4. HYDROGEOLOGY OF THE SEROWE AREA

INTRODUCTION

Serowe is the administrative capital of the vast Central District and, with a de facto population of 15 723 (1971 Census), is Botswana's third largest town. As only 2 593 out of a total of 4 444 dwellings in Serowe were occupied at the time of the census because of traditional migrations to agricultural areas etc., it is possible that the population could rise to about 27 000 at certain times of the year, making it far and away the largest town in Botswana. The town is completely dependent on boreholes as a source of water for domestic and industrial needs, while a certain amount of small stock watering is carried out on the margins of the town. Prior to about 1966, little geohydrological data was available and there was concern whether the increasing demand for water, resulting from a rise in the standard of living, demographic growth and industrial development, could contiue to be met by ground water supplies or whether a supplementary source of surface water would have to be found. As a result of this concern, the Geological Survey purchased twelve water meters and installed them on key boreholes in order to obtain a quantitative estimate of the amount of water being used. At about the same time, observation boreholes were established in which water levels were measured at regular intervals, while three boreholes were equipped with automatic water stage recorders.

This programme was later supplemented by a research programme involving the regular collection of samples for tritium and chemical analysis. This latter programme was conducted in collaboration with the Nuclear Physics Research Unit of the University of Witwatersrand.

Previous reports on the hydrogeology of the Serowe area have been made by Jennings (1967) and Robins (1972).

PHYSIOGRAPHY

Serowe is situated at a mean altitude of about 1 128 metres near the eastern margin of the prominent escarpment forming the eastern rim of the Kalahari Plateau. The edge of this plateau coincides roughly with Du Toit's (1953) Kalahari - Rhodesia axis of upwarp. This plateau has a mean altitude of about 1 219m.

A number of ephemeral rivers forming part of the headwater system of the Lotsane River system drain eastwards off the escarpment west of Serowe.

An arcuate range of low hills runs northwest from Swaneng to the Serowe hills in the centre of the village and thence eastwards for several kilometres. These hills are formed by a resistant post-basalt dolerite dyke aligned along a fault. (Plate 62)

Pl. 62 Serowe - Cave sandstone in foreground. Dyke forms hills in distance.

Pl. 63 Well point - Motloutse Sand River.

EROSIONAL AND DEPOSITIONAL CYCLES

Several cycles of erosion can be recognised. The summit plain of the plateau, which forms the oldest surface present, contains a thin veneer of Kalahari sediments which are the depositional equivalents of the denudation cycles present farther east. This older surface corresponds with the African (Early-Tertiary) cycle of erosion, while several late Tertiary cycles are present forming the younger compound surface below the main escarpment.

RAINFALL

The average annual rainfall, which falls during the summer months and, measured over a 35 year period, is 468,4mm.

GEOLOGY

The following stratigraphic succession has been determined for the area (Jennings, 1965): (See Fig. 92).

TABLE OF GEOLOGICAL FORMATIONS

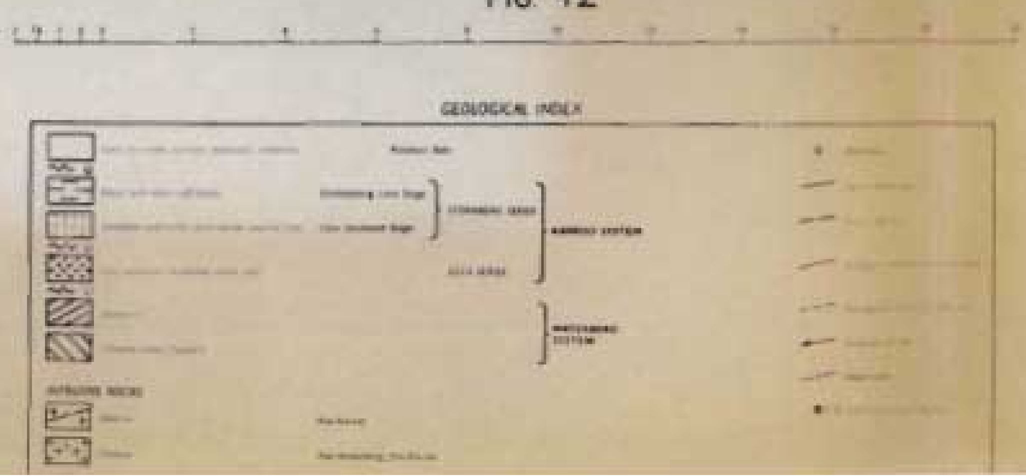
SUPERFICIAL DEPOSITS			Soil, alluvium, sand, calcrete diatomaceous calcrete
		- Unconformity -	
KALAHARI GROUP			Sand, ferricrete, chalcedonic or opaline silcrete, sandstone, silicified sandstone, limestone, conglomerate calcareous sandstone or sandy calcrete
		- Unconformity -	
KAROO SUPERGROUP	Stormberg Group	Drakensberg Lava Subgroup	Basaltic lava with minor tuff bands
		Cave Sandstone Subgroup	Sandstone minor limestone, marl and shale.
		- Unconformity -	
	Ecca Group	Upper Ecca Subgroup	Mudstone, siltstone and coal
	Dwyka Group	Middle Ecca Subgroup	Gritty felspathic sandstone
		- Unconformity -	
WATERBERG SUPERGROUP		Lotsani Shale Group	Quartzite, dark grey, pink, purple and khaki shale and siltstone
INTRUSIVE ROCKS			
Dolerite			Karoo age
Diabase			Post Waterberg Supergroup [illegible]

GEOLOGICAL SURVEY OF BECHUANALAND

GEOLOGICAL MAP OF THE SEROWE AREA

QUARTER DEGREE SHEET

FIG. 92



WATERBERG SUPERGROUP

A small inlier of flat-lying grey and red banded flaggy siltstones is exposed three kilometres northeast of Serowe. In addition, two boreholes drilled just north of the village encountered Waterberg Supergroup shales below about 30m of sandstone of the Cave Sandstone Subgroup.

KAROO SUPERGROUP

Virtually the whole of the Serowe area is underlain either by lavas or sandstones of the Stormberg Group.

Stormberg Group -

Cave Sandstone Subgroup

This subgroup consists of fine-grained white, pink or buff standstone with less permeable marl and shale towards the base of the subgroup. The sandstone attains a thickness of about 100 m. Just northeast of Serowe the Cave Sandstone overlaps onto pre-Karoo Waterberg Supergroup shaley siltstone which probably represents a pre-Karoo topographic high.

Drakensberg Lava Subgroup

The Cave Sandstone is overlain in the Serowe area by up to 137 m of basaltic lavas poured out in a series of flows of varying thickness.

INTRUSIVE ROCKS

A major post-Karoo dolerite dyke forms a prominent arcuate line of hills in the Serowe area. Amygdales were noted in one locality in this dyke indicating that, at the time of intrusion, the Karoo cover was probably not very thick.

KALAHARI GROUP

A thin succession of unconsolidated sands, ferricrete and silcrete form a capping less than 15 m thick at the top of the escarpment west of Serowe.

HYDROGEOLOGY (See Fig. 94)

In Serowe the basalt/sandstone contact and the Cave Sandstone itself form the main aquifers. Recent deep drilling into the Ecca Subgroup has proved the presence of a further deep-lying aquifer. Boreholes in northern and northeastern Serowe, e.g. 489, in the area of Cave Sandstone outcrop, are generally low-yielding because faulting followed by erosion has resulted in only the lower portion of the Cave Sandstone subgroup being present. Because this lower section consists largely of marl and shale, boreholes sunk on the eastern upthrow side of the Serowe fault are generally blank or low yielding and often have poor quality water.

Elsewhere good yields are obtained on the basalt/sandstone contact with further supplies being obtained at greater depth in the sandstone itself. An example of this is borehole 11, which gave a tested yield of 57 litres per minute for a borehole depth of

85m,but gave a yield of 114 litres per minute when the borehole was deepened to 122m. Borehole 670, north of the hospital, obtained a supply if over 190 l/min. in the basalt itself, probably in a basin of decomposition in the basalt. On sustained pumping, this yield dropped to 38 l/min which is the average yield of water encountered at the basalt/sandstone contact. It is interesting to note that this borehole is rapidly recharged in the rainy season with consequent large rises in water level (See Fig. 93). These are accompanied by noticeable differences in tritium levels and chemical composition in the water.

As in the Orapa area, water encountered on the basalt/sandstone contact probably enters the borehole along fissures and solution cavities in the calcareous sandstone near the contact.

Boreholes drilled through the Cave Sandstone into the underlying Waterberg shaley siltstones north of Serowe, are invariably blank or low yielding because of the low permeability of these sediments (e.g. Borehole 485, blank).

