceptable for direct use. The transmissivity is initially moderately high, from 25 to 40 m^2/d, but decreases with time at WW6. This would suggest a lateral decrease in transmissivity, or a depletion in storage, both of which would limit the long term viability of sustained supplies. Site WW6 was located close to a possible fault and the supply may be localized but an area of similar geology may extend from the ridge feature at WW2 to WW6, as far as the Motsetse Fault.

4. Elsewhere, local supplies of groundwater are present in the Ntane Sandstone but these are also very saline and unacceptable as a direct source of supply. The transmissivity is very low, from 1 to 3 m^2/d and only low pumping rates are possible. The aquifer thickness appears to increase westwards towards WW1. The aquifer is thin in the area of WW7 and the occurrence of potable water at this site could be partly related to the proximity of the Motsetse river.

Recommendations

It must be stressed that the exploratory programme was intended as a reconnaissance of groundwater occurrence and quality in the area east of the development site. The results are tentative and must be supported by further exploration before proceeding to a wellfield design, particularly since the supply must be guaranteed for perhaps 20 or more years in an area of limited groundwater resources in which aquifer conditions are variable and unpredictable.

Industrial Water Supply

The saline water in the Mea Arkose around WW6 and in the Ntane Sandstone from WW3 to WW1 is unsuitable for industrial use without blending from other sources. It would also appear that the yields decline with time due to lateral change in the aquifer characteristics or depletion in storage. The yield from boreholes in the Ntane Sandstone would be determined largely by the available drawdown to the top of the saturated aquifer. Recharge is most unlikely and continuous depletion of the groundwater resources ('groundwater mining') would occur, requiring new boreholes in order to maintain supplies. Monitoring of the initial abstraction would determine the viability of using groundwater from the same sources or source areas for the future increase in demand. The pipeline direction and arrangement should be determined by the likely area(s) where future expansion would take place.

The Mea Arkose at WW6 appears to be the best source of industrial water supply in the area investigated with a blending scheme to obtain an acceptable quality. Development of sustained supplies would require further drilling and testing to determine whether the aquifer characteristics are merely localized or more regional in extent and to assess the degree of confidence in predicting their occurrence. Tentatively we have selected the area south of the ridge passing WW3-WW2 to the Motsetse river extending 8km west of the Motsetse Fault (Figure 1). We would suggest the construction and testing of three boreholes of a pre-production well design in this area, one site having an observation well and a long-term test to determine the storage co-efficient. Each borehole is likely to be 100m deep, and, together with WW3 and WW6, should be geophysically logged.

Assuming that the initial supply consists of an equal blending of saline and fresh water, the saline water contribution would require a wellfield consisting of, say, four boreholes with one extra as standby, each producing 1 l/s (86 m^3/d). Assuming a transmissivity of 25 m^2/d and a low storage co-efficient of 1 x 10^{-5}, the drawdown at 1 km of 2.25m after about 2 years. These predicted drawdowns are based on early test data results. We have strong doubts as to the long-term potential of supplies from the Mea Arkose and one further site with an associated observation well may be sufficient to determine whether the area around WW6 is a potential source of groundwater abstraction for industrial water supplies.

Fresh Water Supply

Fresh water was encountered only at WW7. The availability of suitable supplies is very limited but there are two options in the area of investigation: a shallow supply from the Kalahari Beds or a supply from the Ntane Sandstone east of the Motsetse Fault (and perhaps adjacent to the Motsetse river only).

Limited, shallow groundwater supplies occur close to the Motsetse river near Tswane in blocky calcretes. Widely spaced, large diameter wells not more than 5m deep (about 2m below rest water level) could provide emergency potable supplies for short periods if protected against contamination.

Fresh potable water (indeed about the best quality water in the Dukwe region) was located at WW7 close to the Motsetse river at shallow depth at the Ntane Sandstone/Mea Arkose contact. There is insufficient information to decide whether the same quality of water extends northwards away from the Motsetse river and thiswould need to be determined by further exploration.

The yield-drawdown characteristics at WW7 are restricted by the apparent dewatering of the main water-bearing horizon, although the water quality did not deteriorate to unacceptable levels during the pumping test. This site alone would supply the freshwater requirement for the new township but this must be confirmed by further, long term tests at WW7 because of the change in aquifer characteristics with the duration of pumping. Sustained supplies will only be obtained by ensuring that the pumping water level does not fall below the top of the aquifer (at about 35m at WW7) and this limits the pumping rate. Monitoring water levels during actual production or during a long term test at the required rate of 0.6 l/s (52 m^3/d) should determine whether this particular site can sustain supplies in the long term.

A transmissivity of $3m^2/d$, a conservative storage co-efficient of 1×10^{-5} and an abstraction rate of 0.5 l/s (43 m^3/d) would produce 37m of drawdown at WW7 and 15m at a distance of 1 kilometre after about 2 years. This would exceed the available drawdown, determined largely by the top of the main water-bearing horizon, by a factor or two. Consequently, there is still some doubt as to whether even WW7 can maintain essential potable supplies as an independent source.

In order to utilize the saline water west of the Motsetse Fault, supplies would be required totalling initially 4 l/s (345 m^3/d) from the freshwater source east of the Motsetse Fault for blending purposes. This would require at least eight boreholes. In view of the poor aquifer characteristics of the Ntane Sandstone, the prospect for obtaining and sustaining these supplies is not encouraging.

To determine the viability of a blended supply, using equal supplies from either side of the Motsetse Fault, will require further investigation. The area with potential supplies of water with a low dissolved solids content could occur east of the Motsetse Fault in a strip some 6 kms wide, between the Sua-Dukwe road and the Motsetse river (Figure 1). We would recommend three further exploratory sites in this area 80 to 100m deep, one of which should have an observation well. Drilling a test hole with an observation well first should determine whether the remaining holes should be drilled. Each should be geophysically logged, including WW7.

Combined Industrial/Fresh Water Supply

The use of a blended supply to meet the industrial water requirements depends on obtaining a sustained supply of fresh water. Whilst the potable supply could be met from the area of WW7, subject to further investigation, the poor aquifer characteristics and variability of the Ntane Sandstone would suggest that supplies of suitable water for blending may not be sustained at an acceptable cost. The only alternative, apart from desalination, must be the resources identified at Dukwe, which lie outside the area of investigation.

Site W8/E3 near the Nata/Sua road junction, drilled for the Nata-Francistown road, may provide an alternative supply to blending, subject to other potential requirements at Dukwe. This borehole was tested in 1975 up to a pumping rate of 17.4 l/s (1500 m^3/d) continuously for three months as part of the investigations by SWECO. The supply is obtained from the Ntane Sandstone and only 4m of drawdown was measured at this pumping rate, equivalent to an exceptionally high specific capacity of 376 m^2/d. The conductivity was 2800 micromhos but with a relatively high chloride content of 600 to 700 mg/l (WHO limit about 350 mg/l), which would make this supply less acceptable for potable use. Other wells drilled nearby had yields of only 0.2 to 2 l/s (17 to 173 m^3/d), suggesting that the conditions at W8/E3 are very localized. Consequently, it may be difficult to drill additional boreholes to intersect the particularly favourable conditions that produce the supply at this location, which are believed to be due to the intersection of a north-south fault with coarser-grained horizons in the Ntane Sandstone. This site is blocked and a new hole would have to be drilled very close to W8/E3 to obtain the same results. Assuming that this was possible then this site could provide both the industrial and potable water requirements from a single source with greater reliability and at lower cost than a blended supply.

