**REPUBLIC OF BOTSWANA**

# THE MOCHUDI GROUNDWATER EXPLORATION PROJECT

(1982 - 1983) Final Report

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## Department of Geological Survey

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# THE MOCHUDI GROUNDWATER EXPLORATION PROJECT

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## 1. INTRODUCTION

In January, 1982 Mochudi village was identified by the Department of Water Affairs as a major village in urgent need of an extension to its water supply. At that time consultants were being invited to submit proposals for the South East Botswana Regional water study, a study which was expected to review the water supply and demand situation and identify sources of water for the major villages and population centres throughout the eastern part of the country. In view of the shortage of water in Mochudi and contamination of some of the boreholes supplying the village it was decided to carry out groundwater exploration for the village in advance of the findings of the regional study. The Geological Survey was asked to carry out the exploration by the Department of Water Affairs in February, 1982.

It was decided to carry out an exploration project which aimed not only to locate the much needed groundwater but also to take the opportunity to gain a better understanding of the basement rock aquifers which could be of value to future studies in other parts of the country. Work commenced on the project in March, 1982.

## 2. THE AREA

Mochudi is the capital of the Bakgatla tribe and administrative centre of Kgatleng District (7600 $km^2$). It is located close to the Notwane River where it follows the prominent escarpment of Waterberg rocks some 40 km north of Gaborone (Figure 1). The 1981 census shows a *de facto* population of 18613 people and an additional 1475 people are

Figure 1 Location map

resident in the adjacent areas of Pilane, Rasesa, Malotwana and Dikwididi which form Mochudi sub-district.

The village itself has developed on the high ground north of the river on the escarpment. The historical centre of the village is at Phuthadikobo Hill. The village has developed eastwards (Ntshinoge) westwards (Raserura) and south across the river (Boseja). The area south of the river is a vast flat plain of ancient granite-gneiss rock at an elevation of about 950 m and clearly a very old land-surface. Occasional hills rise from the plain (Modipe hill, Oodi hill) but there is generally very little topographic change and no rock outcrop. A dry valley crosses the plain from NE-SW near Moologe and there are a few scattered pans (Mmabe, Matlhage) in slight depressions of the landsurface. North of the village there is rock outcrop where Waterberg rocks overlie granit gneiss to form the prominent escarpment rising to 1000 m. The escarpment can be traced westwards to Molepolole. Eastwards the escarpment becomes less prominent and gradually merges with the surrounding plain.

The Notwane River is ephemeral. It contains water only after rain events in the wet season; there is no permanent baseflow. It drains to the north-east where some 75 km downstream, it joins the Limpopo.

## 2.1 Climate

Botswana lies within a sub-tropical semi-arid season with summer rainfall. The climate is seasonal with a warm rainy season from November until April and a cool dry winter from May to October. Some showers can occur in September and October, but it is not unusual for the rains to be delayed until December. The 50 year mean annual rainfall at Mochudi is 501 mm, similar to Gaborone and is very variable, standard deviation is 126 mm. The most likely rainfall (50% probability) is 480 mm. The temperature ranges from mean maximum daily temperatures of over 30°C (October-March) to mean minimum daily temperatures of <7°C (June, July, August). The daily range in temperature is greatest in winter.

The rate of evaporation in Botswana is very high and with rainfall falling in the summer months evapotranspiration is highest during the wet season. Mean annual class A pan evaporation at most stations in Botswana exceeds 2500 mm and potential evapotranspiration (Gaborone) is about 2000 mm or 4 times the mean annual rainfall. Thus the rainfall intensity is an important factor in deciding recharge for only over short-periods does rainfall exceeds evaporation. Figure 2 summarises monthly mean rainfall, temperature and evaporation and Figure 3 summarises the long term rainfall recorded at the village. Details of climatic factors as they affect groundwater recharge are discussed further in section 9.

## 2.2 Vegetation

The vegetation of eastern Botswana has been classified by de Beer (1962) and Bawden and Stobbs (1963). Valuable information is also given by Miller (1952), and Vermaak (1960).

South of the village the vegetation is typical of acid crystalline rock and Moloto (*Acacia dulcis*) Mopipi (*Boscia rhemannia*)