An examination of borehole sludge samples from Borehole 1056 (yield 15 l/min.), situated south of a prominent dyke indicated that the dyke dipped southwards and had been intersected by the borehole between 43 and 58m. Three further successful boreholes were then sited to intersect this dyke at greater depths than in 1056 and resulted

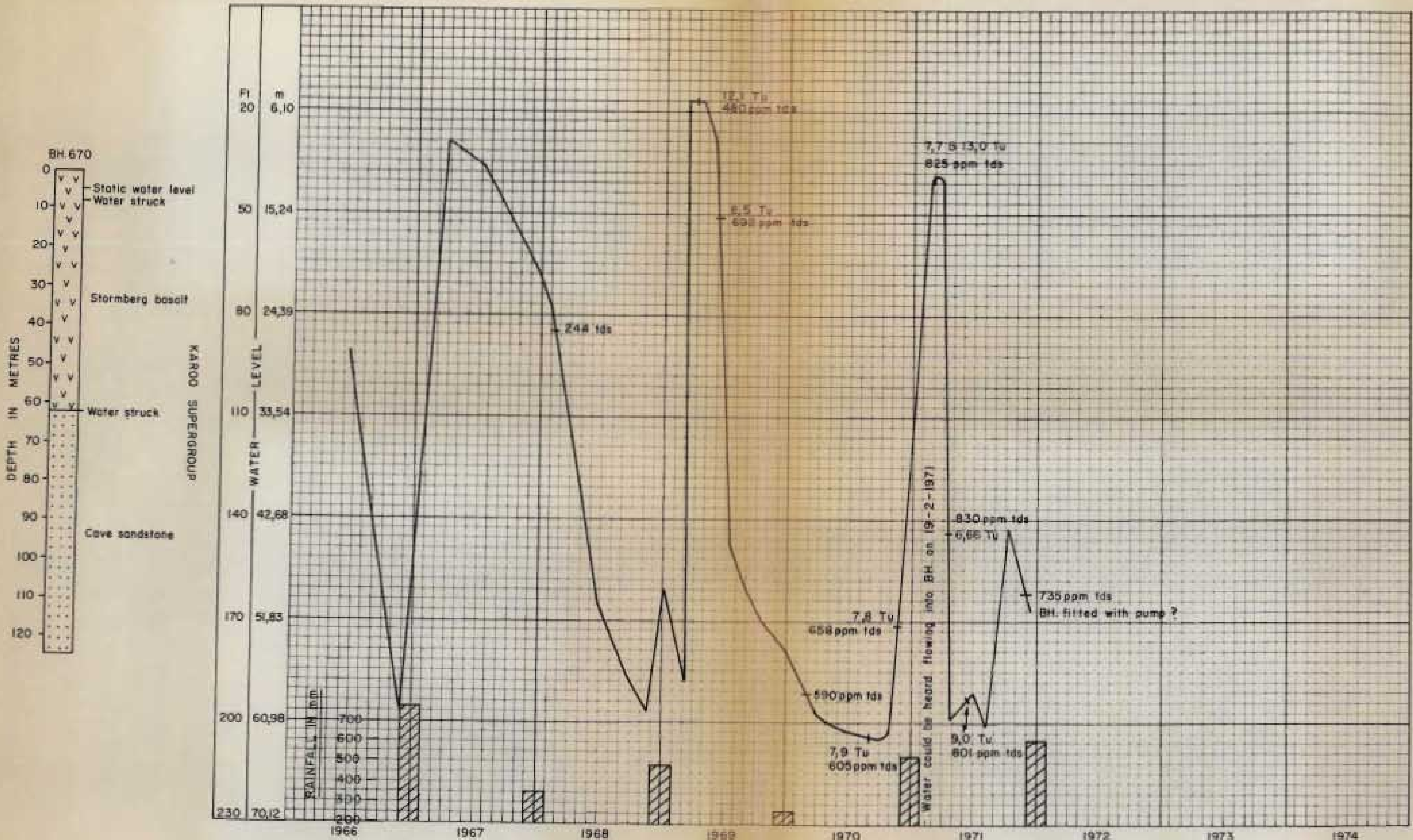


Fig. 93 HYDROGRAPH BH. 670 — SEROWE

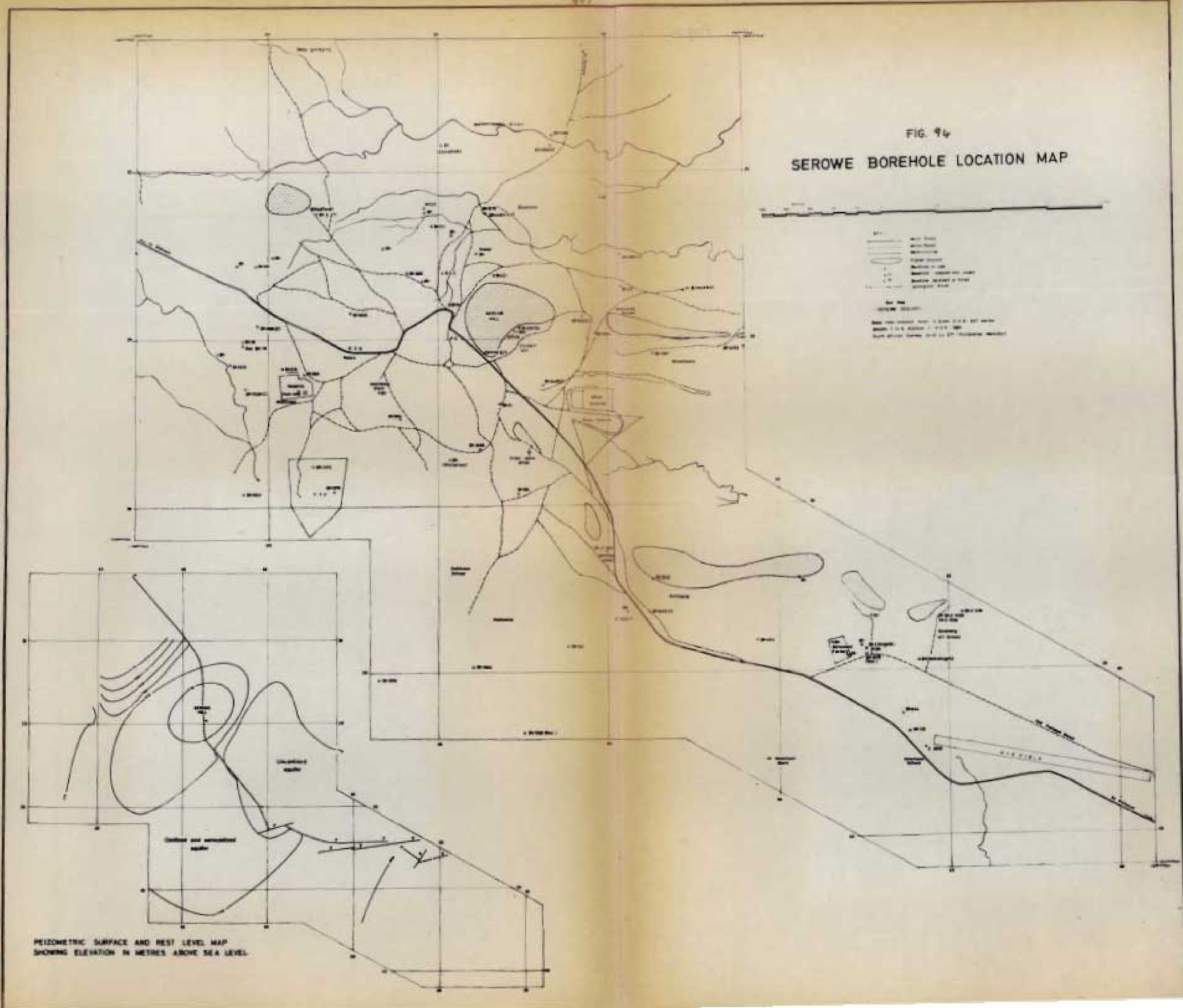


FIG. 94

SEROWE BOREHOLE LOCATION MAP

in yields of 80, 114 and 137 l/min. respectively for boreholes 1387, 1684 and 2453 respectively. These boreholes were sited in an area where previously privately drilled boreholes had proved blank because of the thick shale succession underlying only about 30m of Cave Sandstone.

A recent deep test borehole (number 2446) in the area east of the fault has given important information on the Stormberg/Ecca relationship.

This borehole passes through Stormberg Subgroup sediments and a thick succession of clay and shale (Ecca) into Middle Ecca Subgroup grits. It appears therefore that Beaufort Subgroup sediments are completely absent. An abbreviated log is given below:-

0 - 28m	Cave Sandstone	Stormberg Group
28 - 110m	Pale green clay	
110 - 179m	Dark grey shale with clay intercalations near the top	Ecca Group
179 - 215m	Ecca grit	

This borehole encountered water at 30, 163 and 210m, has a static water level of 29,11m and gave a tested yield of 167 litres per minute. This deep borehole has therefore revealed that, in addition to occasional perched aquifers present in the Stormberg basalt, on the basalt/sandstone contact, and within the Cave Sandstone itself, a fourth aquifer is present at a depth of approximately 200m in Ecca grits. This aquifer produces water of poor quality with over 2 000 parts per million total dissolved solids but is nevertheless potable and could form a valuable additional source of water in Serowe in years to come, as water consumption increases.

SEROWE WATER SUPPLY

The first government borehole (official number 11) drilled in Serowe, was completed on 1st December 1930. Prior to this villagers relied on springs as a source of water supply. These springs have since dried up, but probably emerged from near the basalt/sandstone contact in the vicinity of the gulley west of Serowe hill. Since 1930 some 42 successful and 4 blank or low yielding boreholes have been drilled by government in Serowe, of which 30 boreholes were for tribal use, while the remainder were drilled for government houses, schools, hospitals etc. (See Appendix 5 for list of government boreholes and yields in Serowe.) Statistics relating to these boreholes are given in Table. 51.

TABLE 51

BOREHOLE STATISTICS - GOVERNMENT BOREHOLES IN SEROWE

Total successful	42
Total blank	46
Total tested yield	61550 gph or 4663 l/min.
Average yield (successful bhs)	1465 gph or 111 l/min.
Average depth (successful bhs)	292 ft = 89m

In addition, there are a further 18 privately drilled boreholes (10 successful, 8 blank or low yielding) for which completion certificates have been submitted while it is estimated that there are a minimum of 10 further private boreholes for which no completion certificates have been submitted to the Geological Survey.

There are thus approximately 56 -yielding boreholes in Serowe all of which have been drilled with no regard to even distribution or to obtaining maximum development of the Cave Sandstone aquifer. An example of this haphazard and uncontrolled development of ground water supplies has occurred recently in the eastern suburb of Serowe (Newtown) where more than 14 boreholes are present in an area of approximately 1,6 square kilometres.