Table 1

SUA PAN PROJECT

PLANT/FRESH WATER SUPPLIES

SITE SUMMARY

Borehole Number (prefix WW)

	1	2	3	4	6	7
Map Sheet (1:50000) :	2026 C1	2026 C1	2026 C1	2026 C1	2026 C2	2026 C2
Grid reference E :	417500	417000	421600	435000	422750	428500
(UTM Grid) N :	7729200	7723500	7740000	7716500	7716000	7717650
Elevation m (SA) :	915	925	930	910	928	940 937
Total depth (m) :	224	54	145	25	82	73
Depth water struck (m) :	32	Dry	48	Seepage	51	35
Rest water level (m) :	12	-	21	6.5	19	20
Casing (150mm) (m) :	18-72	-	0-6	-	0-78	0-39
slotted :	-	-	-	-	74-78	35-39
Date completed	16.2.83.	8.2.83.	11.2.83.	17.2.83.	4.3.83.	7.3.83.
Status	Capped	Abandoned	Capped	Abandoned	Capped	Capped
Electrical conductivity (μmhos/cm)	26000	(21400)	28000	4300	20000	820
Water sample	✓	-	-	✓	✓	✓
Pumping test	11.2.83. (upper 67m)	-	12.2.83.	-	5.3.83. 12.3.83.	11.3.83.

Geological Succession

Alluvium				Recent
Calcretes and Silcretes				
		EROSION FAULTING?		
Dolerite Intrus~~t~~ions				Post-Karroo Intrusions
Ntane Sandstone			Stormberg series	
		EROSION FAULTING		
Tlapana Mudstone	Non-carbonaceous		Beaufort	
	Carbonaceous		Upper Ecca	
Mea Arkose			Middle Ecca	Karroo Supergroup
		EROSION UPLIFT		
Dukwe Mudstone			Upper Dwyka?	
Dukwe Formation			Lower Dwkya	
		MAJOR HIATUS		
Mosetse River Gneiss				Precambrian Complex

Borehole logs

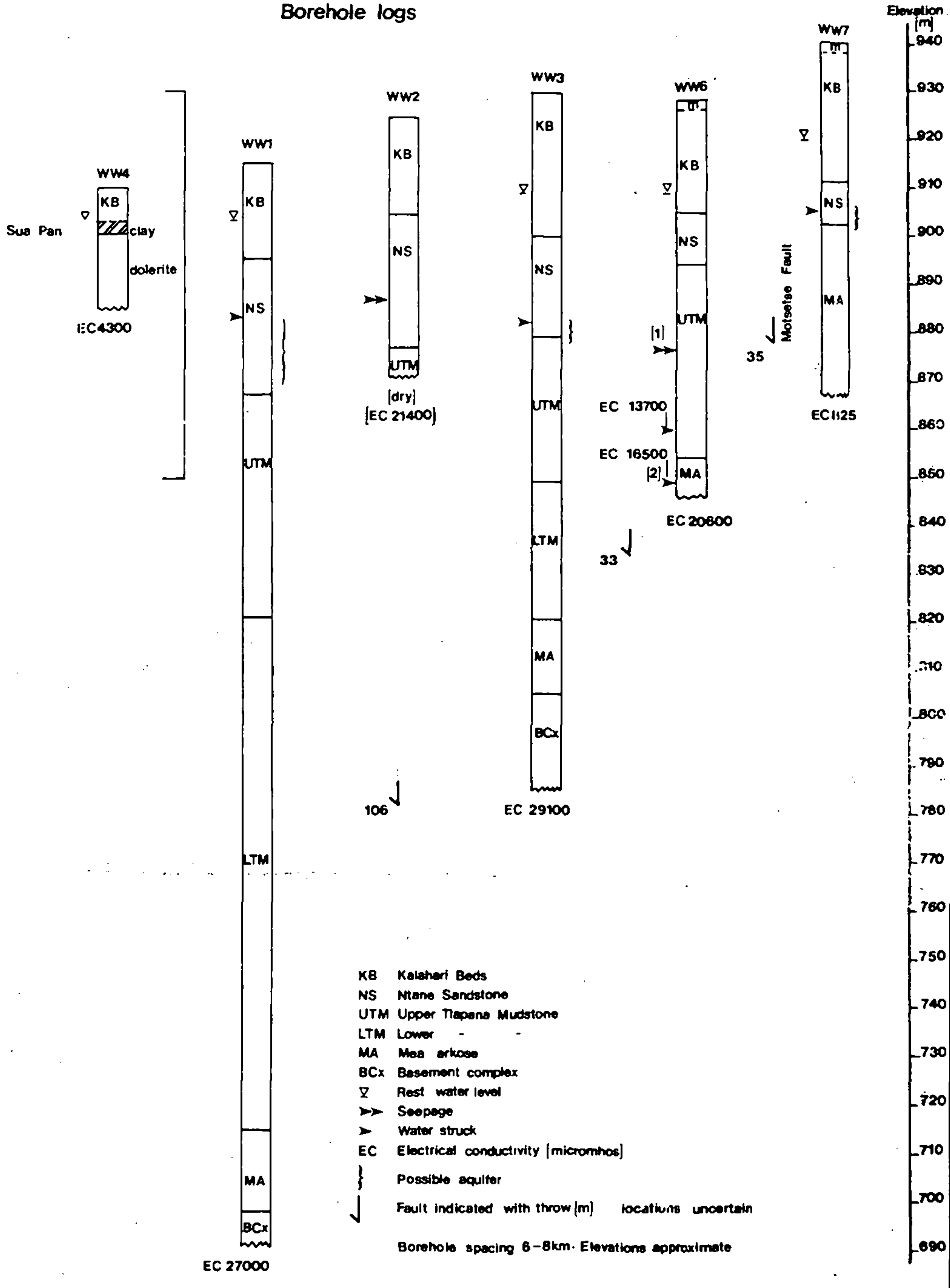


Figure 2

Table 3

SUA PAN PROJECT

PLANT/FRESH WATER SUPPLIES

SUMMARY GEOLOGY

Borehole Number (prefix WW)

	1	2	3	4	6	7
Topsoil	0 - 1	0 - 2	0 - 2	-	0 - 3	0 - 3
Alluvium	-	-	-	-		
Calcrete and Silcrete (Kalahari Beds)	1 - 20	2 - 21	2 - 30	0-7	3 - 23	4 - 29
Cave (Ntane)Sandstone	20-65(?)	21-48(?)	30-53	*	23-34(?)	29-38
Upper Tlapana Mudstone	65-94	48-54+	53-81	-	34-74	-
Lower Tlapana Mudstone	94-200	-	81-109	-	-	-
Mea Arkose	200-217	-	109-125(?)	-	74-82+	38-73+
Basement Complex	217+	-	125+	-	-	-