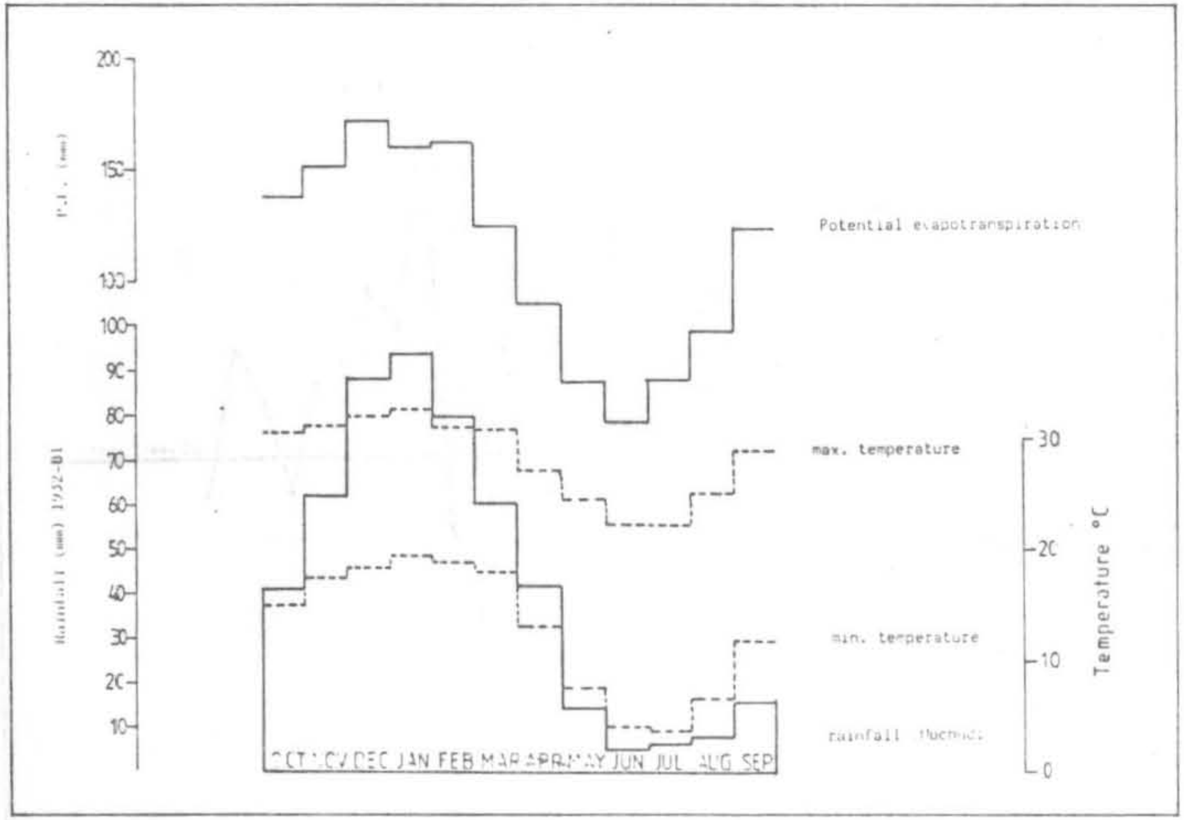

Figure 2 Monthly means

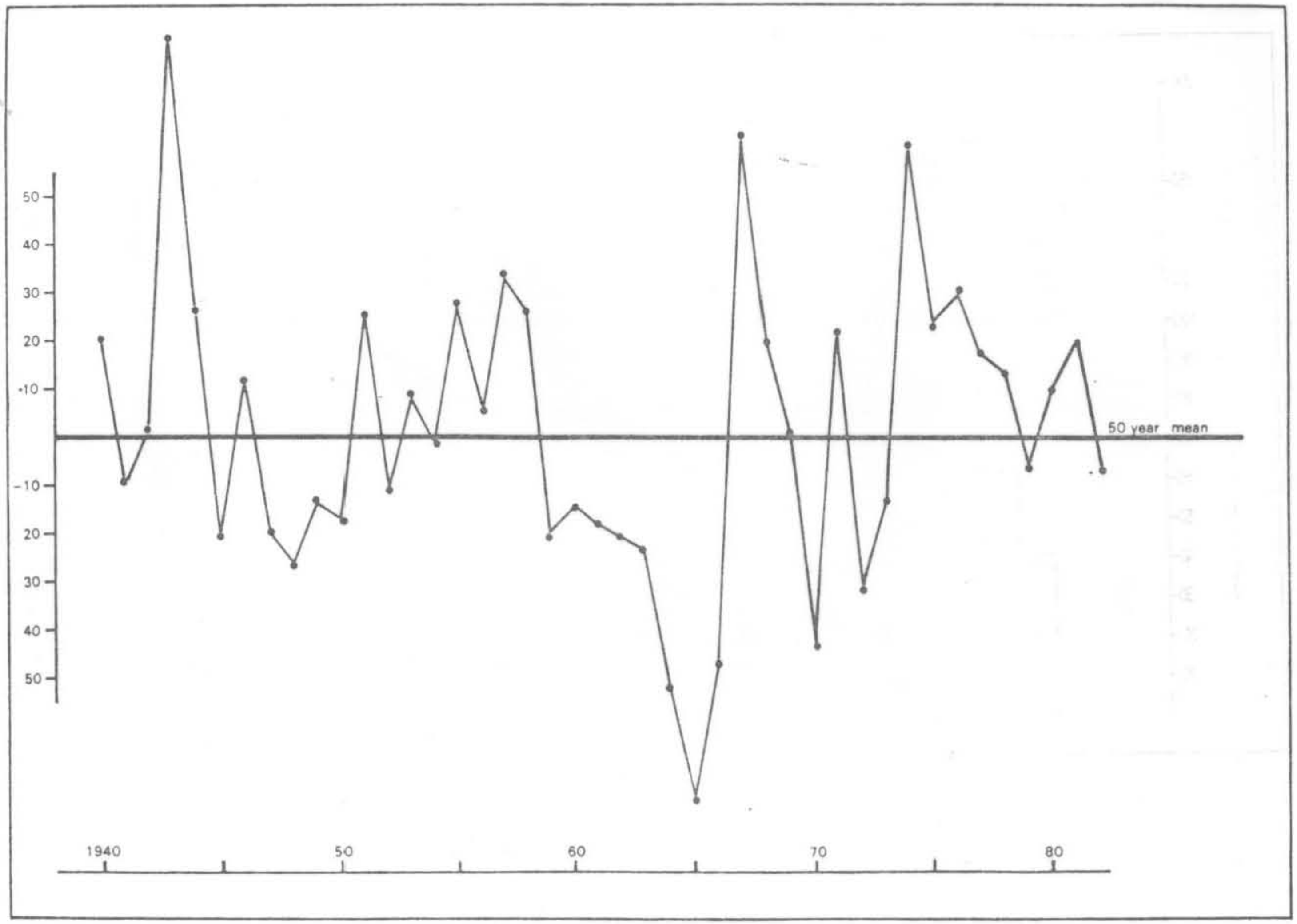

Figure 3 Percentage rainfall variation, Mochudi 1940 - 1982

Motlopi (*Boscia Albitrunca*) Mogwani (*grevia cana*) and Moretlwa (*grevia flava*) are commonly found on the pinkish to buff sandy soil. Dolerite intrusions are common and give rise to a characteristic red/orange soil usually having a sparse vegetation of short grass, presumably on account of overgrazing by goats.

North of the village the vegetation cover is decidedly more dense on the Waterberg rocks. The soil is more sandy, grey to buff in colour and supports a dense scrub of schrubs and small trees. Mogonono (*terminalia sericea*) is the dominant bush and is excellent for pegging cut lines. Marula (*sclerocarya caffier*) Mosetlha (*pellophorum africanum* Modubu (*combretum sp.*) and Mogotlho (*acacia giraffae*) are also present. Both large Marula trees and Mogonono bushes occur on parts of the soil cover on the granite-gneiss south of the village and there is evidence that some of the large marula trees were planted there by villagers. This may explain the anomalous area mapped as Waterberg rocks in this area on the geological map (2426A). Drilling confirmed granite-gneiss under the area having a colluvial cover of weathered granite-gneiss which included Waterberg fragments.

## 3 EXISTING WATER SUPPLY

### 3.1 Introduction

Mochudi village was originally established in 1871 when Bakgatla moved from the Transvaal because of oppression by the boers. There is evidence however that the village site was occupied in Stone Age and Iron Age times probably because of its strategic position and availability of water. (Grant, 1983). It is almost certain that the village water supply in early times would have been supplied by shallow hand dug wells in the valley now occupied by the Mission Hospital where water level is close to the surface and natural seepage occurs. The Notwane river would also be used as a supply during the wet season.

The earliest record of borehole drilling in the village for water supply dates from 1934 (borehole 35 Ralebotsa) although this does not discount earlier drilling, records were only kept from 1929 onwards. There are now records of more than 60 boreholes drilled in the village for water supply, mostly low yielding. Six boreholes are presently used for the village water supply.

Prior to 1977 the District Council was responsible for the operation and maintenance of the supply and in recent times the Council operated at least 13 boreholes (official numbers, 35, 38, 789, 792, 850, 1018, 1162, 1668, 2108, 2784, 2786, 3136 and 3137). Two small dams exist, one close to the Mission Hospital, the other high in the Makakatlela valley though neither are used for public supply. Before 1975 individual boreholes were generally equipped with diesel driven pumps and fed standpipes in the immediate vicinity.

There was little reticulation. Following recommendations made by Gibbs (1975)[5] a reticulation system was installed in the village. Boreholes 38, 850, 789, 1162, 1668, 2784, 2786, 3136 and 3137 were linked to a collected mains, and a high level storage tank (474 $m^3$) was constructed on Phuthadikobo Hill. Stand pipes were placed so that all people had access to a stand pipe within 400 metres. A central pumping and treatment works was recommended south of the river close to borehole 850 but was

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[5] A report by Sir Alexander Gibb and Partners.

never constructed. Instead water was, and still is, pumped directly into the distribution system from individual boreholes.

Borehole chlorine dosing equipment was recommended by Gibbs (1975) and units were installed at borehole 850, 2784, 2786, 3136 and 3137 but thereafter their operation proved inconvenient and they were discontinued. Water needs are presently supplied by 6 boreholes, 850, 2108, 2784, 3136, 3137 and 3990 and water enters the distribution main from these sources directly and untreated. The level of demand at the present time is such that the high level storage only fills when demand is low.

### 3.2 Current abstraction

Since the Department of Water Affairs took over the waterworks responsibilities in 1977 daily records of water pumped, pumping hours and water consumed have been kept and regular chemical and bacteriological tests are performed. A summary of the quantities of water pumped from the boreholes is given in Table 1 where abstraction is seen to have increased from 175516 $m^3$ in 1978 to 246403 $m^3$ in 1982, giving a daily average abstraction of 675 $m^3$. (The low total in the first part of 1978 is because borehole 2786 and 3990 were not in use). Consumption figures from the Department of Water Affairs are set alongside the abstraction totals in Table 1 and demonstrate that losses or metering errors in the Mochudi system are very high with a yearly mean loss of 28-37%.

An analysis of the monthly totals shows that abstraction is significantly greater in September, October, November and December and is much lower in January, February, March, April and May. This is surprising in view of the high mean temperatures during these months. The mean monthly abstraction over the period 1979-82 (which avoids the lower biased totals of 1978) is shown in Figure 4 and a factor responsible for this reduced consumption in the hot months is a reduction in demand due to a seasonal migration of part of the population to the lands and the cattle post, and the possibility of an alternative water supply after rainfall (rain-water, river water etc).

After harvesting people return to their dwelling in the village and often at this time receive visitors from other villages so that the urban water demand is normally reduced during the growing season and increases during September, and October. If the rains are poor then the water demand may not reduce as anticipated and greater abstraction will be necessary. Table 2 below indicates the increase in demand during the period September to December. It is about 34% higher than the January to September demand, and about 20% higher than the yearly mean.

| Year | Mean Daily Abstration (m$^3$/d) | | |
|---|---|---|---|
| | Year | Sept-Dec. | Jan-Sept. |
| 1978 | 480 | 690 | 380 |
| 1979 | 660 | 790 | 600 |
| 1980 | 660 | 800 | 600 |
| 1981 | 650 | 755 | 600 |
| 1982 | 675 | 700 | 660 |

Table 2: Mean daily abstraction, Mochudi 1978-1982

### 8.2.5 Borehole top elevation survey

The elevation of the top of all project boreholes and several important existing boreholes was determined by GS surveyor. A list of 58 well top elevations is given in the Appendix. Where boreholes have more than one casing inserted the elevation given is the top of the smallest diameter casing. For existing boreholes that are equipped or have no access to casing top the elevation given is for floor level. The elevation of the ground surface at two dugwells was also included.

### 8.3 Geophysical borehole logging

It was planned to obtain geophysical borehole logs of the most important boreholes drilled to record reistivity, natural gamma and caliper information to compare with other results. Unfortunately operating difficulties of the equipment meant that the program was started but not completed. It is hoped to complete this work and report on it when new equipment arrives.

### 8.4 Pumping tests

At boreholes where a promising water flow was obtained (5 cm + over a 90° V-notch weir) pumping tests were conducted to establish the borehole yield and give information on aquifer properties. Both constant rate and step-drawdown tests were conducted. The routine testing procedure of Water Affairs was to run a 48 or 72-hour constant rate test using an electric submersible pump placed a few metres above the bottom of the hole. Water level measurements were made with an electric indicator through an access pipe. The access pipe was necessary because of large drawdown and to avoid problems with cascading water. The discharge rate was measured using a commercial flowmeter or by filling a drum to capacity.

The test procedure of Water Affairs was not entirely satisfactory for the analyses of aquifer properties. Its main limitation being that in the low-yielding aquifers it was not always a constant rate test.