During 1967 a survey of the main water users was made and the average monthly water consumption is given in Table 52.

TABLE 52

ESTIMATED AVERAGE MONTHLY

WATER CONSUMPTION IN SEROWE (JENNINGS, 1967)

	Gallons	m^3
Tribal boreholes	1017 200	4623
Government camp	473 000	2150
Hospital and New Look Township	472 000	2145
Teachers Training College	599 000	2723
Swaneng Hill School	108 000	491
N.I.D.C.O. Factory	105 000	477
Private boreholes (estimated)	400 000	1818
Unmetered tribal boreholes (estimated)	501 000	2277
Serowe Hotel (estimated)	100 000	455
TOTAL:	3 775 000	17159

Robins (1972) estimated that current usage, allowing for industrial expansion, had risen to 30 000m^3 per month by that year, i.e. an average of 1 000 m^3 per day.

It is interesting to note that 73 per cent of the water in Serowe is consumed by an estimated 3 per cent of the population. This 3 per cent of the population (government and District Council officials, teachers, traders etc.) enjoy a considerably higher standard of living than the average Serowe resident and hence have a far higher per capita consumption of water. The present maximum pumping capacity of existing boreholes in Serowe is estimated at 56 x 111 l/min.

$$= 6217 \text{ l/min.}$$

$$= 373042 \text{ l/hour}$$

$$= 373 \text{ m}^3\text{/hour}$$

Serowe's present water needs can therefore be met by pumping all boreholes in Serowe for only 2,68 hours a day. It is thus obvious that much needless capital has been spent on drilling and pumping equipment which, had water development been invested in one authority, could have been avoided. In fact, thirteen average yielding boreholes, pumping at maximum capacity for only twelve hours a day, could provide all Serowe's water requirements instead of the current 56.

HYDROGEOLOGICAL RESEARCH

Following the realisation, in about 1966, that fairly large scale abstraction was taking place without any knowledge of resulting changes in the water table, thirteen observation boreholes (existing unused boreholes and one new borehole) were established, and water level measurements taken on a bi-monthly basis. Three of the thirteen boreholes were fitted with automatic water stage recorders. At about the same time regular sampling of water from unused and pumped boreholes was commenced for tritium and chemical analysis.

GROUND-WATER LEVELS, STORAGE AND REPLENISHMENT

No aquifer evaluation tests have been carried out in Serowe because of the continuous pumping taking place at present to keep the village supplied with water. If, however, the values for the coefficient of storage obtained for the same aquifer at Orapa are applied to Serowe, then for every square kilometer of aquifer, a total of between $5 \times 10^6 m^3$ and $26 \times 10^6 m^3$ of water will be present in storage.

A study of the hydrographs of all boreholes in Serowe shows that marked seasonal fluctuations take place which directly reflect the amount of recharge that has taken place. In the vicinity of boreholes 670 and 1510 (Figs. 93, 95) little recharge took place in the 1967/68 season and again in the 1969/70 season. In the 1966/67, 1968/69 and 1971/72 seasons major recharge took place, while less recharge occurred in the 1970/71 season. These fluctuations are generally of the order of three to five metres but, in the case of borehole 670 (Fig. 93), may be up to 60 metres.

Borehole 489 (Fig 96) is a low yielding borehole sited in the lower Cave Sandstone stage and consequently penetrated less than 30m of sandstone before going into