* Lacustrine clays 7 to 9m, dolerite 9 to 25m+

SUA PAN PROJECT

PLANT/FRESH WATER SUPPLIES

SUMMARY OF PUMPING TEST RESULTS

Borehole Number	Type of test	Duration (mins)	Pumping Rate (1/s)(m^3/d)	Drawdown	Specific Capacity (m^2/d)	Transmissivity (m^2/d)
WW1	Step (2)	180	1.14 (98)	24(t100)	4	
	Recovery					1 (approx)
WW2	-					
WW3	Step (2)	80	1.53 (132)	15 (t50)	8	3
		110	2.6 (225) to 1.27 (110)	67 (t100)	2.5	(.8)
WW4	-					
WW6	Step (4)	240 (total)	1.75 (151)	1.8(t30)	84	40
			4.46 (385)	7.2 (")	53	-
			8.4 (726)	17.8(")	41	-
			16.1 (1391)	38.4(")	36	-
	Constant	1060	4.03 (348)	6.3(t30)	55	25 (t<60)
				20 (t1060)	17	
	Recovery					33 (early data)
WW7	Constant	440	1.5 (130)	12.5(t30)	10	3 (early t<60)
				34.3(t440)	4	1 (late t<60)
	Recovery					10 (late data)

Borehole WW1 tested when borehole depth 67m.

t = time in minutes

SUA PAN PROJECT

GROUNDWATER ANALYSES

	WW6 5.3.83.	WW7 5.3.83.	WW7 11.3.83.	E3 [1] 20.2.76
Total dissolved solids (mg/l)	16160	372	556	1604
Electrical Conductivity (micromhos)	20600	630	825	-
Chloride (mg/l)	7008	6.5	7.0	735
Sulphate (")	1728	5	8	161
Bicarbonate (")				655
Total Hardness (as $CaCo_3$) (mg/l)	304	178	230	
Nitrate (")	.04	.10	.04	(<5)
Fluoride (")	3.84	.5	.76	.7
Magnesium (")	62	35	13.1	54
pH	7.65	7.55	7.25	-

[1] From SWECO May 1976 Sua Project: Dukwe New Town

Appendix B

Details of Exploration Boreholes

SUA PAN PROJECT

PLANT/FRESH WATER SUPPLIES

SITE LOCATIONS

Borehole Number	Location Description
WW1	14 km E along road to Dukwe from BP Camp then 2.2km N to cut line and 2.3 km W along cut line (approximately 1 km W then 1.3 km N)
WW2	14 km E along road to Dukwe from BP Camp then 2 km S then about 800m east along cut line into prominent line of high trees.
WW3	18km E along road to Dukwe from BP Camp then 1.5km S along cut line towards WW6.
WW4	17km S of BP Camp along Tswane road then 1km E along track 300m before Motsetse river.
WW6	18km E along road to Dukwe from BP Camp then 10km S along cut line to 100m before Motsetse river.
WW7	As WW6. 7km E along cut line 500m N of WW6.

BORЕHOLE WW1

This borehole was drilled to test the occurrence and quality of water in the Cave (Ntane) sandstone and Mea Arkose. A test was carried out when the borehole had been drilled to 67m, fully penetrating the upper Cave sandstone sequence from 20 to 48m. Water was struck at 32m under confined conditions (rest water level 12m) suggesting a saturated thickness of not more than 16m. The borehole was pumped at 1.14 l/s ($98m^3/d$) for three hours when the pumping water level was 38m (drawdown 26m). No breakaway is apparent from the data, even though the aquifer was partially dewatered. Analysis of the recovery data shows a very low transmissivity (T) of about $1\ m^2/d$, indicating a permeability (K) of .06 m/d. These results are very much lower than those, for example, from the Cave Sandstone near Serowe (average T 15 m^2/d, K 0.15 m/d). The water salinity is high with a conductivity of about 26000 μmhos.

Subsequently, after casing was placed to 72m, the borehole was drilled to a total depth of 224m through a particularly thick sequence of carbonaceous mudstones about 135m thick, some 17m of Mea Arkose and into Basement Complex gneisses. There was no indication of a significant increase in supply and the conductivity increased to 30000 μmhos in the lower part of the sequence. The casing was broken on pulling the drill string and the planned testing of the Mea Arkose could not be carried out.

Borehole WW1 : Log Description

Depth (m)	Sample Description	Stratigraphic Unit
0 - 6	Light green to light grey calcareous sandstone with dark brown silcrete at 3-5m	
6 - 10	Predominantly angular dark silcrete	'Kalahari Beds'
10 - 20	Pale, slightly pinkish rounded returns of light grey sandstone becoming powdered return at 15-16 m	________________
20 -25	Pinkish return, soft fine-grained, silty sandstone with a few coarse returns	
25 - 38	Pink to buff fine-grained sandstone, slightly clayey from 32 - 38	Upper Cave (Ntant) Sandstone
38 - 40	Buff, fine-grained sandstone with angular returns of dark brown quartzite	
40 - 48	Silty, orange-brown fine to medium . grained sandstone, becoming more silty at 48 m.	------------------
48 - 52	Yellow, clay return with banded orange to light green mudstone	Lower " (?)
52 - 56	Orange to yellow clay return of purple and green mudstone	
56 - 65	Mixed purple and green mudstone return, predominantly purple from 62m.	________________
65 - 67	Dark grey to black, carbonaceous mudstone	
67 - 69	Predominantly khaki mudstone	Upper Tlapana Mudstone
69 - 71	Orange-brown mudstone	

Borehole WW1 : log description (continued)

71 - 80	Grey-khaki clay return of grey mudstone	
80 - 85	* Mixed grey/white/pink sandstone, predominantly grey mudstone from 83m	
85 - 92	Light grey mudstone	
92 - 94	Light coloured return of mixed crange and brown mudstone and buff fine to coarse grained sandstone.	-------------
94 - 200	Light grey shales, becoming black, highly carbonaceous from 123m.	Lower Mapana Mudstone
200 - 217	Grey (light grey from 203 m) fine to coarse grained sand return, felspathic	Mea Arkose
217 - 224	Light yellow, quartz sand return with pink quartz, chlorite and angular chippings gneiss	Basement Complex