The Geological Survey conducted step-drawdown tests at 5 sites, partly to help analyse the aquifer properties and to investigate the yield-drawdown relationships. Up to 6 steps of 100 minute duration were chosen.

The constant rate data were analysed using the Theis method and its Cooper-Jacob straight-line modifications, and by the Boulton method. The step drawdown data were analysed by methods given by Brereton (1979) Eden and Hazel (1973) and Bierschenk and Wilson (1961). Observation wells were used at only one site (4345) where a 5 day constant rate test was run by Geological Survey.

### 8.4.1 Constant rate tests

Twenty-one constant rate tests were performed and a summary of test results is given in Table 12. Details of individual tests including the step-drawdown testing are given in a separate report (GS/DKB/5/83) where an unusual aquifer response from some tests is described.

a) Borehole 3990

Borehole 3990 was tested by Water Affairs on 9/9/82 for 48 hours of drawdown and 3 hours of recovery. The pumping rate was 15.6 $m^3/h$. The drawdown measurements are unusual because they show water level never changed after 10 minutes, and the recovery water level was 8 metres higher than the pre-pumping level. The recovery measurements don't match the drawdown so the measurements are obviously suspect. There was no opportunity for a re-test because the well was equipped shortly afterwards.

b) Borehole 4198, 4202, 4205

These boreholes were tested by Water Affairs in [illegible]ember 1982, and a semi log plot of the drawdown measurements is shown in Figure 26. The effect of testing with too large a pump is apparent from the measurements and no slope can be used to give a T value. In all boreholes the water level was drawn down to a few metres above pump suction near the bottom of the hole during testing. Transmissivity values were obtained however from step-drawdown testing.

c) Borehole 4234

At borehole 4234 the yield was higher and sufficient that water level was not drawn down to pump suction. It was tested by Water Affairs for 48 hours starting on 27/01/1983.

Discharge rate varied from an initial 527 $m^3/d$ to 272 $m^3/d$ near the end of the test. Recovery was measured for 3 hours only. The early slope of the semi-log drawdown measurements gives a T of 11 $m^3/day$. When drawdown was 14 m corresponding to a PWL>46 m the drawdown increased. The measurements are poor and a final slope transmissivity cannot be obtained precisely. The levelling of water

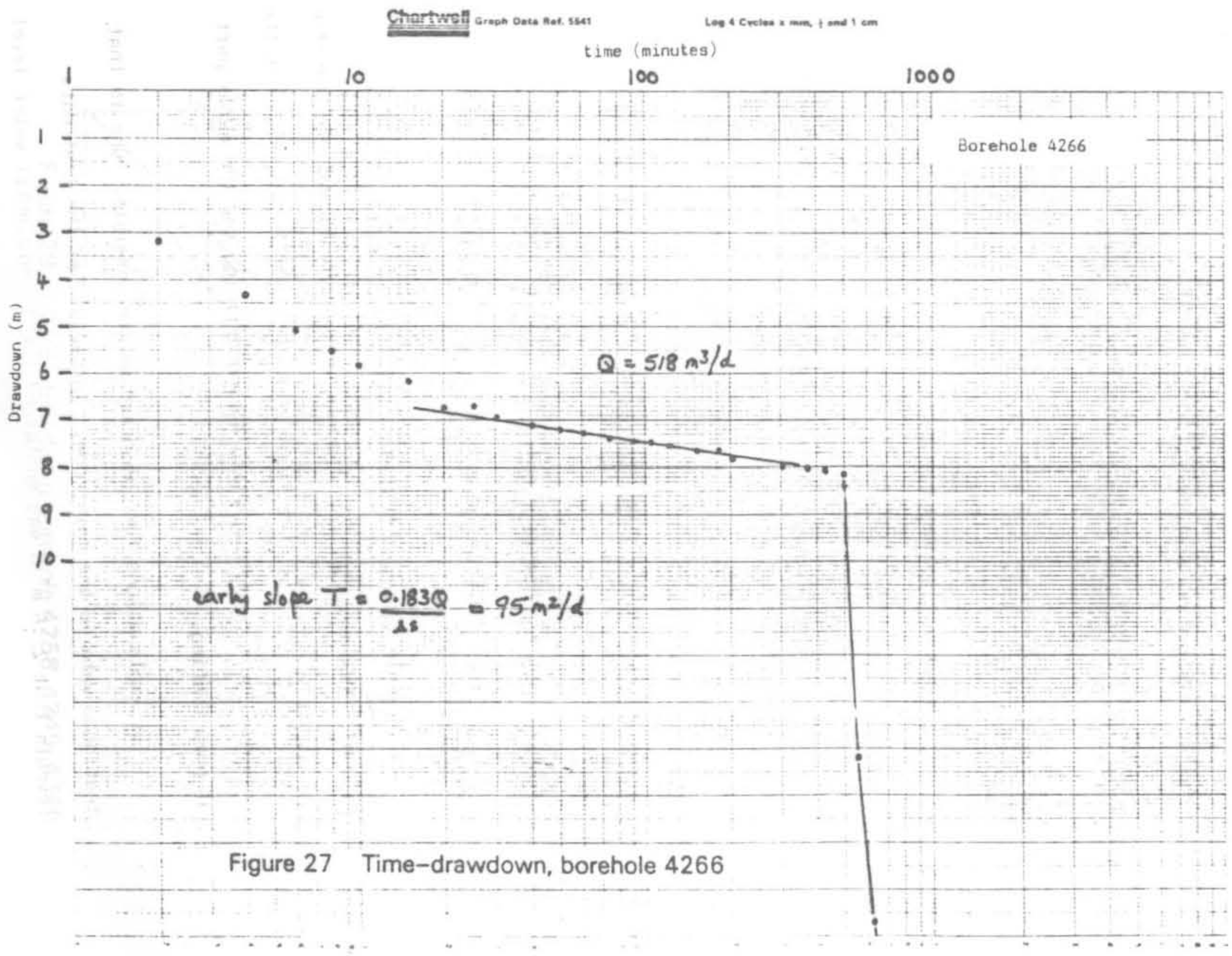

Figure 27 Time-drawdown, borehole 4266

level from 400-900 minutes has no natural explanation.

The early more favourable slope could be affected by wellbore storage (WBS).

Wellbore storage is satisfied when....

$$\frac{Ttr}{rw^2} > 25$$

where tr = time after which WBS is not applicable

rw = well radius

T = transmissivity

Using a final T of say 2 $m^2/d$ all of the early slope up to 180 minutes could be accounted for by wellbore storage. A transmissivity obtained from step-drawdown testing (18 $m^2/d$) however suggests that WBS should be satisfied within 20 minutes. A more likely explanation for the increase in drawdown at 20 minutes is a partial dewatering of the upper water zone and this was later confirmed by flow-meter logging.

d) Borehole 4266

Borehole 4266 was tested by Water Affairs for 48 hours on 4/8/83. The drawdown measurements were again unusual and are shown in Figure 26 and 27. The final yield is given as 1.3 $m^3/h$ yet the borehole had a promising yield during drilling and the early part of pump testing.

Two explanations for the drawdown are possible. One is that testing dewatered the main zone. Inspection of the test data reveals that 21.6 $m^3/h$ was sustained for 9 hours until water level