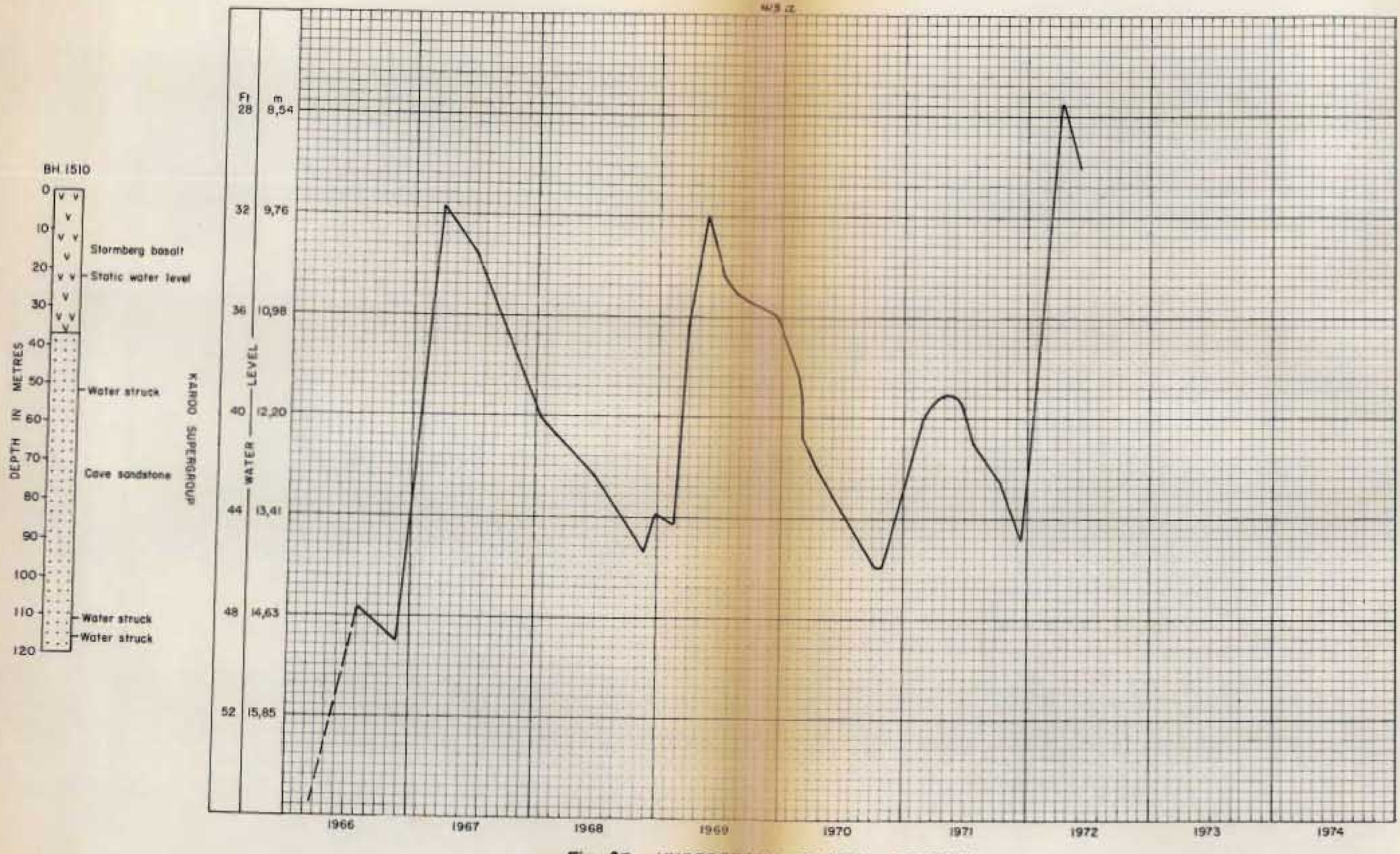


Fig. 95 HYDROGRAPH BH. 1510 — SEROWE

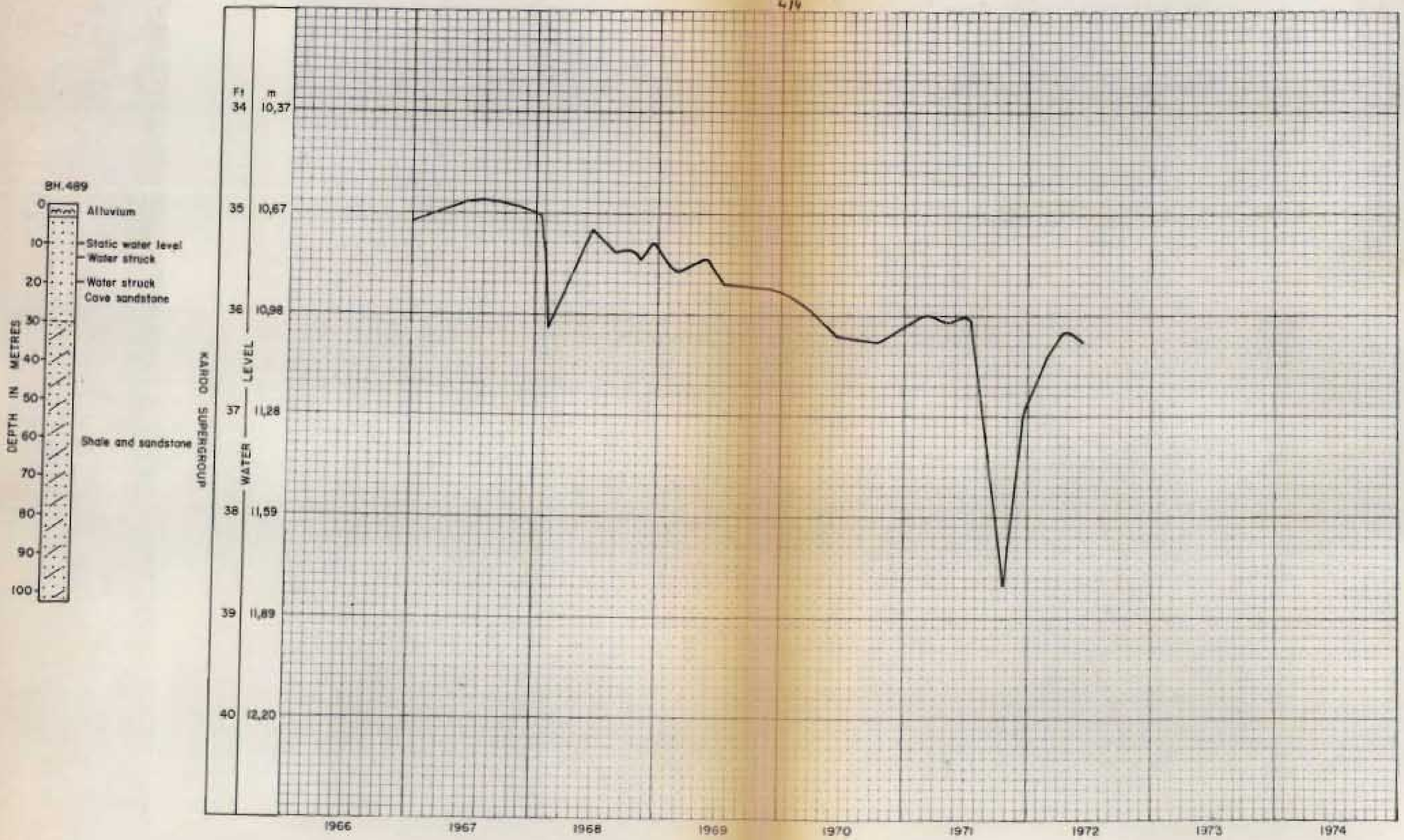


Fig. 9b HYDROGRAPH BH. 489 — SEROWE

impermeable shales. This borehole is the only borehole in the area to show a steady recession in water level. Borehole 1643 (Fig. 97) on the other hand shows a steady overall rise in water level. Because of the exact coincidence between peak rainfall and water level rises in Serowe, it is concluded that infiltration to the main Cave Sandstone aquifer takes place extremely rapidly either by direct infiltration through decomposed zones (borehole 670) joints and faults,or by direct infiltration through the unsaturated zone in areas where the Cave Sandstone is exposed. The enigma of apparent immediate rises in water level in areas in which the aquifer is confined by 50 to over 100m of basalt,can probably be explained by differences in hydrostatic loading in the unconfined areas.

Borehole 1976 (Fig. 98), shows an interesting combination of water level fluctuations due to pumping of nearby boreholes, tidal fluctuations, diurnal pressure changes and recharge due to 21,4mm of rain on 17th March 1967.

Borehole 1509 (Fig. 99),shows a rise in water level due to recharge during January and February 1972.

Recharge

Assuming an average monthly abstraction of 30 000 cubic metres of water from the Serowe area and as there has been no overall drop in water levels in Serowe since the commencement of régular water level measurements in observation boreholes in Serowe, then it may be safely concluded that at present an equilibrium

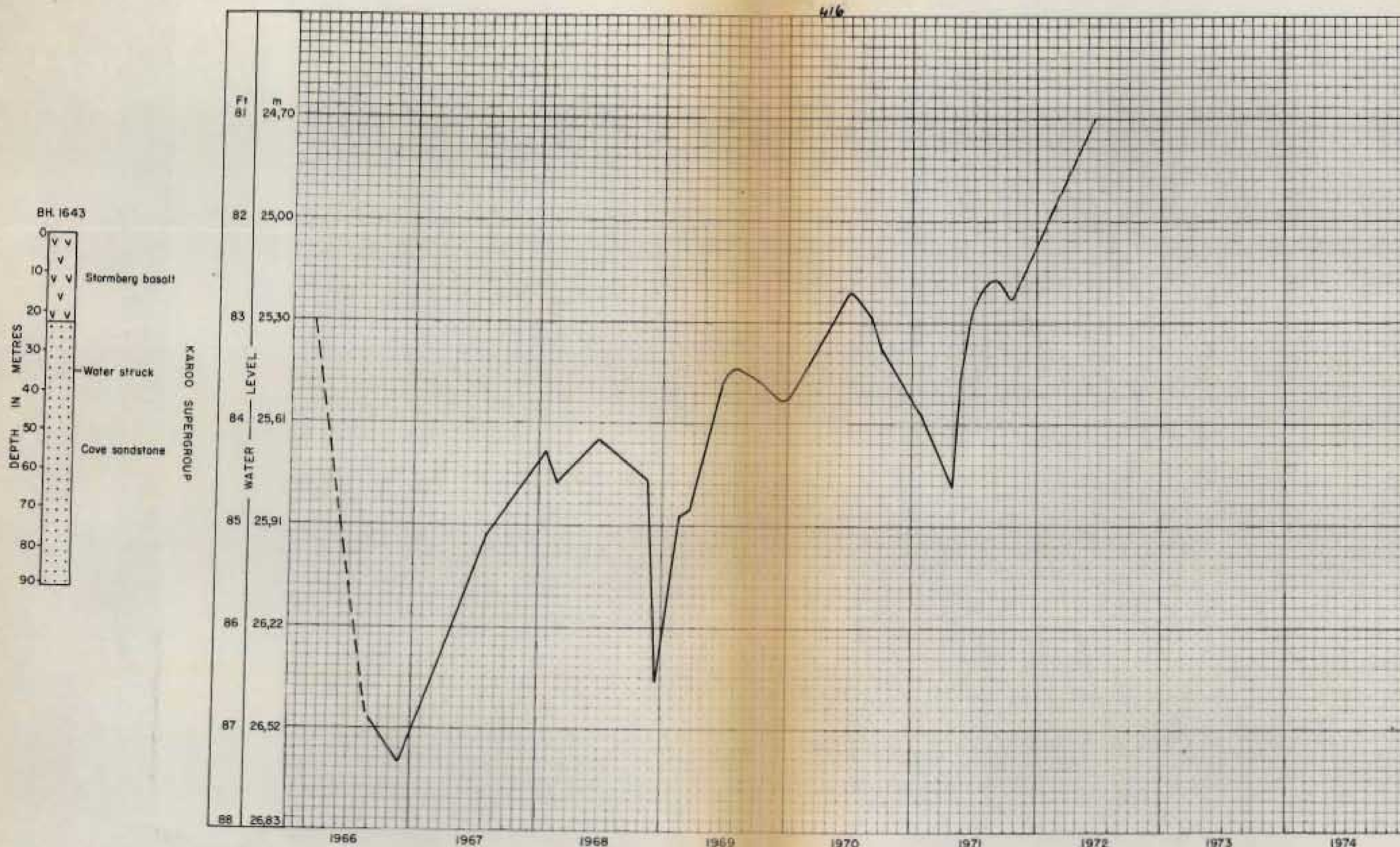


Fig. 97 HYDROGRAPH BH.1643 — SEROWE

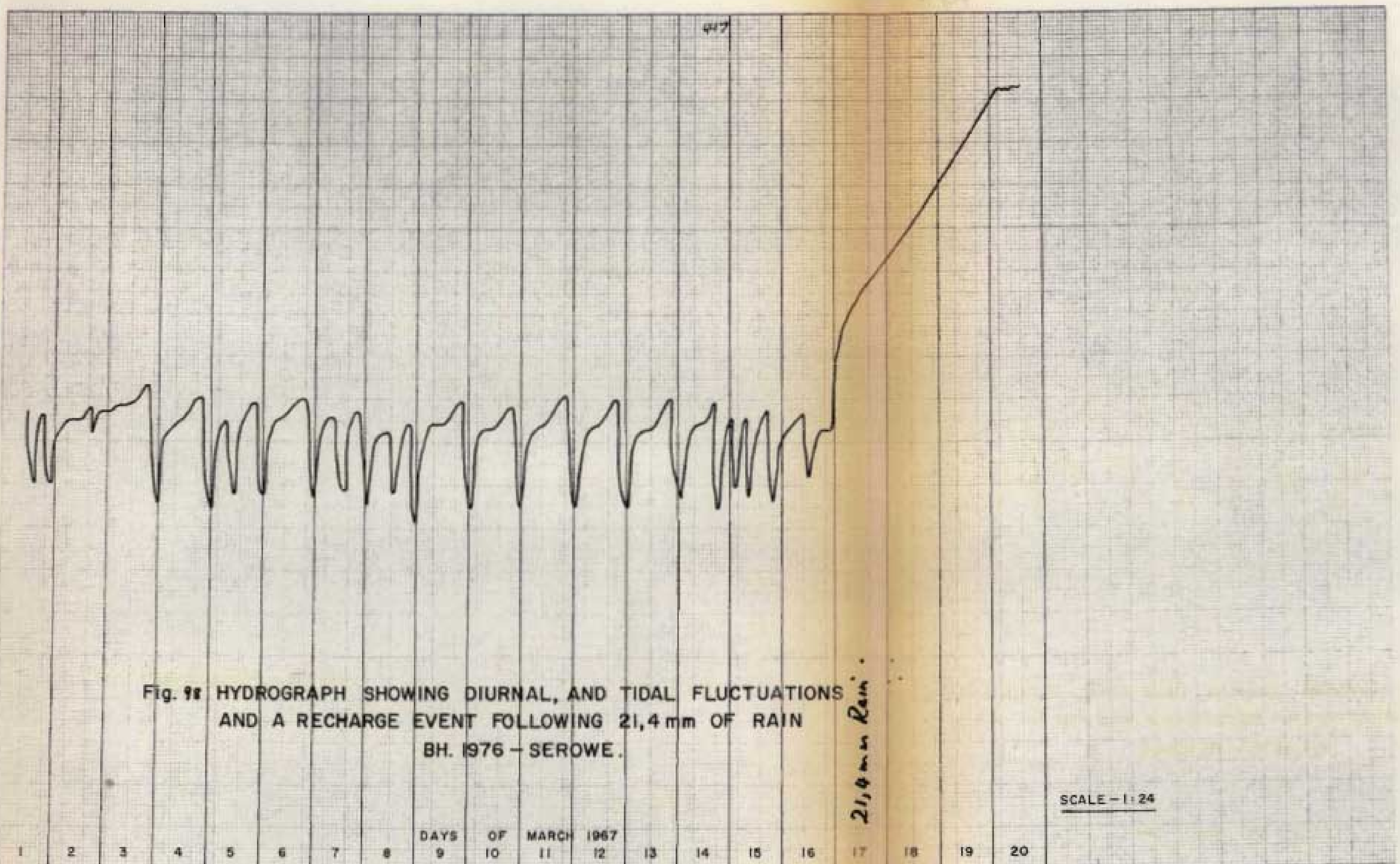


Fig. 9a HYDROGRAPH SHOWING DIURNAL, AND TIDAL FLUCTUATIONS AND A RECHARGE EVENT FOLLOWING 21,4 mm OF RAIN BH. 1976 – SEROWE.