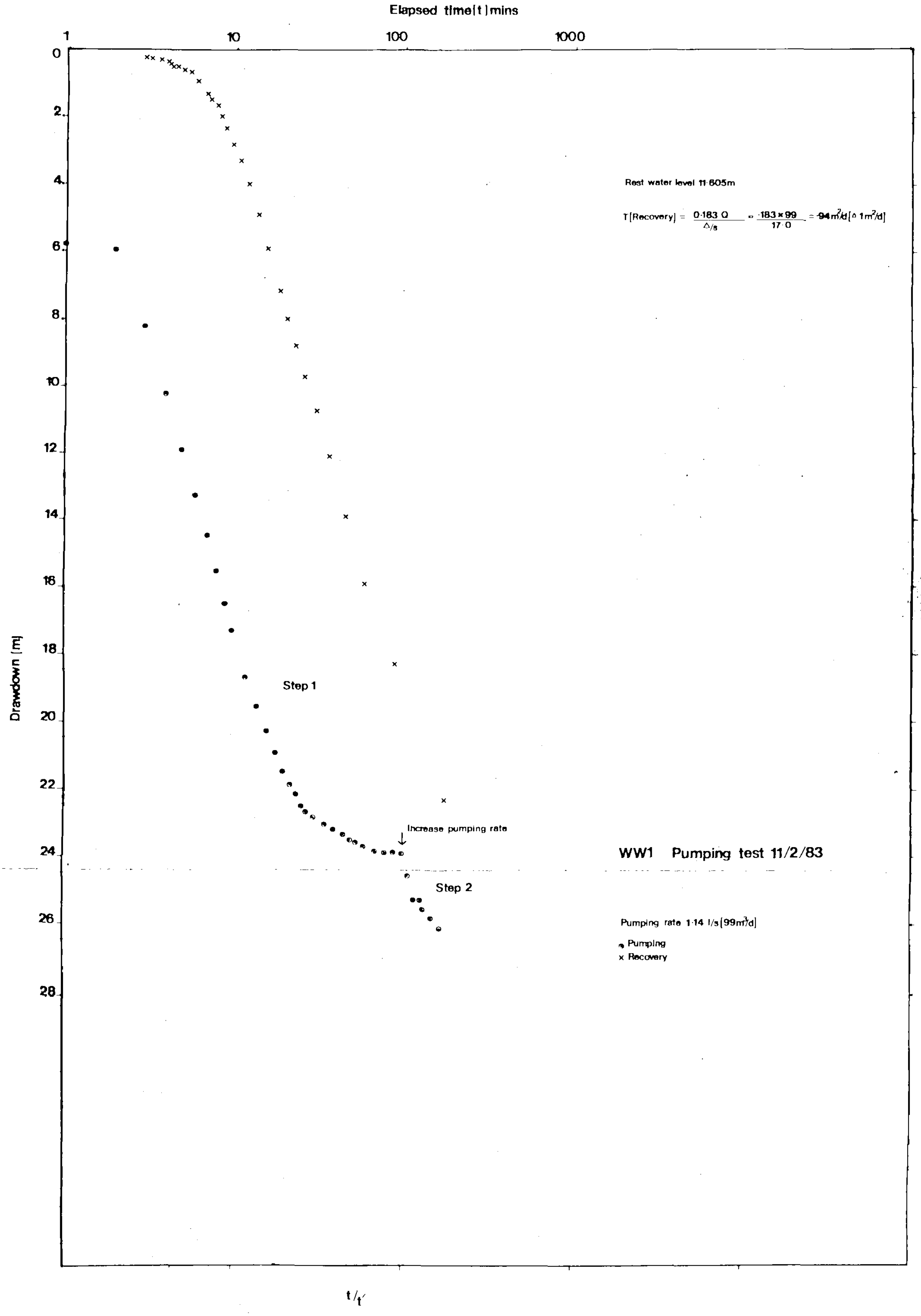
224 End of hole.

* Contaminated sample.

Remarks

Sequence from 48 - 65m assigned to lower part of Cave Sandstone by similarity to Cave Sandstone of Serowe area but might also be upper part of Tlapana mudstone (non-carbonaceous). Decrease in rate of penetration at 217m.

Conductivity about 25 to 27000 μmhos to about 175m, increasing to 39000 μmhos from about 190 to 210m.



Elapsed time(t) mins
1
10
100
1000
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Drawdown (m)
Rest water level 11·605m
T(Recovery) = 0·183 Q / Δ/s = ·183 × 99 / 17·0 = ·94 m²/d (≏ 1 m²/d)
Step 1
Increase pumping rate
WW1 Pumping test 11/2/83
Step 2
Pumping rate 1·14 l/s (99m³/d)
Pumping
x Recovery
t/t'

BOREHOLE WW2

This site was chosen to examine a sand ridge with prominent mopane trees for shallow potable supplies. It was drilled to 54m fully penetrating the Ntane Sandstone and into the Upper Tlapana Mudstones. There was a slight show of water at 38m and the zone from 38 to 42m. depth was cleared and drilling halted temporarily in case of a suppressed inflow. Further very slight shows occurred subsequently at 47-48m and at 51m in grey mudstone. A sample of water from this zone had a conductivity of 21400 micromhos. There was no water in the borehole the day after drilling nor when re-visited about one week later.

Borehole WW2 : Log Description

Depth (m)	Sample Description	Stratigraphic Unit
0 - 2	Brown, silty sandy soil.	
2 - 3	Buff, predominantly medium grained unconsolidated sand	
3 - 4	Pale to buff coloured fine to coarse grained sand, silcretes	Recent (? aeolian or bar deposits)
4 - 5	White, calcarecus "	
5 - 7	Loosely cemented, fine tc coarse grained sand	____________
7 - 13	Light green, calcareous fine to coarse grained sandstone	
13 - 15	" " " with reddish silcretes, coarser returns	'Kalahari Beds'
15 - 16	Greyish, calcareous sandstone with some white fine-grained sandstone	
16 - 21	Light grey to white fine-grained sandstone as fine to medium return with brownish silcrete.	______________
21 - 32	Powdered return, slightly pinkish fine grained sandstone, pinker from 25m.	Upper Cave (Ntane)Sandstone
32 - 35	" , buff coloured.	
35 - 39	Pink " and silty at 39m, some purplish sandstone	---------------
39 - 48	Brown return of brown and green mudstone, rust coloured from 45m.	Lower "
48 - 54	Brown clay return @ 50m, light coloured clay return @ 54m with greyish mudstone	-------?-------- Upper Tlapana Mudstone (?)

Remarks

Sequence at 5-7m possibly weathered Kalahari Beds, slightly damp.

" 48-54m assigned to Upper Tlapana mudstone on basis of grey colour.

BOREHOLE WW3

Originally, this site was to be drilled into the same ridge as WW2 but in view of the results from WW2 it was re-located near the junction of two possible faults about 1km north. However, the topography, superficial deposits and vegetation prevented precise target location.

Water, with a conductivity of about 28000 µmhos, was encountered at 48m under confined conditions (rest water level 21m) near the base of the Cave (Ntane) Sandstone, indicating a saturated thickness of about 3m. The borehole was continued to a depth of 145m through carbonaceous shales from 81 to 109 and Mea Arkose from 109 to 125m (?) and into Basement Complex gneisses. No significant change in conductivity was observed during drilling or any significant increase in yield.