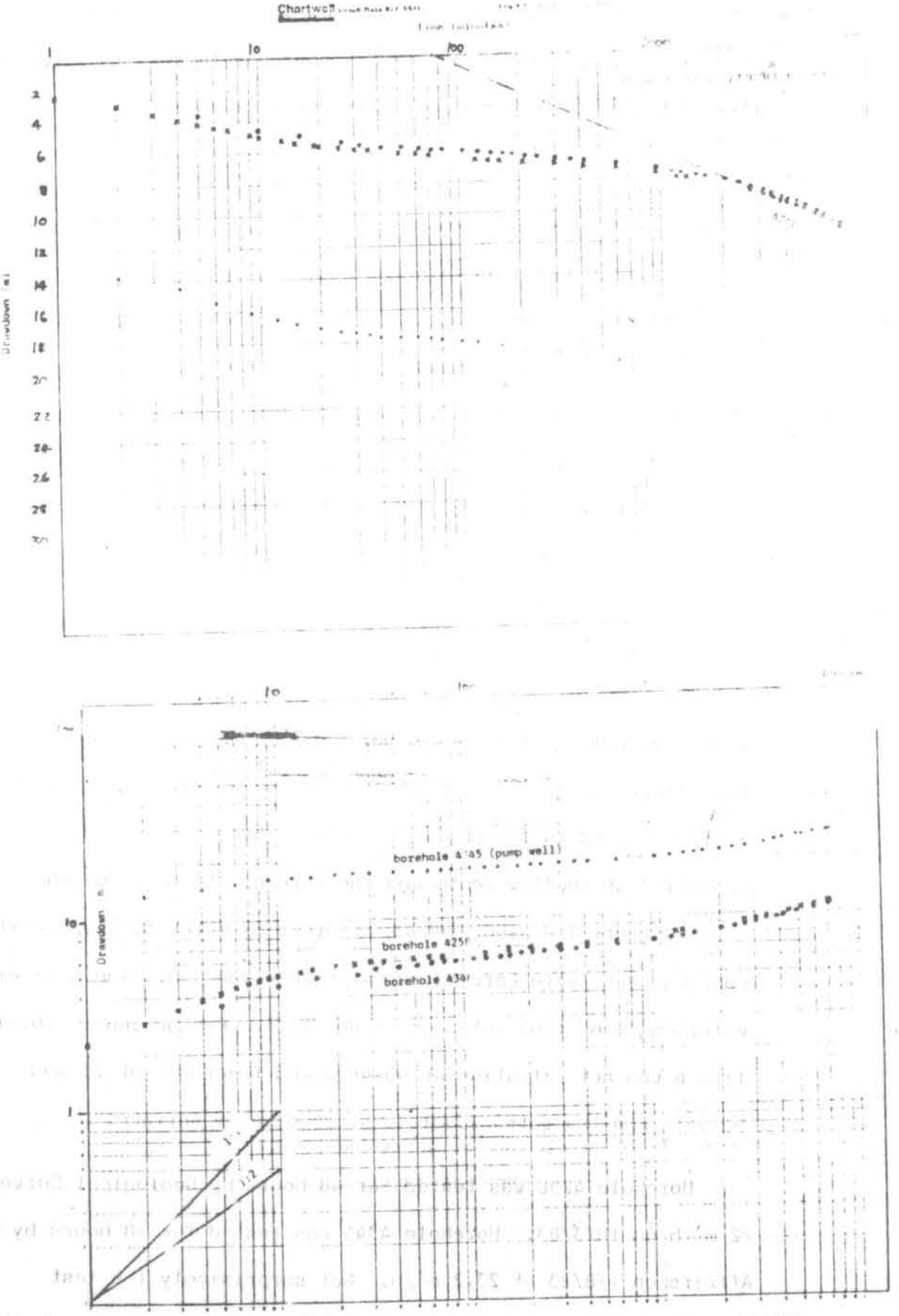

Figure 28 Time–drawdown borehole 4258, 4345, 4346

reached the presumed main inflow. Thereafter water level fell rapidly to pump suction and the discharge rate fell to a sustained 1.3 m³/h. If this is correct then the maximum inflow is 1.3 m³/h and the early high discharge is water being removed from storage.

An alternative explanation is that the lower part of the aquifer is cased off. Blank and slotted casing were used in construction and reference to the details in the Appendix indicates that there is some uncertainty by the driller where the casing was placed. It is possible that the increased drawdown at 46 m coincides with a section of blank casing. A CCTV inspection to check the construction of this hole is therefore recommended to confirm this before the pump test data can be properly analysed.

e) Borehole 4258, 4345

Borehole 4258 and 4345 are 3 m apart in area west of the main road about 10 km north of Mochudi near Malotwana. After drilling borehole 4258 was found to be blocked and it was impossible to lower the pump to the required depth. However the pump was installed at shallow depth and the borehole tested. Borehole 4345 was later drilled alongside at a larger diameter to replace it. Pumping tests were carried out at both boreholes. The aquifer is Waterberg sandstone intruded by dolerite. Production is obtained from a contact situation at 45-48 m and fractures at 78 and 90-95 m and the water level is at 28 m below surface.

Borehole 4258 was tested for 48 hours by Geological Survey at 22 m³/h on 18/3/83. Borehole 4345 was tested for 48 hours by Water Affairs on 1/8/83 at 23.2 m³/h. Not surprisingly the test measurements are similar (Figure 28). A line drawn through the late drawdown data gives a T of 66 m²/d (4258) and 108 m²/d (4345) although the measurements do not form a single straight line.

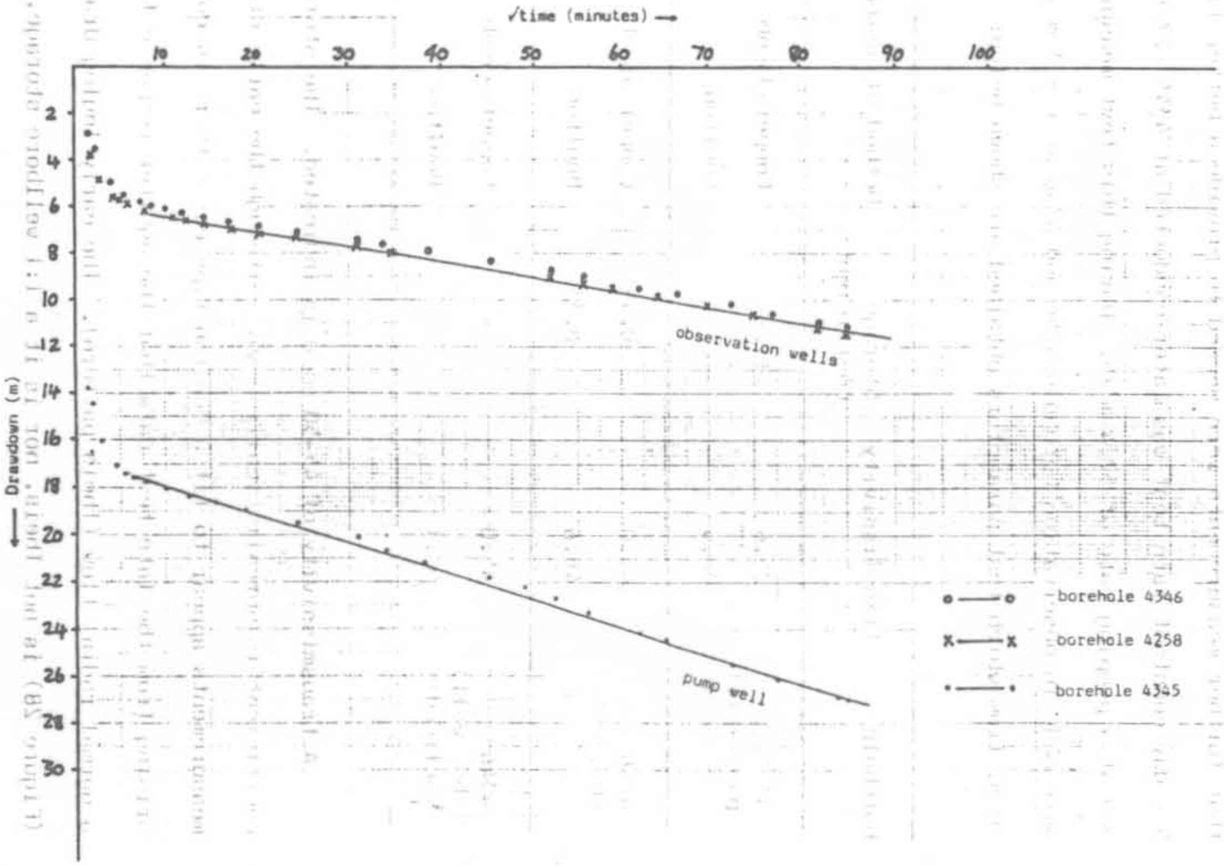

Figure 29 √t–drawdown, borehole 4258, 4345, 4346

The measurements fit a Boulton loglog curve fairly well from which an early T of 50.6 $m^2/d$ and a late data T of 46.9 $m^2/d$ are obtained which are probably closer to the real value than the semi log interpretation. Matching the data to the curve showed that further measurements were needed to provide a better fit. A 5 - day constant rate test was later conducted at 4345 (27/8/83) and at a pumping rate of 57.4 $m^3/h$. During this test measurements were made in observation borehole 4258 and 4346 at $r$ = 3 m and 30 m, from which test parameters obtained are shown below:

| Borehole | Transmissivity | Storage Coefficient | Method of Analysis |
|---|---|---|---|
| 4345<br>(pump well) | 25.6 | - | Cooper-Jacob |
| | 30.4 | - | Boulton |
| 4258<br>(obs. well) | 45.0 | 0.49 | Cooper-Jacob |
| | 48.6 | 0.33 | Boulton |
| 4346<br>(obs. well) | 45.0 | - | Copper-Jacob |
| (inclined) | 52.1 | - | Boulton |

A transmissivity of 45-50 $m^2/d$ is indicated. The storage coefficient is unrealistically high. Although the early drawdown measurements appear to fit a Boulton type curve there is doubt arising from the late test data that the aquifer response follows a normal radial flow (Theis pattern). The early loglog drawdown (Figure 28) is not Theis, nor is it a 1:1 wellbore storage, or a 1:2 linear drainage slope. The loglog plot gives a straight line up to 1000 minutes and the semilog data form a curve. Such a response suggests linear and not radial flow. A plot of $\sqrt{t}$ versus s (Figure 29) gives a straight line which further suggests linear flow.

The test data for borehole 4258 were also analysed by VIAK using a method more applicable to fractured aquifers. Their analysis based on an improved radial flow model which accounts for wellbore storage and skin effect obtained a transmissivity of 260 $m^2/d$ for very early data and a more realistic storage $(1 \times 10^{-2})$.