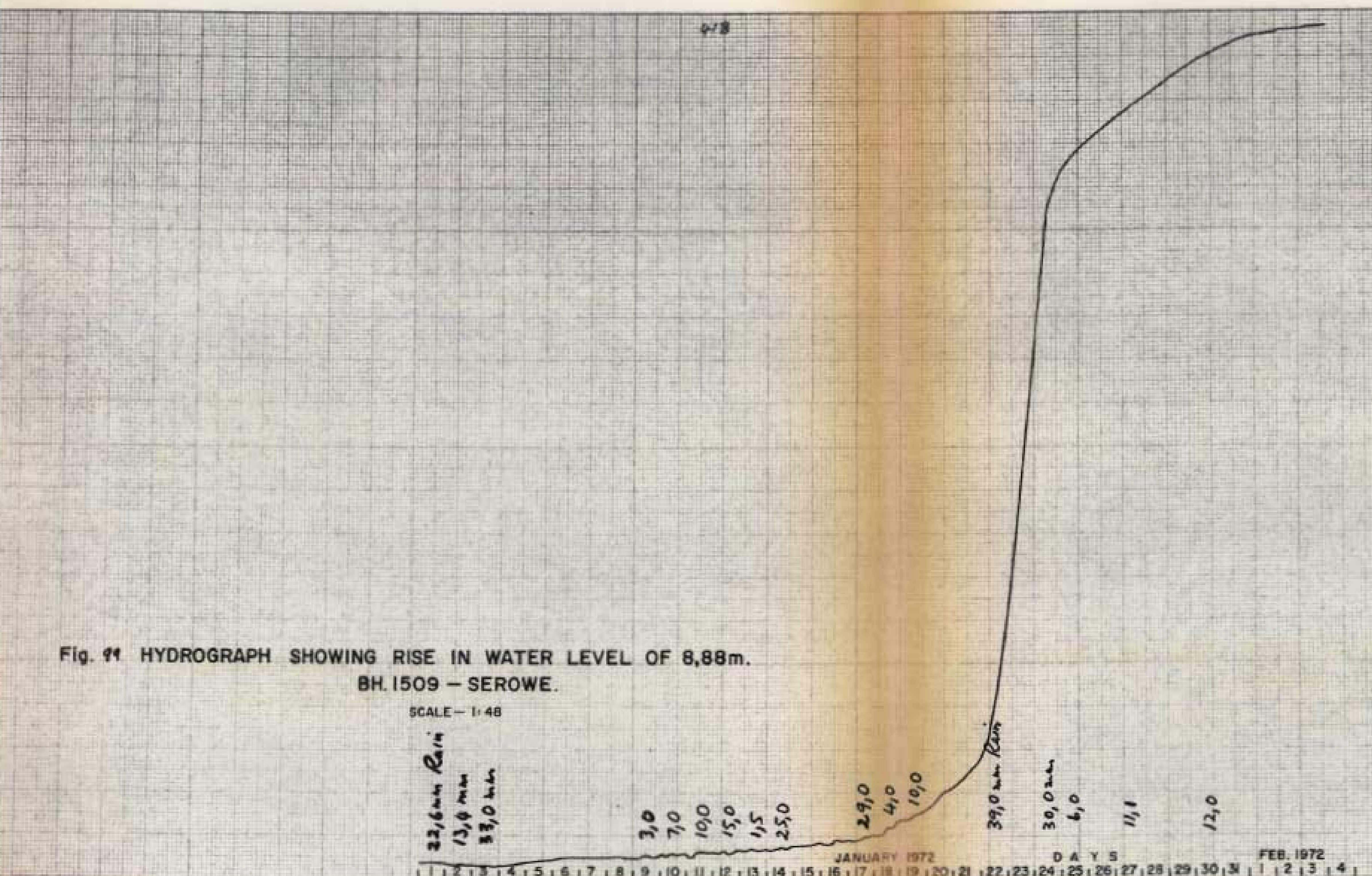


Fig. 11 HYDROGRAPH SHOWING RISE IN WATER LEVEL OF 8,88m.
BH. 1509 — SEROWE.

relationship exists between pumping and recharge i.e. An average of 30 000m^3 per month or 360 000m^3 of water are being replenished annually. Robins (1972) has shown from plotting isopiezometric levels that a ground water mound exists in the vicinity of the Serowe hill and hence that recharge takes place in this vicinity. This fits in with geological mapping of the area, which indicates that this is the main area west of the Serowe fault in which the Cave Sandstone is exposed and hence where unconfined conditions exist which facilitate direct infiltration of rain water. As geological and geomorphological conditions clearly define the limits of the recharge area, bounded on the west by a sand covered escarpment, from which no run-off can take place, and on the east by a fault and impermeable sediments, the area in which rainfall is contributing to recharge in the vicinity of Serowe hill can be fairly closely delineated and is approximately five square kilometres in extent. As an average of 500mm per annum of rain fell between 1966/67 and 1971/72, an average recharge rate of 30 000m^3 per month represents an average infiltration of 72mm per annum over this area or 14,4 per cent of the mean annual rainfall. It is possible that the above assumed recharge area is too small. This would lead to a smaller figure for the infiltration.

ENVIRONMENTAL ISOTOPE STUDIES

Results of environmental isotope studies carried out in Serowe have been described in detail in the chapter on Environmental Isotopes and only a brief summary will be given in this section.

Tritium

Systematic sampling of either pumped waters or waters sampled at different depths in unused boreholes, has shown that higher tritium values are found in waters immediately west, northwest, south and southeast of Serowe hill which generally become much lower radially from this point indicating that recharge takes place in the vicinity of Serowe hill. Robins (1972), has shown than a ground-water mound exists in this vicinity, thus lending credence to recharge being most active in this area. Evidence from two boreholes (670 and 1929) indicates that direct recharge takes place through the basalt and then slowly mixes with the whole ground-water reservoir. (See Table 53).

TABLE 53

TRITIUM CONCENTRATIONS SHOWING DOWNWARD MIXING: Bh 670 AND Bh 1929 IN SEROWE

Bh 670			Bh 1929		
Depth (metres)	TU		Depth (metres)	TU	
	3/69	6/69		3/69	6/69
15	12.0±1.8	8.7±1.0	30	15.8±1.8	8.3±0.9
60		8.8±0.9			
90	12.3±1.7	8.1±0.7	90	1.6±0.3	3.4±0.4

Borehole 1929

Water from this borehole was sampled at different depths varying from 30m to 103m. Both tritium and the chemistry show extremely interesting variations both in depth and with time.

TABLE 54

CHEMICAL STRATIFICATION IN BOREHOLE 1929

Depth :	30m	90m	107m	30
Date	23.3.69	23.3.69	23.3.69	16.5.69
pH	7,90	8,20	8,40	7,10
CO_3^{--}	-	63	57	-
HCO_3^-	115	871	910	471
Cl^-	11	36	43	14
SO_4^{--}	10	22	17	7
F^-	1	1	1	1
Total anions	137	993	1028	493
K^+	1	6	6	5
Na^+	7	225	235	43
Ca^{++}	30	107	101	69
Mg^{++}	10	32	36	31
Total cations	48	370	378	148
Sum total	185	1363	1406	641
T U	15,8±1,8	1,6±0,3	-	8,3±0,9

Depth:	60	90	107
Date	16.5.69	16.5.69	16.5.69
pH	7,65	7,65	7,70
CO_3^{--}	56	-	-
HCO_3^{-}	929	1145	1145
Cl^{-}	22	29	39
SO_4^{--}	8	12	12
F^{-}	1	1	1
Total anions	1016	1187	1197
K^{+}	7	6	6
Na^{+}	200	275	285
Ca^{++}	99	101	103
Mg^{++}	47	30	28
Total cations	353	412	422
Sum total	1369	1599	1619
T U	$3,4 \pm 0,4$	-	-

The first sampling on 23rd March 1969 was taken when the water level in the borehole was at a peak following recharge during the 1968/1969 season. Water from the 30m level was both high in tritium (15,8TU) and very low in t.d.s. content (152 ppm). At 90m however, the tritium content was 1,6T.U. while the water contained 1140 ppm t.d.s.

By 16th May 1969 the tritium content at 30m had dropped to 8,3 TU while at 60m it was 3,4 TU. Corresponding dissolved chemical content of the water was 392 ppm t.d.s. and 916 ppm t.d.s. respectively.

By 15th October 1970, the tritium content at 30m had dropped to only 1,0 TU, with a corresponding t.d.s. content of 804 ppm while by 18th february 1971, the tritium content was 0,4 TU and the t.d.s. 700 ppm. The t.d.s. on 18th February 1971, at 105m was 1168 ppm, thus showing a persistence in slight chemical stratification from the marked earlier stratification. This data is interpreted as giving clear evidence of fresh high T water replenishing the aquifer from the top and gradually mixing downwards over a period of just under two years until entirely mixed with a very large volume (relative to replenished volume) of zero T activity water stored in the main Cave Sandstone aquifer. Comparison of the hydrograph for Borehole 1929, with other hydrographs in the Serowe area, shows that the 1969/1970 season resulted in virtually no replenishment of ground water and conditions were thus ideal to determine the time taken for complete mixing of water in the aquifer (Figs. 95, 100).