This site was used to test the joint yield from the Cave (Ntane) Sandstone and Mea Arkose. However, the test had to be stopped due to sediment (from either inadequate cleaning or hole collapse). The early drawdown data indicated a transmissivity (T) of about 3 m^2d (data for less than 60 minutes) with an increase in the rate of drawdown after about 55 minutes (pumping water level about 37m). The rate of drawdown for the first 8 minutes of pumping during the second step of the test is approximately the same as the first part of step one. However, a rapid increase in drawdown (breakaway) occurs at this time (pumping water level 49m) and after about 100 minutes the pumping water level fell to about 92m.

The breakaway occurs at about the base of the Cave Sandstone aquifer and could indicate a thin water bearing horizon, such as a fracture, but could also be due to a lateral barrier boundary condition.

Borehole WW3 : Log Description

Depth (m)	Sample Description	Stratigraphic Unit
0 - 2	Surface grey to brown sandy soil	
2 - 3	Yellow-white, partly cemented (or decomposed) fine to medium grained sand	
3 - 5	White, hard, calcareous sandstone	'Kalahari Beds'
5 - 12	Light green to light grey calcareous sandstone with silcrete bands	
12 - 30	Fine, powdered return with white sandstone becoming pinker from 24m	
30 - 43	Pink return of fine-grained sandstone becoming harder at 43m.	Cave (Ntane) Sandstone
43 - 51	Pink sandstone, fine grained becoming orange coloured from 47m.	
51 - 53	Orange-brown, clay return with pale mudstone	Lower "
53 - 57	Light coloured return with light grey mudstone	Upper Tlapana Mudstone
57 - 76	Brown return of decomposed sandstone, clayer from 59m.	
76 - 81	Light yellow, clay return with yellow mudstone and sandstone at 80m.	
81 - 109	Black, carbonaceous shale in clay return	Lower " "
109 - 121	Grey fine to medium grained sandstone as sand return with mica, felspar, some gneiss fragments (weathered). Lighter coloured from 111m and fine to coarse grained.	Mea Arkose

Borehole WW3 : Log Description (continued)

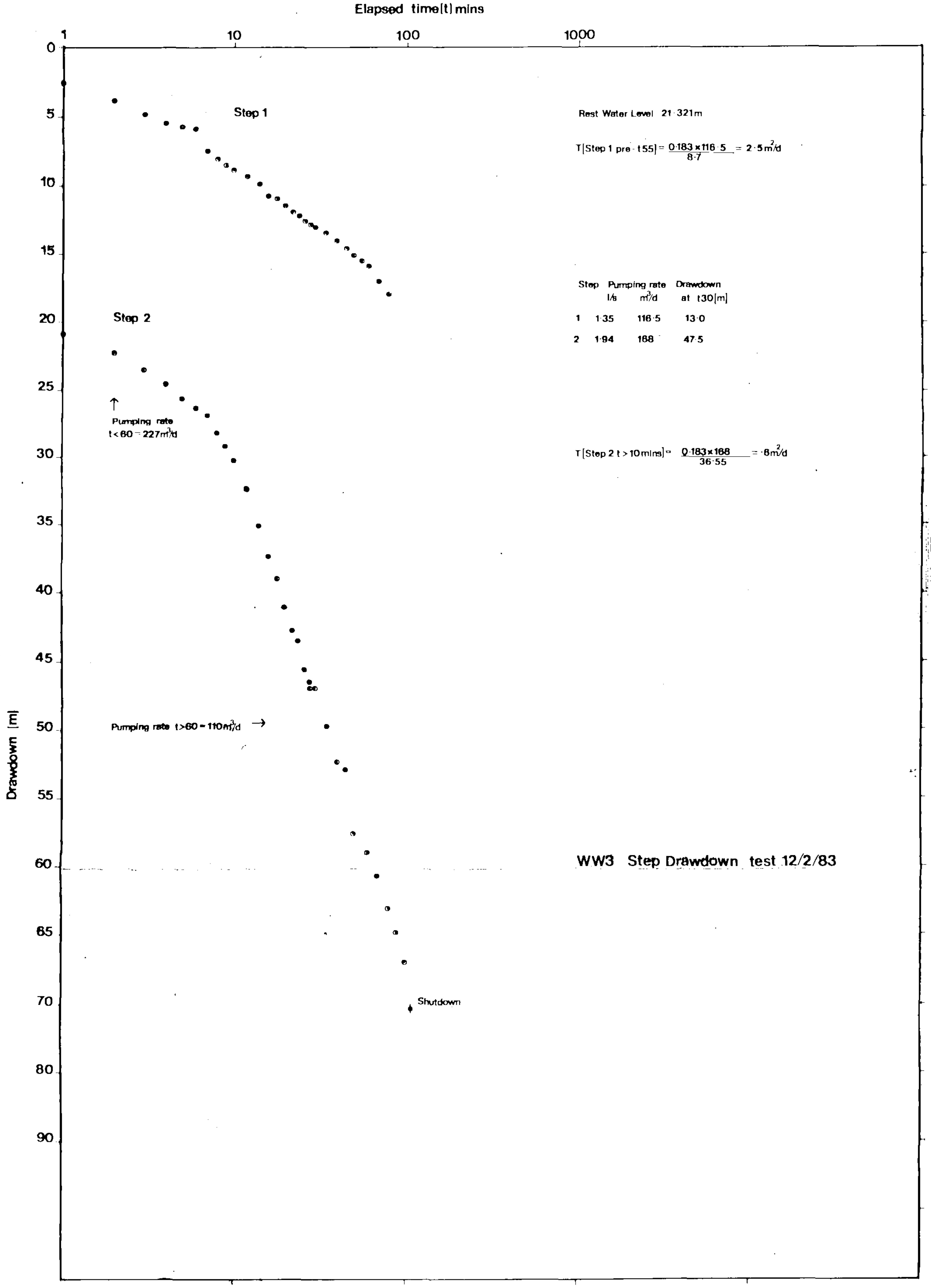
122 - 125	Ditto, with abundant grey laminated mudstone in sand return	?
125 - 128	Clean, sand return, fine to coarse grained with quartz and fragments of gneiss	Basement Complex
128 - 144	Sand return with pale, weathered gneiss fragments, fresh mica at 139.	
144 - 145	Dark grey to black, hard returns of fresh hornblende gneiss	

End of hole 145m.

Remarks

Absence of grey mudstone and presence of weathered gneiss fragments taken to indicate Basement Complex but upper part of this sequence may be Mea Arkose.

Many samples contaminated.



Elapsed time(t) mins
1
10
100
1000
Drawdown (m)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
80
90
Step 1
Step 2
Pumping rate
t<60 = 227m³/d
Pumping rate t>60 = 110m³/d
Shutdown
Rest Water Level 21·321m
T[Step 1 pre - t55] = 0·183 x 116·5 / 8·7 = 2·5m²/d
Step | Pumping rate l/s | m³/d | Drawdown at t30(m)
1 | 1·35 | 116·5 | 13·0
2 | 1·94 | 168 | 47·5
T[Step 2 t > 10mins] = 0·183 x 168 / 36·55 = ·8m²/d
WW3 Step Drawdown test 12/2/83

BOREHOLE WW4

A location for this site was chosen some 300m north of the Motsetse river near Tswane. Blocky calcretes occur at the surface as well as in the river bed. The borehole was drilled to 27m through calcretes, silcretes, a prominent green clay and into weathered dolerite at 9m. It was dry at the time of drilling but when visited one week later had a water level of 6.5m and a conductivity of 4300 micromhos. A pumping test was not carried out.