However it is doubtful whether their improved analysis is applicable to the hydraulic response which is characterised by a continuing drawdown at late times. The same response is evident at borehole 4448 in the same formation, and also in tests analysed by VIAK at Molepolole (3530, 3543, 4287). A pumping rate cannot therefore be predicted for borehole 4258 by normal Theis theory.

A plot of drawdown versus $\sqrt{t}$ for borehole 4258 (not shown), which gives a straight line, indicates a 1-year drawdown of 21.4 m and a 5-year drawdown of 42.7 m at 22 $m^3/h$. The same plot for borehole 4345 (figure 29) indicates that 57 $m^3/h$ is excessive and the borehole could only sustain this rate for 6 months (s = 78m). It is suggested therefore that a pumping rate of $\sim$30 $m^3/h$ be used and water levels should be monitored to provide data to assist modelling of this aquifer response.

In both rock types local enhancement of permeability is noted close to dolerite intrusions where either pre-existing structures occur or where baking, brittle fracture and the development of parasitic fractures has occurred. There is evidence that such features occur at a fairly uniform elevation within the region, they are not extensive, but they are locally important.

A discrete ground water flow in channels regulated by fractures has some implications for borehole spacing. In these aquifers it is not unusual for more drawdown to be recorded at distant observation wells than in wells closer to the pumping well. This is due to the better location in the channel of the more distant borehole. There is therefore a directional factor involved if spacing is properly considered and where the spacing is not deliberately chosen for some other reason such as to prevent overgrazing. An alternative view in low-yielding aquifers is to ignore the general guidelines for spacing because the borehole is such an inefficient structure anyway and more than one is preferred to abstract water efficiently. Locating boreholes at least 300 m part (a standard practice) in many cases will miss the water-bearing feature altogether.

### 8.5.4 Water level fluctuations

Automatic water level recorders were set up on borehole 4234 (granite-gneiss) and 4258 (Waterberg) to provide a continuous record of water level changes. Part of the record is shown in Figure 31 where it is seeen that there is a semi-diurnal (twice-daily) rise and fall in water level of up to 6 cm. This is due to barometric pressure changes as the curve for barometric pressure shows. The irregular rise and fall in water level is due to longer term changes in the barometric pressure. This fluctuation is a well effect and is not occurring in the aquifer. It is apparent that there is very little net change in level over the period of record and it is intended to maintain records over a full season or more to record the replenishment (if any) and depletion.

The barometric pressure trace (inverted and expressed as cm. of water) in Figure 31 shows a maximum change of about 10 cm. Water level fluctuations much in excess of 10 cm are therefore unlikely to be barometric effects and are more likely to be due to earth tides or to pumping.

Instantaneous changes in water level on 15 and 26 May and 17 June are thought to be due to distant earthquakes. The 4 cm change recorded on 26 May interesting occurred at the time of the large earthquake at Akita in Japan.

### 8.5.5 Groundwater flow

The static water levels measured after drilling show that the water-table is very flat and so it is difficult to appreciate the direction of groundwater flow. These low gradients and the transmissivity of the aquifer imply very little throughflow which in turn suggests that the aquifer must behave largely as a storage tank.§ Because the measured water levels reflect the topographic elevation (unconfined aquifer) it is evident that on a large enough scale they will indicate a flow direction which will be the same as the surface drainage, i.e. to the NE. In detail it is clear that this is not the case because the flow directions are governed by the fracture compartments and no flow is expected to cross a fracture (except possibly through the overlying weathered zone).

Figure 24 indicates that the local ground water flow is instead in a NW-SE direction with a ground water divide under the high land of the escarpment separating flow to the NW from one towards the village. At the foot of the escarpment in the village there is a ground water discharge area which accounts for the high water levels and the number of dugwells in that area. (It is obviously one of the reasons for the early settlement of the village).

Figure 25 demonstrates no obvious flow direction because the water levels are very flat and small differences in level could be exceeded by surveying errors, but like figure 24 the area is part of a SW to NE directed <u>surface</u> drainage and on a large scale that would be the expected flow direction.

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§ The steady-state throughflow between borehole 4198 and 4234 is 5.8 $m^3/d$ $(20 \times \frac{1}{3500} \times 1000)$ assuming an aquifer width of 1 km. This is equivalent to 2 mm recharge/year. If you consider the aquifer is <1000 m wide, say 500 m then the throughflow is negligible).

8.5.6 Water quality

Water samples were collected from the most promising boreholes drilled and from many existing boreholes in the region for chemical analysis. Table 15 summarises the water chemistry of the boreholes drilled and Table 16 summarises chemistry of some existing boreholes including the Notwane river water in the village. Most of the existing borehole waters in the village are modified to a greater or lesser extent by the effects of pollution so that the freshly drilled borehole waters in Table 15 are more representative of the unreacted aquifer water.

It is clear from the Table that the waters have moderate to low TDS content and there is no real difference in chemistry of the waters from the three aquifer types, gneiss, dolerite or sandstone. The waters are generally dominated by the Mg and Ca cations and by bicarbonate.

The low TDS content and similar chemistries of all the waters is a reflection of the generally chemically inert aquifer material and the lack of movement within the aquifer. The aquifer material for all waters is basically a crystalline rock of silicate minerals. The chemical evolution of the ground water is largely dominated by the weathering process and mature groundwater will have a composition tending towards equilibrium with the various clay minerals. Thus the cations present in the groundwater are largely those released during weathering of the primary minerals present and their relative reactivities. Biotite is a source of dissolved $Mg^{2+}$ Fe and K, pyroxene of $Ca^{2+}$ and $Mg^{2+}$ and plagioclase of $Ca^{2+}$ and Na+.

The dominant anion in the unreacted, freshly drilled waters is $HCO_3$. Atmospheric $CO_2$ content is $\sim$0.03% and this is increased up to 100 x in the soil due to root respiration and decay of soil organic matter. The alteration of silicate minerals to clay minerals in the weathering zone also releases $HCO_{3-}$ and $SiO_2$ so that these are high in waters infiltrating from the surface. Bicarbonate is thus very high to high and in analyses ranges from 181-717 mg/l. $SiO_2$ is also high and ranges from 56-114 mg/l, with slightly higher values noted in waters from Waterberg rocks.

The $(Ca + Mg)/HCO_3$ ratios in Table 15 and 16 demonstrate that carbonate equilibrium is achieved in most waters. The analysis showing $(Ca + Mg)/HCO_3$ ratios >>1 demonstrate a natural evolution and/or pollution towards increasing $Na^+$, $NO_3^-$ and $Cl^-$ (borehole 4234, 4222, 4232 and 3990). On a tri-linear diagram (Figure 32) the waters plot in different fields as indicated. The diagram also separates out 4234 as high $Na^+$ and $HCO_3^-$, and is the only water with a $(Ca + Mg)/Na$ ratio <1 (0.72). The preferential weathering of plagioclase to release $Na^+$ or ion-exchange is a likely control of this chemistry.

Borehole 4232 is somewhat unusual in having a high nitrate content (76 mg/l) yet the borehole is remote from habitation being located in a field. Background nitrate levels from adjacent drillings are < 10 mg/l. Such a high value could be indigenous, through concentration in soil moisture and remobilisation. Application of fertilizer is ruled out. High indigenous nitrate levels of up to 100 mg/l unrelated to pollution have however recently been reported in Kalahari sands (Heaton, Talma and Vogel, 1983) so that a concentration factor could be responsible. Samples from different depths in borehole 4232 demonstrate the highest nitrate and chloride levels are at the watertable decreasing with depth suggesting an input from the unsaturated zone with some denitrification in the saturated zone. The nitrate levels may also be influenced by land use. During testing the water quality improved slightly as water was being taken from deeper levels in the aquifer. (TDS 1690→1376 mg/l).

Borehole P-499 is moderately saline (TDS=3587 mg/l) with elevated $Na^+$ and $Cl^-$ content. Only one analysis of this water is available (Table 16) but it is thought that mineralisation has always been present principally due to the aquifer (siltstone) and possible later modified by contamination at the cattle post. The (Ca + Mg)/Na ratio is <1 (0.62) which is similar to 4234 (0.72). Borehole 4205 close to the cattle post was not full analysed but had unacceptably high chloride (995 mg/l) and TDS (1580 mg/l) for public supply although an acceptable nitrate content (28 mg/l).

All other waters in Table 15 with exception of 3990 ($No_3$>100 mg/l) are suitable for domestic purposes. No element is present in dangerous quantities. Some further details of water quality are given in section 10 in discussion of pollution.

### 8.6 Critical review of borehole siting techniques

The techniques used for borehole siting - review of existing known aquifers, the identification of lineaments on satellite imagery and then on air photos followed by confirmation on the ground by electrical resistivity and magnetometer traversing is a standard approach but the results of drilling have been generally poor. If it is accepted that the main lineament directions are the main groundwater flow channels then the low yields typical of many boreholes suggest that they penetrate only the minor fractures and have missed the main channels. Boreholes located in the channels at 4234 and at channel intersections 4258, 4345, 4346 and ? 4448 demonstrate a strong groundwater circulation. Other boreholes drilled on presumed intersections of structures have been less successful. This may be due to missing the feature or a very poor groundwater circulation within some fractures.