Borehole 1929 penetrated only 18,29m of Stormberg basalt before encountering Cave Sandstone (Stormberg Karoo Supergroup). As can be seen in Fig.100, the water encountered in the borehole is sub-artesian and hence confined conditions must be present and water probably infiltrates in an area of exposure of Cave Sandstone nearby and then moves laterally under semi-artesian conditions. This water probably moves through the upper portion of the Cave Sandstone (but,

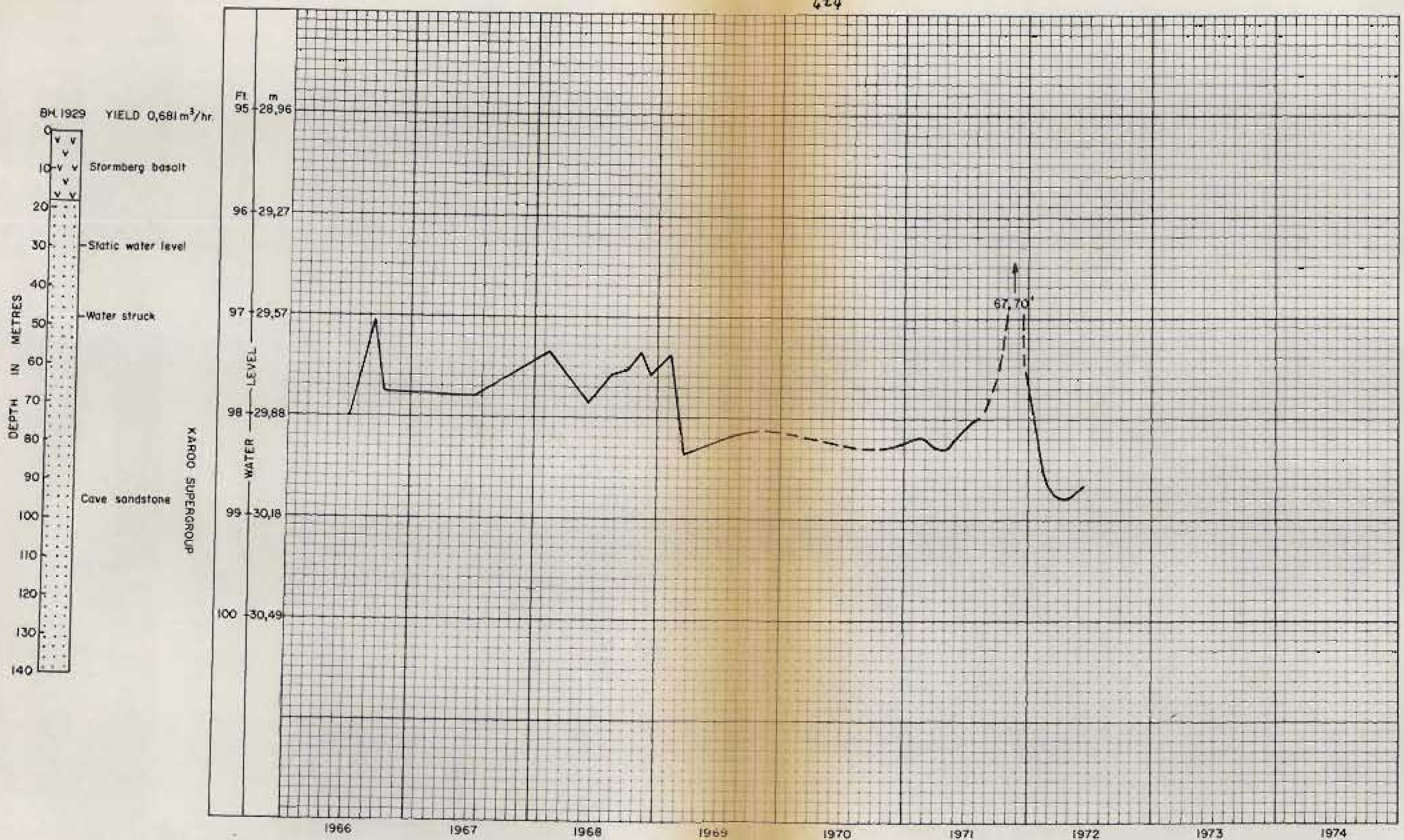


Fig. 100 HYDROGRAPH BH. 1929 — SEROWE

in this case, not apparently along the contact zone with the overlying basalt) and then mixes slowly with the main body of water present throughout the lower portions of the sandstone aquifer. This mechanism of downward mixing provides important evidence of the nature of recharge and also belies the statement made by Anon (1969) that water is probably only present in the upper portion of the Cave Sandstone aquifer.

A very high value of 22 TU was obtained for borehole 1538, situated alongside a concrete walled dam 6m high across the ephemeral Metsemasweu River, which is now completely filled with sand. This acts as an articifical recharge medium and assists direct and rapid recharge to the shallow aquifer tapped by Borehole 1538.

Carbon Fourteen

Results of carbon -14 datings are given in the Table below:-

TABLE 55

SEROWE ISOTOPE DATA (After Mazor et al 1974)

	^{14}C p.m.c.	$\delta^{13}C$ ‰	Age (yrs.)
Swaneng Hill School	103,0+2,5	-11,4±0,12	post 1952
Leitho spring	100,2±2,6	-11,4±0,20	"
Serowe Hotel (2850)	99,1±1,2	-11,04±0,27	"
Borehole 2162	94,8±2,3	-10,72±0,15	"
Borehole 1378	13,2±0,7		15200

	T.U.	$\delta D ^o/oo$	$\delta^{18}O ^o/oo$
Swaneng Hill School	3,8±0,8	-30,5±1,4	-4,03±0,09
Leitho spring	17,4±0,4	-10,9±1,4	-3,00±0,09
Serowe Hotel (2850)	0,5±0,2	-25,1±0,9	-4,98±0,1
Borehole 2162	0,7±0,2	-33,5±1,8	-4,56±9,09
Borehole 1378	1,0±0,3	-39,7 ±1,4	-6,68±0,1

Carbon-14 values range from 13,2 per cent modern carbon (pmc) to 103,0 pmc. The very high ^{14}C content in all but borehole 1378, which is confined, indicates post-1952 recharge and fits well with the known hydrogeology, i.e. all the first 4 samples were collected from areas in, or in close proximity to, the unconfined Cave Sandstone aquifer.

Stable Isotopes

Stable isotope data (Table 55) indicate that recharge takes place under conditions of heavy rainfall and in which little evaporation took place prior to infiltration. In the case of the Leitho spring some evaporation probably took place after the water emerged from underground. The deuterium values for borehole 1378 indicate that climatic conditions under which recharge occurs have not changed over at least the last 15 200 years.