Borehole WW4 : Log Description

Depth (m)	Sample Description	Stratigraphic Unit
0 - 1	Light grey, hard calcareous sandstone with grey silcrete	'Kalahari Beds'
1 - 7	White calcareous sandstone, with grey silcrete at 6-7m	
7 - 9	Prominent green silty plastic clay with soft sandstone grains (glaucomite?)	
9 - 10	Khaki coloured "	[(Weathered) Dolerite]
10 - 25	Brown stained, angular fragments of dolerite in khaki return, becoming greyer and fresher from 21m.	Karroo

End of hole 25m

BOREHOLE WW6

This borehole was located about 100m north of the Motsetse river to intersect a possible fault line. The alluvium is only a few metres thick at this location and a small seepage was not encountered until a depth of 51m in mudstones of the lower part of the Cave (Ntane) Sandstone (?). The conductivity of this supply was 13700 μmhos. Drilling was continued to a depth of 82m with a large supply of water, with a conductivity of about 20000 μmhos, encountered in the Mea Arkose at about 79m. The rest water level is 19m. The lower part of the Tlapana Mudstone sequence is either thin or absent at this site (although parts of the mudstone sequence from 34 to 74m are slightly carbonaceous) and the Mea Arkose could not be fully penetrated due to the risk of surface collapse from the flow of water during cleaning. Casing was installed to 78m to support the mudstone sequence, with the lower 4m length torch slotted.

The borehole was tested using four consecutive steps, each of 60 minutes, at rates up to 16.1 l/s (1391 m^3/d) to draw water levels down as far as possible. The pump intake at 60m was reached during the fourth step. The early drawdown data during step one indicate a transmissivity (T) of 40 m^2d and a permeability (K) of about 5 m/d (assuming the main aquifer is from 74 to 82m). However, during each step the rate of drawdown began to increase after about 40 minutes into each step and finally broke away during the fourth step (at a pumping water level of about 40m).

A constant rate test was carried out at 4.03 l/s (348 m^3/d) for 1060 minutes. Analysis of the early drawdown data (less than 60 minutes) gives a transmissivity (T) of 25 m^2d and from early recovery data 33 m^2d. The rate of drawdown after 60 minutes gradually increases which suggests a lateral barrier boundary condition rather than dewatering of the aquifer. The conductivity remained at 20000 μmhos during the test.

Borehole WW6 : Log Description

Depth (m)	Sample Description	Stratigraphic Unit
0 - 2	Dark brown, silty clay alluvium	
2 - 3	Light grey return of fine to coarse grained, subrounded quartz sand alluvium	Recent
3 - 8	Light green return of soft, calcareous sandstone and dark silcrete	
8 - 9	White calcareous sandstone, no silcrete	
9 - 12	White return of fine to coarse grained sand and 10m gravel, predominantly orange-stained quartz, subrounded with white calcareous matrix	'Kalahari Beds'
12 - 23	Light to slightly pink return of calcareous sandstone with abundant brown silcrete	
23 - 28	Pink, powdered return of moderately hard fine to medium grained sandstone with white mottling. Orange silcrete (or quartzite) at 27m.	Cave Sandstone
28 - 34	Orange return of fine to medium grained sandstone with some rounded pink sandstone returns (? contaminated sample)	
34 - 35	Yellowish, clayey return with light grey mudstone	Upper Tlapana
35 - 36	Orange brown, sandy return with brown mudstone	Mudstone (?)
36 - 37	Pale, sandy return with light grey and yellowed mottled mudstone	
37 - 45	Light grey to buff return of light grey and purplish mudstone	

Borehole WW6 : Log Description (continued)

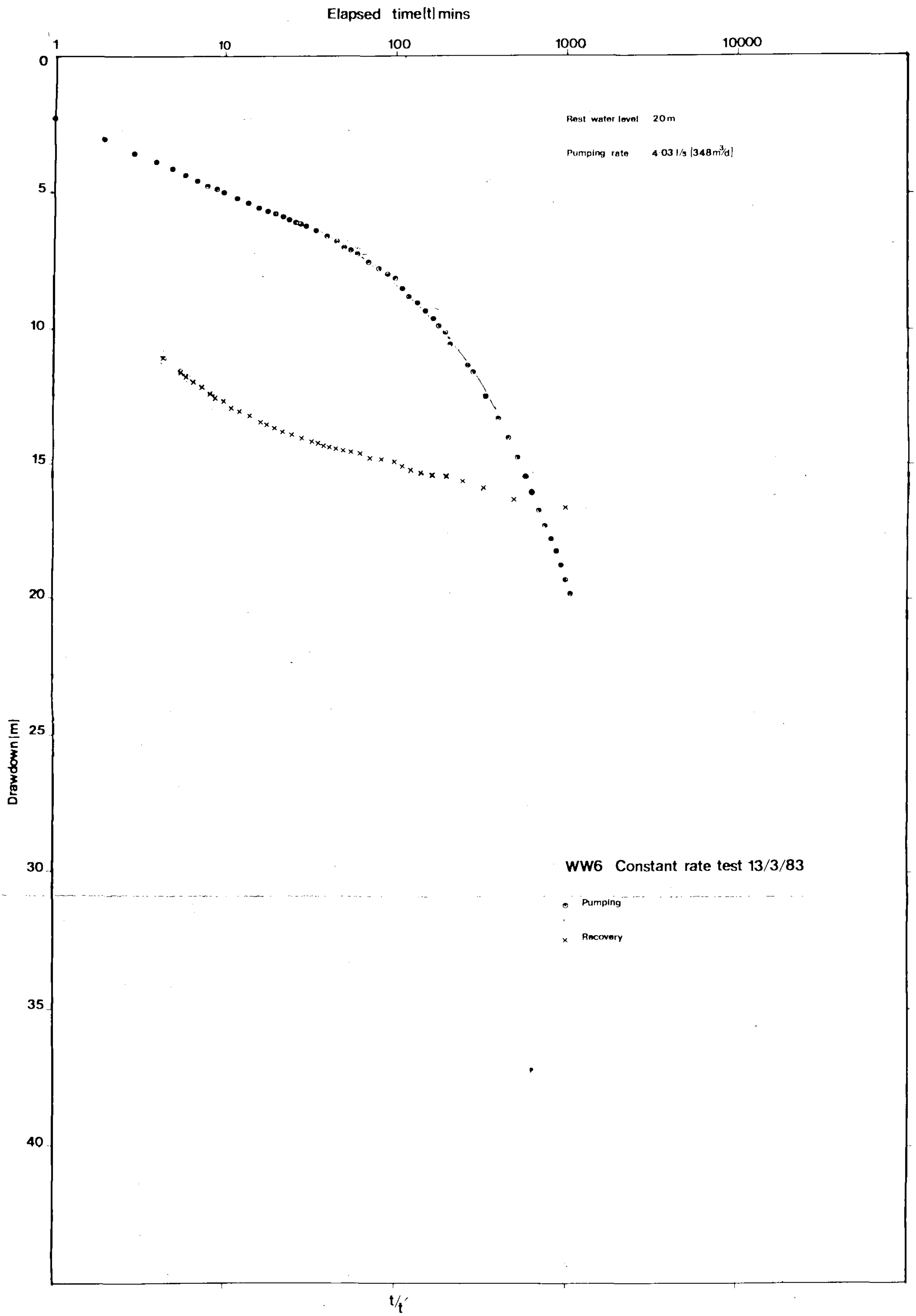
45 - 74	Brown, clay return with purple mudstone, slightly carbonaceous. Clay slurry return only from 51m but pinkish and lighter in colour, more sandy from 70m.
74 - 82	Light grey, fine to coarse grained sand return, sub angular predominantly clear quartz with medium grained white felspar and weathered mica schist. Mea Arkrose