There is increasing evidence, these drilling results included that the prominent lineations and crush-zones are <u>not</u> always the main routes for groundwater and groundwater prefers a less-obvious path of minor fractures related to the main structure (see Kohut. Foweraker et.al. 1983). If this is so it would appear that the strategy of drilling on prominent lineations is not reliable, and an analyses of the tectonic pattern in the area followed by selection of specific lineaments is necessary. Other fractures were naturally taken into account when selecting sites including locating sites close to drainage lines, considering vegetation (large trees etc.) animal indicators (termite mounds) and water-divining. Water-divining was used quite frequently to locate actual drill sites within a previously identified anomalous area, and gave a significant indication at borehole 4258. I have no doubts that water divining can be useful, and an explanation of why the method works can be found in several publications (e.g. New Scientist Vol. 81 1979, p371, 20-27 December 1979).

In the Waterberg which is a layered formation certain layers can be identified as better prospects from their physical properties and lithology. Thus although the main objective has been to locate fracturing, lithology is still important because of its control over the type and nature of the fracturing which occurs close to intrusions or faulting.

Conclusions that can be drawn from this study are that the main lineament directions are not always the main directions of groundwater circulation and other features may be more important. Consideration should therefore be given to determine which lineaments in a given area are more likely to be productive.

It has also been found useful to prospect for sites close to drainage lines. Drainage lines may have developed over major (permeable) fracture zones, but some drainage lines do develop on impermeable solid rock platforms, so sites have to be investigated carefully. It is also useful to prospect for sites near to rock outcrop. In some areas it is probable that the easiest access for water ro reach a groundwater body is through fractured rock outcrop and areas of very thin soil. A groundwater circulation is therefore more likely to exist close to fractured rock outcrop. The intersection of lineaments has been demonstrated as an important target where greater fracturing exists and where groundwater circulation from different areas comes together. Local fracturing close to the margins of intrusions has also been demonstrated as a useful local target.

Exploration techniques which examine lateral differences in rock properties, including magnetometer measurements, resistivity measurements and conductivity (VLF) and inclined borehole drilling are seen as most appropriate in these narrow vertical aquifers.

## 9. WATER RESOURCES

The outcome of this study is that the resources of the fractured aquifers at Mochudi are difficult to quantify with precision. This should not be surprising. The exact dimensions of the aquifer are not known and recharge, which is suspected, requires long term monitoring to measure it. To obtain information for precise calculation would require a large input of drilling and geophysics out of proportion to the scale of the supply. Furthermore the most important aquifer tests do not demonstrate a normal Theis response to pumping so that the interpreted aquifer properties and forecast drawdown is not as certain as it could be.

In fractured aquifers there is no way of predicting in advance the response to pumping and whether the main fractures will be dewatered during development or whether recommended yields are over-pumping or under-pumping the resource. This is why it is important to keep accurate long term records of pumping and water levels to monitor the situation. The methods used here to calculate the resources thus rely heavily on assumptions and should be viewed accordingly.

If the groundwater resources are regarded as fossil resources, i.e. without current replenishment then the quantity available can be calculated from the dimensions of the aquifer and its appropriate storage properties. If for example the existing wellfield aquifer is 10 km long by 0.5 km wide (a reasonable assumption) with a specific yield of 1% then the yearly abstraction would produce a fall in water level of 5 m. This would have occurred each year since production started and if it were the case then the water levels would now be 60-70 m below surface and the boreholes would be dry.

However it is believed that there is a certain amount of current recharge. Nitrate pollution and a reducing chloride content after rain (see Figure 34 and 35) is some evidence for this, and the ability of the boreholes to sustain production is another indication. An evaluation of recharge thus requires consideration of the hydrological processes involved.

## 9.1 Hydrological processes

The hydrological processes involved can be summarised quite simply. Rain falling on the surface in the normal wet months of November, December, January and February is partitioned into run-off and infiltration by the soil and weathered zone. Where there is little soil cover, on rock outcrop for example, water may reach the watertable relatively quickly through fracture connections, otherwise water enters soil moisture storage. When rainfall is insufficient to saturate soil moisture and unsaturated weathered zone storage to field capacity little or no run-off occurs and there is no excess infiltration to become recharge. After soil moisture and unsaturated zone storage is raised to field capacity both run-off and groundwater recharge can occur and groundwater levels will begin to rise.

Throughout this process evapotranspiration is occurring and water is lost from the soil to crop growth, and the aquifer loses water to natural flow processes. These losses continue through the dry season and aquifer water levels are expected to reach their lowest immediately prior to the onset of the rains.

Under the prevailing climatic conditions in Botswana an excess of water over soil moisture and evapotranspiration requirement is rather rare so that recharge through the soil can be expected to occur only occasionally, perhaps only once or twice in several years.

In areas where the soil is thin or fractured rock is exposed it is expected that recharge occurs more easily and may be the dominant process. This could partly explain why water levels generally rise above water strikes during drilling.

### 9.2 A water balance

A water balance calculation is useful in summarising the hydrological processes and in obtaining estimates of different components of the hydrological cycle. Because of the difficulties of measurement and the particular uncertainties in the evapotranspiration estimate and soil moisture storage a precise water balance cannot be attempted for the area studied. Such a study would require a controlled experiment in a natural catchment. Despite these uncertainties and the likelihood that errors in the estimates would exceed the value of recharge obtained the method is useful in giving a guide to the probable quantities involved. A simplified balance written for groundwater recharge is as follows:-

$$Gr = P - EA - \Delta Sm - RO$$

Where:

Gr = groundwater recharge

P = rainfall

EA = losses by evapotranspiration

$\Delta Sm$ = change in soil moisture/unsaturated zone storage

RO = river run-off

The largest uncertainty is in the evapotranspiration factor. Actual evapotranspiration is not normally known so that it is usually replaced by a calculated amount (potential evapotranspiration). Potential evapotranspiration (PE) is a theoretical calculation of the amount of water that can be removed by transpiration of vegetation when sufficient water is available in the soil to meet the demand. In humid countries this concept is relatively close to real conditions, but in arid and semi-arid countries the supply of soil moisture is limited, crops always wilt and the potential figure greatly exceeds the actual evapotranspiration.

Potential evapotranspiration estimates for Mochudi are shown in Table 17. Potential evapotranspiration is highest from October - February (160 mm/month) reducing to minimum values (40 mm/month) in June and July. Table 17 reveals that potential evapotranspiration always exceeds mean monthly rainfall and the probability of mean monthly rainfall exceeding PE is very low (0.15). On a monthly mean basis the water balance thus never allows any recharge. It is more useful therefore to consider actual rainfall over shorter periods and this has been done in Figure 33 where actual rainfall is compared with PE over 10-day periods between July 1982 and June 1983. The excess rainfall over evaporation for this period is 94 mm. (See also Table 18).

## 9.3 Groundwater Recharge

It is likely that two recharge mechanisms exist. A slow diffuse infiltration through the soil and a more rapid infiltration through fractured rock outcrop. Before diffuse recharge can occur it is expected that the soil moisture deficit must be satisfied. This has not been measured but has been estimated from measurements of soil moisture at Sebele supplied by J. Sinclair (personal communication). These measurements show a seasonal depletion in the top 0.9 m of soil of ∿ 100 mm. A certain amount of storage will exist in the unsaturated zone between the soil and the watertable. At 0.4-0.5% porosity this would require 100-125 mm so that an unsaturated and soil moisture deficit of ∿ 200 mm must be satisfied before diffuse recharge can occur.