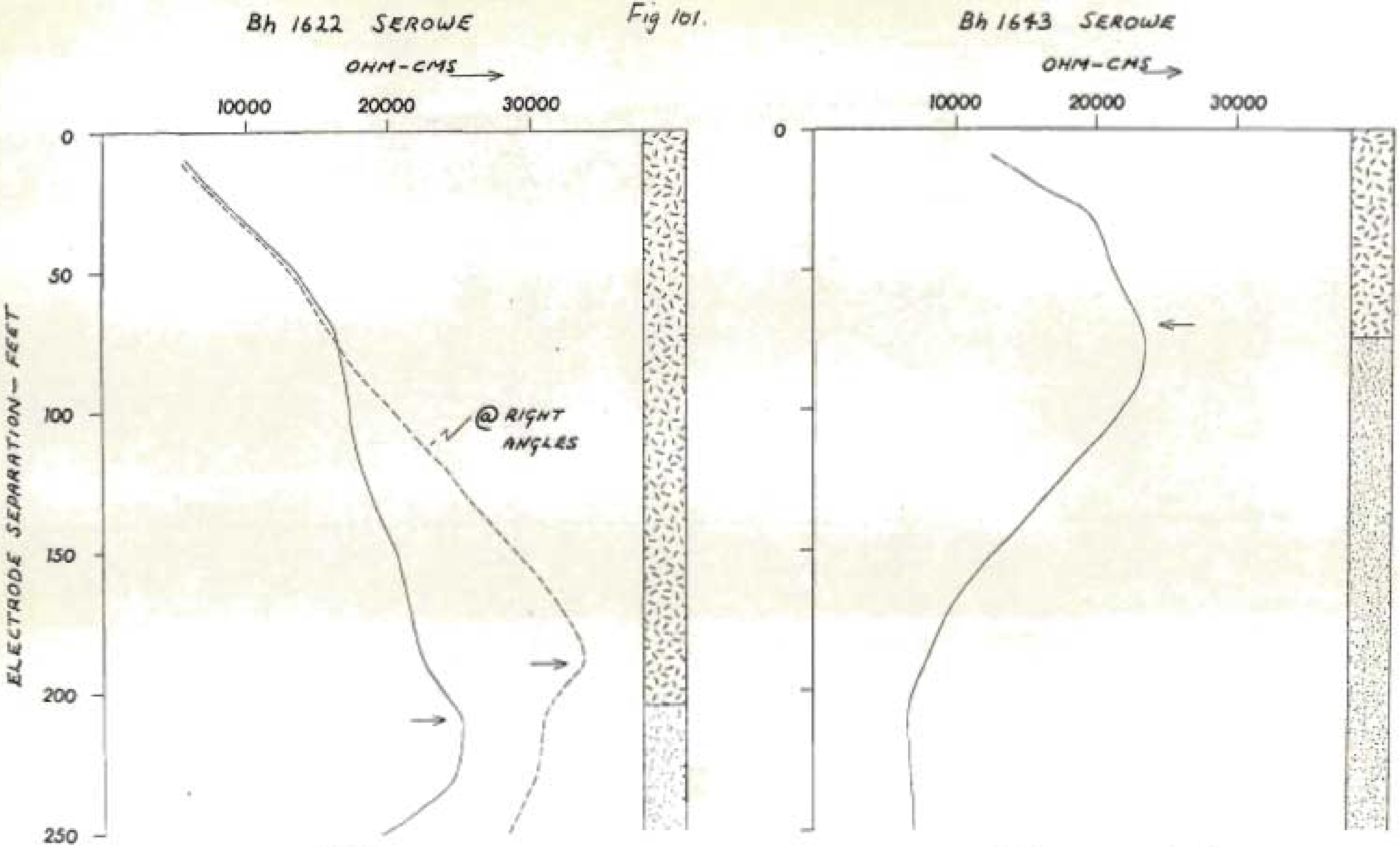
THE SITING OF BOREHOLES IN SEROWE

The relatively simple geology in Serowe makes the siting of boreholes west of the Serowe fault , a simple matter as virtually all boreholes are likely to be successful. Boreholes sited in the basalt should be drilled to a sufficient depth to penetrate the basalt and, where possible, should be continued to the base of the Cave Sandstone. Drilling in the area east of the fault should be avoided,except where boreholes can be sited to intersect the east-west dolerite dyke or where it is planned to intersect the deep-seated Ecca Group aquifer. Drilling north of the east-west dyke should be avoided,as boreholes sited in the lower Cave Sandstone Subgroup aquifer are likely to be low-yielding and of poor quality and are,furthermore, likely to penetrate into Waterberg Supergroup shales and siltstones,which are extremely poor water bearers.

Where the depth of the Stormberg lavas is unknown, electrical resistivity methods can be successfully used to determine their thickness. (See Fig. 101).

An attempt was made to site a borehole on joints in the basalts (shown up on aerial photographs by prominent vegetation lines),but this proved to be no higher yielding than average.

Fig 101.



DEPTH	400'
WATER STRUCK	205', 380'
REST LEVEL	98'
YIELD	+2500 g.p.h.

BASALT

CAVE SANDSTONE

DEPTH	300'
WATER STRUCK	110', 270'
REST LEVEL	73'
YIELD	2700 g.p.h.

Fig. 101

HYDROCHEMISTRY

. In 1969 a research programme was commenced in Serowe in which water from a number of boreholes was sampled at regular (bi-monthly) intervals from both pumping and unused boreholes. The unused boreholes were sampled at different depths using a sampler of the type described in the Chapter on Environmental Isotopes.

The water quality encountered in boreholes penetrating the basalt/Cave Sandstone contact is generally of excellent quality (of fresh sodium bicarbonate type). An example representative of this type of water is given in Table 56.

Boreholes drilled in the unconfined Cave Sandstone aquifer are of much poorer quality than that of the confined aquifer. This water is of weakly saline, calcium-magnesium-bicarbonate-chloride-sulphate type (Table 56.)

TABLE 56

SHOWING WATER TYPES IN UNCONFINED AND CONFINED AQUIFERS

	Unconfined aquifer		Confined aquifer
Bh number	14	489	1378
Date sampled	7.12.71	15.5.69	15. 2.71
pH	7,65	7,10	7,70
CO_3^{--}	26	-	13
HCO_3^-	361	323	102
Cl^-	270	116	36
SO_4^{--}	144	461	15

	Unconfined aquifer		Confined aquifer
F^-	1	1	1
Total anions	802	901	167
K^+	1	2	1
Na^+	52	38	48
Ca^{++}	254	178	13
Mg^{++}	110	94	7
Total cations	417	312	69
Sum total	1219	1213	236
Tds	1116	1412	228
Theor. Tds	1040	1048	186
K	2000	1580	250

Stiff diagrams showing these two main water types are shown in Figure 102.

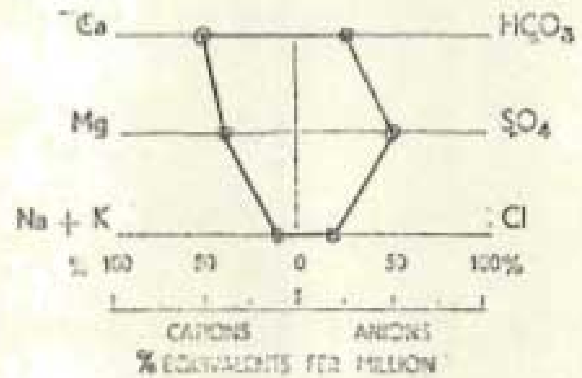
Water quality fluctuations with time

Figure 103 shows a plot of water quality (total dissolved solids) versus time for a number of boreholes in Serowe. Virtually all boreholes show small fluctuations in water quality with time which accords well with the data on water level fluctuations indicating that replenishment of the aquifer takes place in most years. The poor recharge 1969/1970 season (Figs. 93,104,105) is also clearly reflected in most water quality graphs (e.g. Boreholes 489, 521, 670, 1049, 1622, 1678). It is interesting to note, however, that instead of a decrease in dissolved solids at the end of the rainy season (i.e. about March), an increase in

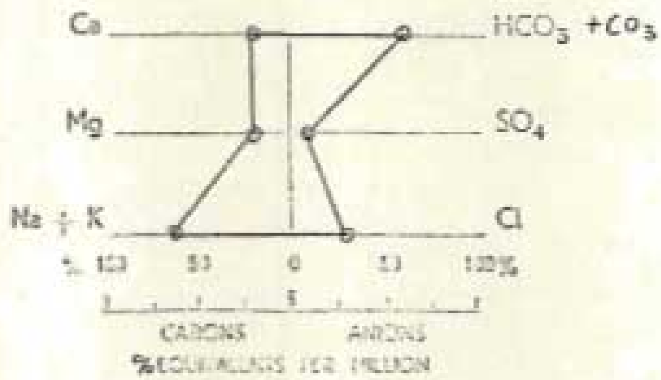
Fig. 102

Water Types in Serowe (Stiff Diagrams).

Bh 489 (15-5-61)



Bh 1378 (15-2-71)



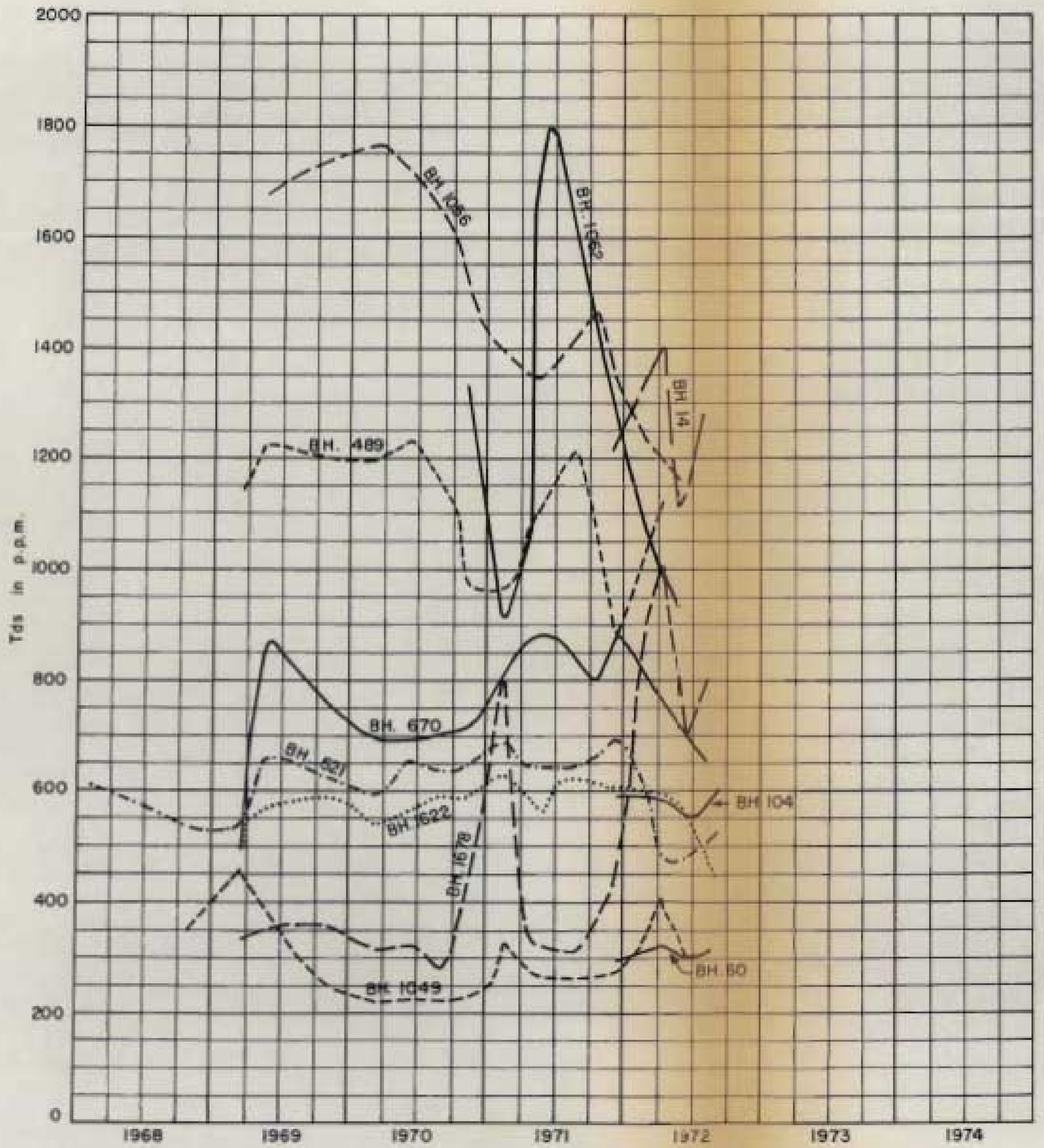


Fig. 1·3 SHOWING QUALITY FLUCTUATIONS WITH TIME — SEROWE.