End of hole 82m.

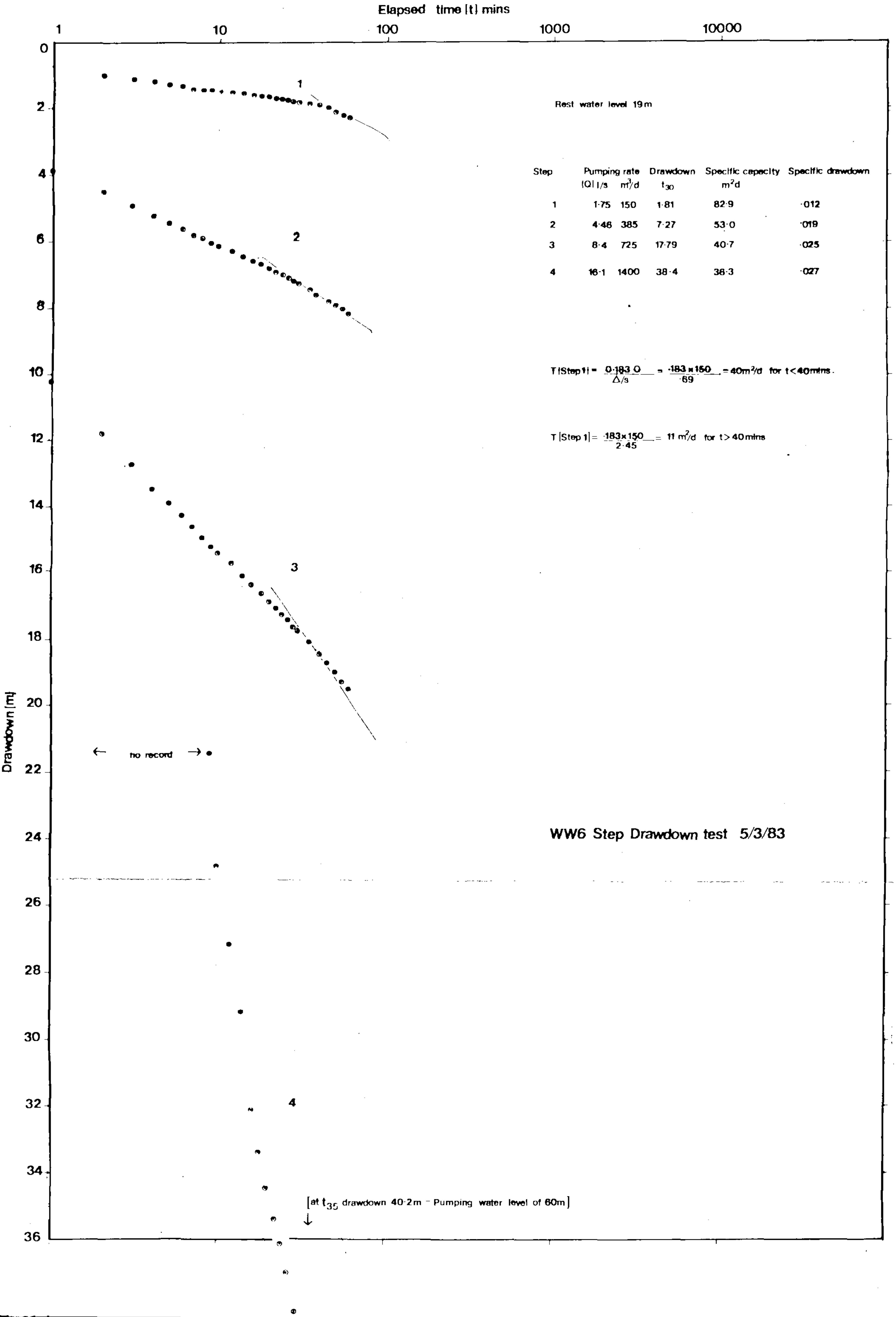
Remarks

Lower carbonaceous Tlapana Mudstone absent and sequence from 34 - 74m may be lower part of Cave Sandstone.

Water struck at 51m but main supply from 74m.



Elapsed time(t) mins
1
10
100
1000
10000
0
5
10
15
20
25
30
35
40
Drawdown (m)
Rest water level 20m
Pumping rate 4·03 l/s (348m³/d)
WW6 Constant rate test 13/3/83
Pumping
Recovery
t/t′



Rest water level 19m

Step	Pumping rate (Q) l/s	m^3/d	Drawdown t_{30}	Specific capacity m^2d	Specific drawdown
1	1·75	150	1·81	82·9	·012
2	4·46	385	7·27	53·0	·019
3	8·4	725	17·79	40·7	·025
4	16·1	1400	38·4	36·3	·027

$$T\,(\text{Step 1}) = \frac{0{\cdot}183\,Q}{\Delta/s} = \frac{{\cdot}183 \times 150}{{\cdot}69} = 40\,m^2/d \quad \text{for } t < 40 \text{ mins.}$$

$$T\,[\text{Step 1}] = \frac{{\cdot}183 \times 150}{2{\cdot}45} = 11\,m^2/d \quad \text{for } t > 40 \text{ mins}$$

WW6 Step Drawdown test 5/3/83

BOREHOLE WW7

The site for this borehole was chosen to intersect or be just east of a major north-south fault and close to the Motsetse river. Fresh water, with a conductivity of about 630 µmhos, was struck at 35m near the base of the Cave (Ntane) Sandstone. The rest water level is 21m. The mudstone sequence encountered at the other exploratory boreholes is absent at this location and the Cave Sandstone appears to rest on Mea Arkose, which is present from 38 to at least 73m. No significant increase in salinity or flow was recorded during drilling and the borehole was stopped at 73m due to the risk of surface collapse. Casing, slotted over the bottom 4m, was installed to 38.5m prior to continuing drilling to the full depth.