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean max. temperature (°C) | 32.6 | 31.2 | 31.1 | 27.2 | 24.6 | 22.2 | 22.3 | 25.5 | 29.1 | 30.7 | 32.2 | 32.[illegible] | |
| Mean min. temperature (°C) | 19.7 | 19.0 | 18.0 | 13.1 | 7.6 | 4.0 | 3.6 | 6.5 | 11.9 | 15.5 | 17.5 | 18.4 | |
| Average air temperature (°C) | 26.1 | 25.1 | 24.5 | 20.1 | 16.1 | 13.1 | 12.9 | 16.0 | 20.5 | 23.1 | 24.3 | 25.2 | |
| Average downpoint (°C) | 15.5 | 15.8 | 14.2 | 11.3 | 6.3 | 2.1 | 1.4 | 2.2 | 4.4 | 8.6 | 12.0 | 11.4 | |
| Radiation ($M/m^2$) | 200 | 206 | 182 | 136 | 138 | 124 | 131 | 153 | 180 | 186 | 177 | 214 | |
| $^1$Potential evapotranspiration (mm) | 163 | 133 | 118 | 75 | 53 | 32 | 36 | 74 | 119 | 161 | 155 | 160 | 1278 |
| $^2$Potential evapotranspiration (mm) | 156 | 141 | 157 | 123 | 122 | 114 | 118 | 140 | 160 | 165 | 153 | 173 | 1724 |
| $^2$Actual evaporation (mm) | 17 | 21 | 2 | - | - | - | - | - | - | | 10 | 8 | |
| Pan evaporation (mm) | 293 | 226 | 214 | 157 | 138 | 106 | 124 | 184 | 259 | 309 | 286 | 298 | |
| $^3$Mean precipitation (mm) | 96 | 79 | 59 | 39 | 12 | 5 | 4 | 4 | 13 | 39 | 62 | 89 | 501 |
| P. rain = $^1$PE | 0.11 | 0.10 | 0.13 | 0.14 | 0.05 | 0.11 | 0.02 | 0.001 | 0.001 | 0.02 | 0.04 | 0.11 | |

$^1$10 day mean totals (MSD)

$^2$Morton (1978)

$^3$Mean monthly 1931-82 Mochudi

Table 17: Evaporation estimates, Gaborone data

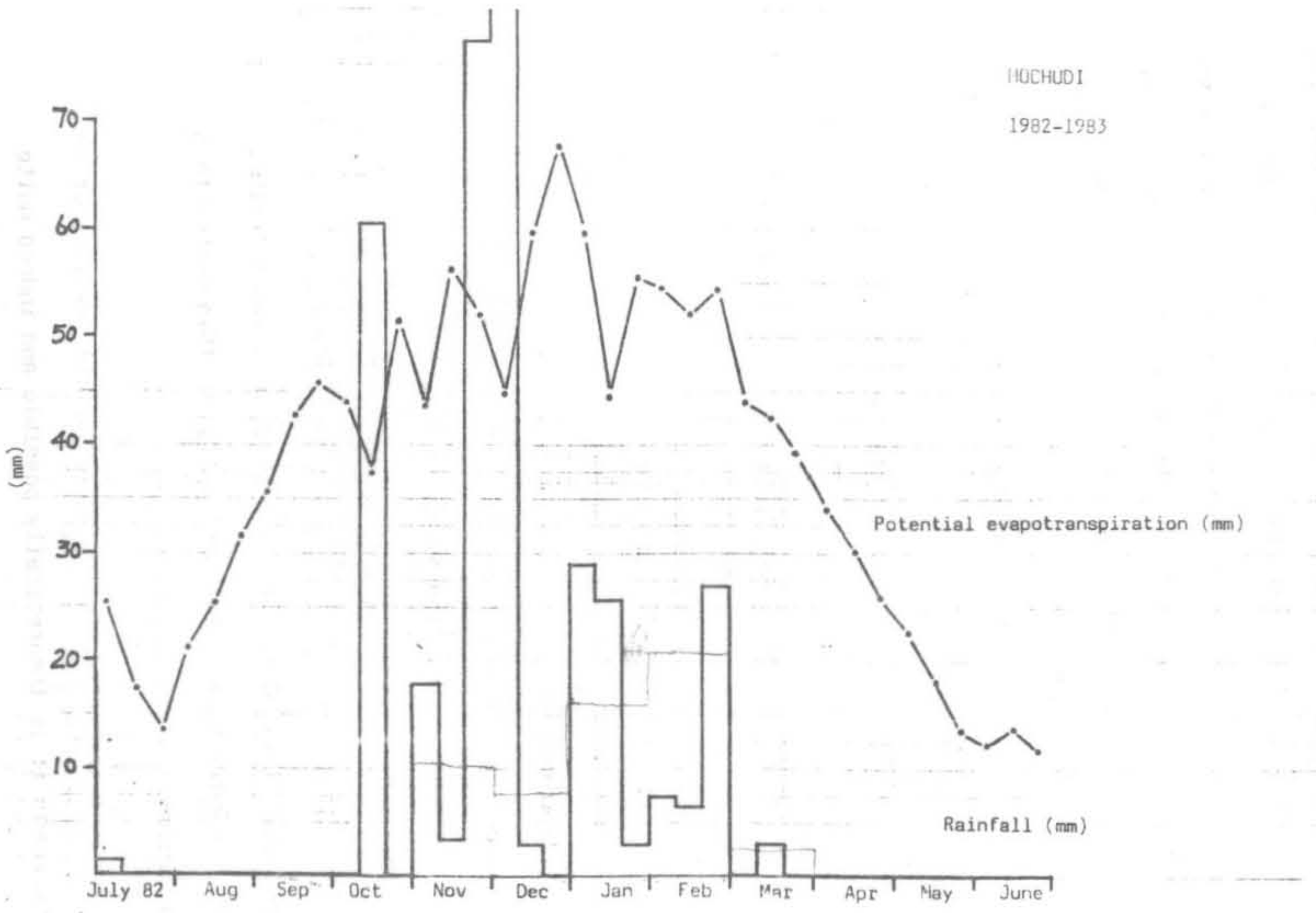

Figure 33 10 day rainfall and potential evaporation, Mochudi 1982 – 1983

If the unsaturated zone storage requirement is 200 mm then only 3 rain events during the 13 year period, 1970-83, (1975, 1977 and 1978) were sufficient to generate recharge and runoff and only 37 mm was available. If it is assumed that the unsaturated requirement is only 100 mm then a much larger amount is available for recharge, totalling 475 mm or a mean annual amount of 36 mm. Obviously actual soil moisture and unsaturated storage amounts are needed to analyse events in this way.

Although potential evapotranspiration estimates have been used in the calculation actual evapotranspiration rates control water losses. Estimates of recharge using potential rates are therefore likely to be underestimates.

Morton (1978, 1983), presented a method for calculating actual evapotranspiration, and estimates using this method are included in Table 17. Note that these are very much lower than potential estimates and during the period April-November they suggest there is no actual evapotranspiration (for reasons of soil dryness). This is close to what is observed at Sebele where evapotranspiration (and drainage) losses from the soil between 28 May and 8 October 1982 were very small (5.29 mm). Lack of reliable runoff data prevents further analysis of the water balance but application of this method to a controlled catchment would be interesting.

However in a fractured aquifer consisting of vertical or sub-vertical channels it is theoretically possible and indeed quite likely that the quantity of water received by a fracture could exceed the rainfall because the catchment area to the fracture is much larger than its surface area, and under these circumstances a water balance approach will not work. A more appropriate and certainly more convenient method of assessing recharge is therefore to record water level fluctuations and to relate changes to an aquifer storage.

PENMAN POTENTIAL EVAPOTRANSPIRATION (MM) 10 DAY TOTALS, MOCHUDI FAO/BMS

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 55 | 47 | 42 | 31 | 22 | 12 | 10 | 20 | 34 | 50 | 52 | 53 | |
| 2 | 55 | 44 | 41 | 24 | 17 | 10 | 11 | 24 | 40 | 56 | 51 | 53 | |
| 3 | 52 | 42 | 35 | 20 | 14 | 10 | 15 | 30 | 45 | 55 | 52 | 54 | |
| Total | 162 | 133 | 118 | 75 | 53 | 32 | 36 | 74 | 119 | 161 | 155 | 160 | 1278 |

| Year | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Excess rain-fall (mm) | 25 | 125 | 48 | 52 | 143 | 235 | 140 | 201 | 201 | 117 | 73 | 153 | 85 |
| Rain Events >PE | 2 | 4 | 3 | 3 | 7 | 6 | 6 | 4 | 4 | 2 | 2 | 6 | 4 |

Table 18.10-day mean Penman potential evapotranspiration and excess rainfall events, Mochudi 1970-82

Water level recorders were installed for this purpose on boreholes in May 1983 and water level rises were recorded in borehole 38 during November and December 1983 (5 events), which will be used for calculation of an aquifer storage.

## 9.4 Aquifer storage

Another method of estimating recharge is to calculate the present wellfield abstraction in terms of recharge over the area of aquifer and to see if the amount is reasonable. When considered in conjunction with aquifer storage the recharge estimate can be compared with water level decline.

Only two estimates of aquifer storage ($1\times10^{-2}$, $1\times10^{-4}$) are available for the granite-gneiss aquifer and one ($1\times10^{-2}$) for the Waterberg rocks. It was assumed earlier that the aquifer supplying the village was 10 km long and 0.5 km wide and if this is reasonable the 1982 abstraction is equivalent to 50 mm recharge over the full area. This is a large amount (10% of the rainfall) and is an indication that current abstraction is probably in excess of balanced recharge.

If current recharge is say half of the abstraction (25 mm) then water levels would have to drop by 2.5 m to account for the water removed. Measurement of water level in borehole 38 showed a water level decline of 3.028 m between January and October 1983 during which time abstraction was 240 000 $m^3$. An aquifer storage of 1.6% or a reduction in storage equivalent to 30 mm is indicated.

The regional water level decline that occurs under development in a fractured aquifer may not be as uniform and predictable as in a natural aquifer and well yields could dramatically reduce if water levels are lowered regionally to the principal inflow levels. If this occurs those boreholes having water strikes closest to the watertable would be affected first.