A constant rate test for 440 minutes at 1.5 l/s (130 m^3/d) was carried out at this borehole. The form of the drawdown response is similar to that at borehole WW6 with the rate of drawdown gradually accelerating after about 60 minutes pumping. The conductivity also increased from 720 to 820 µmhos during the first 280 minutes of the test then remained constant at about 825 µmhos. The increase in drawdown rate begins at about the water struck position and could be due to dewatering of the aquifer, which might be a relatively thin zone at the base of the Cave Sandstone or junction with the Mea Arkose. However, the gradual increase could be due to a barrier boundary. Analysis of the test data indicates a transmissivity (T) of 3 m^2/d for the drawdown data prior to 60 minutes and 10 m^2d from late recovery data.

Borehole WW7 : Log Description

Depth (m)	Sample Description	Stratigraphic Unit
0 - 2	Brown, sandy clay alluvium	Recent (alluvium)
2 - 3	Buff, poorly sorted, fine to coarse grained, sub-rounded quartz sand with orange (iron) staining and some felspar	
3 - 4	(mixed 3 and 5m), pale green	
4 - 5	Light green return with up to 25m sub-rounded quartz in calcareous matrix	
5 - 6	" , no quartz gravel	'Kalahari Beds'
6 - 7	"	
7 - 18	White angular returns of decomposed calcareous sandstone, moderately hard, becoming hard, white from 10 to 18.	
18 - 19	White, mixed calcareous sandstone and grey silcrete	
19 - 29	Pink, powdered sandstone return with angular reddish silcrete	
29 - 38	Pink, powdered return, some silcrete (contamination?). Sample at 38m of coarse grained, angular sandstone with clear and some yellow/orange staining and white felspar	Cave (Ntane) Sandstone Mea (weath)
38 - 46	Brown to grey, coarse grained sandstone, becoming lighter coloured from 42m.	
46 - 48	Light return, predominantly medium grained quartz.	Mea Arkose (?)
49 - 53	Orange return, " with some orange mudstone.	

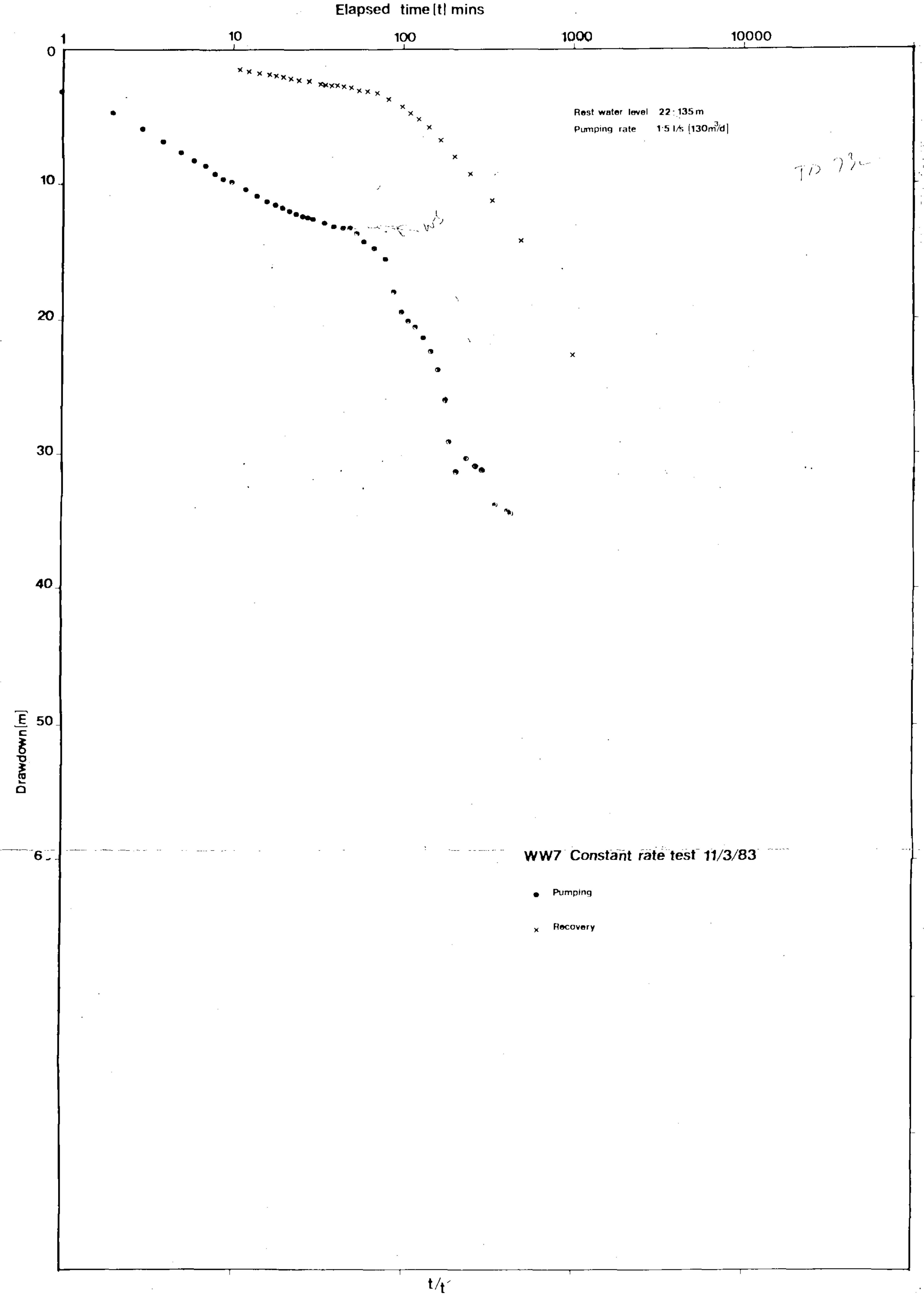
Borehole WW7 : Log Description (continued)

53 - 56	Light coloured sandstone, almost entirely clear quartz from 56m and mica present from 54m.
57 - 66	" , slightly brownish return, becoming fine grained from 63-66m.
66 - 68	Orange return, fine to coarse grained clear quartz.
68 - 73	" , with yellow stained quartz @ 72m.

End of hole 73m.

Remarks

Only thin, upper part of Cave (Ntane) Sandstone appears to be present and mudstones (except for minor bands within Mea Arkose) are absent. Conglomerate (rounded, large clear to grey quartz pebbles) from lower part of sequence and sandstone probably more of a grit comprising 1-2mm clear sub-angular quartz grains in white or pink felspathic matrix.



Elapsed time [t] mins
1
10
100
1000
10000
0
10
20
30
40
50
6
Drawdown [m]
Rest water level 22·135 m
Pumping rate 1·5 l/s [130m³/d]
WW7 Constant rate test 11/3/83
Pumping
Recovery
t/t´