As a provisional estimate to be modified when data becomes available, recharge to the aquifers at Mochudi could be within the range 0-20 mm/year (0-4% of rainfall). In any event it is not likely that a limit to abstraction could be placed on the existing supplies from the current knowledge of recharge. Development of the aquifers to the north and south of the village should be monitored in order to obtain data for such an analysis.

### 9.5 Recommended pumping rates

Abstraction is recommended from borehole 4198, 4202, 4232 and 4234 (4266) south of the village, and from 4258/4345/4346 and 4448, north of the village. The three boreholes 4258 etc. are all close together and in practice only, one, the most efficient, should be used.

Pumping rates have been calculated south of the village assuming a Theis drawdown and pumping rates have been selected so that pumping water level does not reach breakaway position within 500 days. The recommended rates are given in Table 14 from which the quantity of water available from the boreholes south of village is 360 $m^3/d$. Selecting a pumping rate for the Waterberg aquifer boreholes 4258 etc. and 4448 is more difficult because the aquifer response does not fit the Theis model. On the basis of testing at high pumping rates and extrapolation of the drawdown, a pumping rate of 30 m/h (720 $m^3/d$) is provisionally recommend from both sites provided water level monitoring is carried out. The quantity of water available from both areas is thus 1800 $m^3/d$.

## 10. POLLUTION

Mochudi has a certain notoriety as regards pollution because a survey once identified the village as one of the worst affected of all major villages in the country. Several pollution studies have therefore rightly or wrongly focussed on Mochudi. For this reason a fairly full account of the pollution situation is given in this section.

### 10.1 Introduction

Pollution in Mochudi concerns high nitrate and bacteria in the water supply.. High levels of nitrate in excess of the WHO limit (45 mg/l) were not suspected in groundwater in Botswana until investigations by the GS10 Project discovered $No_3^-$ in some Serowe village boreholes during sampling in September and December 1975. Following this discovery a rapid reconnaissance of the major village waters at Mochudi, Thamaga, Molepolole, Moshupa, Kanye and Ramotswa (Hutton, Lewis, and Skinner, 1976) revealed that high nitrate was present in most villages and very high nitrate (exceeding 500 mg/l) was observed in some boreholes.

High amounts of nitrates are known to cause methaemiglobinaemia in infants. Those less than 6 months old are at greatest risk, and the nitrate cannot be removed by boiling. An international standard upper limit of 45 mg/l $NO_3^-$ is accepted by most countries but some believe a higher limit to be safe. For example West Germany and Switzerland allow 90 mg/l $NO_3^-$. In arid countries dependent on well water higher safe levels allow more water to be regarded as potable so that a higher upper limit is reasonable. Botswana currently adopts an upper limit of 100 mg/l, and if no alternative supply is available waters containing >100 mg/l could be considered.

The source of high nitrate in groundwater is currently under investigation in many countries where it is often related to intensive farming and application of nitrogen fertilizer. In Botswana this source is ruled out and the most likely source is from human and animal excreta. The high nitrate content observed at some cattle-post boreholes supports this idea. A recent study (Heaton, Talma and Vogel, 1983) suggested that some nitrates (up to 100 mg/l) do exist naturally in some Kalahari aquifers which are unaffected by pollution. There is however little doubt that the high nitrate and fecal bacteria in waters at Mochudi, and the other villages, is due to contamination from pit latrines as several studies have shown.

## 10.2 Previous pollution studies

### 10.2.1 Hutton, Lewis and Skinner, January 1976

During the original survey by Hutton, Lewis andSkinner in 1975, 9 boreholes with high nitrate were identified in Mochudi. All of these, significantly were north of the river. Two boreholes south of the river (850, 2108) were unaffected as the table below shows:

| | Nitrate (mg/l) | | | Nitrate (mg/l) | |
|---|---|---|---|---|---|
| Borehole | Jan. 1976 | May 1976 | Borehole | Jan. 1976 | May 1976 |
| 35 | 199 | 208§ | 1018 | 514 | 603 |
| 38 | 346 | 414 | 1162 | 100 | 75 |
| 789 | 284 | 363 | 2108 | 18 | 15 |
| 792 | 170 | 203§ | hospital dam | 503 | 584 |
| 850 | 8 | 5 | tap water sec. sch. | 21 | - |

§ Coliform bacteria present.

The intermittent presence of fecal bacteria in the standpipe and tank samples in sections of pipework remote from a possible connection with a contaminated borehole evident in Figure 34 does suggest contamination from the soil through the pipework. It is a fact that the pipe joints of the Mochudi reticulation are of poor quality and fairly regular pipe failures leading depressurisation do occur. It is more likely thereforethat the standpipe contamination is from this source.

### 10.4 Summary and recommendations

The source of high nitrate and chloride in part of the Mochudi water supply is from pit latrines. These contaminants enter the soil and the aquifer from latrines in an area of high housing density north of the river. The potential for contamination from latrines is always present but is particularly high in areas of thin soil and rock outcrop. The intermittent presence of fecal bacteria in borehole 850 indicates a contamination of the aquifer close to the borehole or direct contamination via the borehole itself. Other instances of contamination are thought to arise by contact with soil water through leaky pipe joints following depressurisation. Note:

(1) The source of pollution cannot be removed. Each house or household requires a pit latrine and there is little that can be done to restrict the numbers nor to modify the design to minimise the risk except to avoid fracturing the rock during construction. Some improvement in the location of future latrines could be made but there is limited scope in this direction.

(2) Replacement of the polluted sources by new supplies is a solution. Sufficient good quality water is available from the area to the north of the village that borehole 2784 and

3990 could be taken out of service. However it is recommended that construction of a central storage tank with chlorine treatment should be incorporated into the system using the new water.

(3) If a central storage, distribution and treatment plant was constructed it would allow waters from the various sources to be mixed so that existing high nitrate water could be used as and when required. At present this is not possible because the water goes straight to supply. Central chlorination would also be simpler to administer than the individual chloring dosing at each borehole.

(4) A phased development based on individual borehole connections to a central storage tank is also most logical for future development. New supplies could be connected when discovered and poorer quality existing supplies could be used in emergencies. A site north of the river on the high land is recommended because new sources are likely to come from that direction and the higher land provides convenient elevation for distribution.

## 11. SUMMARY AND CONCLUSIONS

1. Borehole 4345 and 4448 in an area of Waterberg rocks 10 km north of the village near Malotoana can together supply ∿ 1500 $m^3/d$ of good quality water.
2. Borehole 4234, 4198 and 4202 in an area of granite-gneiss 8 km south east of the village could be developed to supply 360 $m^3/d$. The water from both areas is free of high nitrate and is suitable for all domestic purposes. Together supplies from both areas are sufficient to meet the anticipated demand of the village to 1991 (∿ 1800 $m^3/d$).
3. All of the aquifers present in the region are fractured aquifers so that estimation of the groundwater resources is made difficult. Recharge to the aquifers is tentatively estimated to be 0-20 mm/year.
4. The long term response to pumping in fractured aquifers cannot be easily predicted and it is therefore recommended that during any abstraction the amount pumped and the aquifer water levels should be monitored. This is especially true of abstraction from the Waterberg rocks where the aquifer response appears not to follow the normal pattern.
5. Groundwater occurrence around Mochudi is restricted to a network of narrow vertical to sub-vertical fracture zones in the rocks. These are not well-developed and they separate large blocks of dry country. The most successful borehole sites are those which locate the main channels or their intersections.
6. Many of the boreholes drilled on lineaments and fractures in the present study were low-yielding or dry. This may be due to drilling on the margins of the features or may reflect a poor groundwater circulation through the most prominent lineaments. There is some evidence that groundwater circulation may actually prefer less obvious lineament and fracture zones.

7. Borehole siting methods which discriminate lineations and geophysical techniques which investigate lateral variations in rock properties are best suited to identify these aquifers. Inclined exploration borehole drilling was very successful at the one site where it was tested.
8. The Waterberg area north of the village offers better prospects for development than the granite-gneiss area. The largest borehole yields were obtained from faulting in the Masama Sandstone of the Upper Waterberg. Dolerite intrusion is frequently related to structural disturbance throughout the area and locally may improve the permeability.
9. Structures in the siltstone units of the Waterberg rocks appear less productive although this conclusion may be influenced by marginal siting, but the brittle-fracture response of the sandstone units to faulting and intrusion offers greater groundwater potential.
10. The water levels in the present village wellfield appear to be declining and an associated reduction in borehole yield is evident. This is believed due to excess current abstraction, estimated at approximately 50 mm/year, compared to current recharge, estimated approximately at 0-20 mm/year. The situation should be monitored.
11. The pollution problem in Mochudi was investigated and should be viewed as a local feature arising from a combination of circumstances. It is confined to only a small area. The pollution problem can be avoided altogether by locating water supply boreholes away from housing or areas of stock grazing.
12. It is recommended that future groundwater exploration should concentrate initially on the Masama Formation of the Waterberg rocks north and northwest of the village, and also to the east if they are identified in that area. Subsequent to the development of these

supplies further groundwater would have to come from structures in the Karoo rocks further north.

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