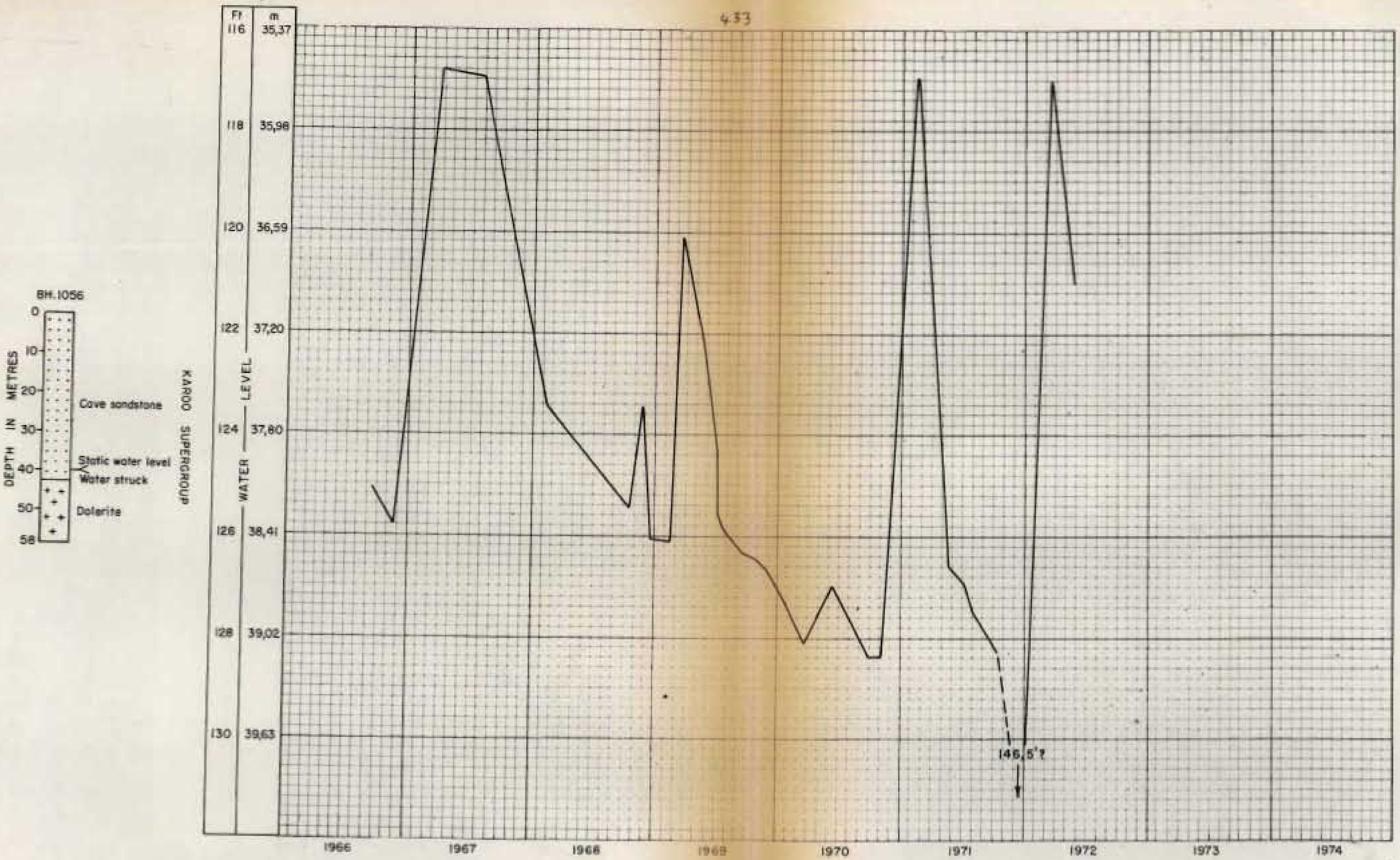


Fig. 104 HYDROGRAPH BH.1056 — SEROWE

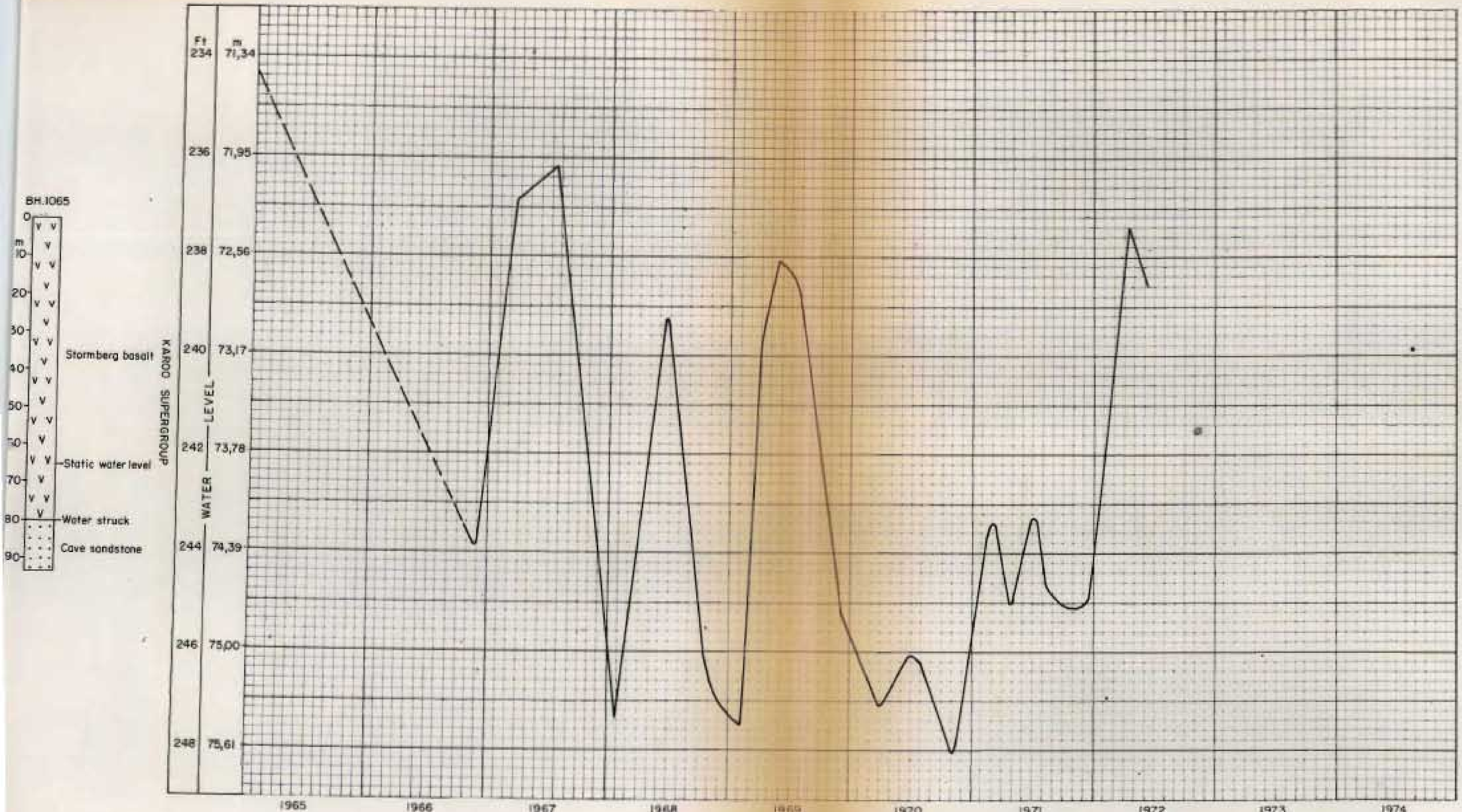


Fig. 105 HYDROGRAPH BH. 1065 — SEROWE

dissolved solids occurs. This seems to indicate that the recharge waters dissolve salts on their way downwards through the unsaturated zone.

Borehole 1538 has a very high tritium content and can therefore be regarded as having a large proportion of recent recharge water. (It is also on the banks of the emphemeral Metsemasweu River). This water is of magnesium - calcium - sodium - bicarbonate type (See Table 57) and has a relatively high dissolved solids content.

TABLE 57

CHEMICAL QUALITY OF RECENT RECHARGE (HIGH TRITIUM) WATER BOREHOLE 1538

Date	13.6.72
pH	7.90
CO_3^{--}	-
HCO_3^-	607
Cl^-	22
SO_4^{--}	16
F^-	1
Total anions	646
K^+	2
Na^+	40
Ca^+	64
Mg^{++}	68
Total cations	174
Sum Total	820

Borehole 1056 shows a remarkable variation in chemical quality (a marked improvement in quality) on the only two occasions on which water was sampled at 76m. Most other depth samplings were taken at 43 and 53m (with a few at 36m). Apart from some fluctuations in quality on 28.8.70-t.d.s. of 562 and 778, and on 22.3.69-t.d.s. 898 the chemical quality ranged between 1400 and 1700 ppm t.d.s. This change in quality is depicted diagrammatically in Fig.106.

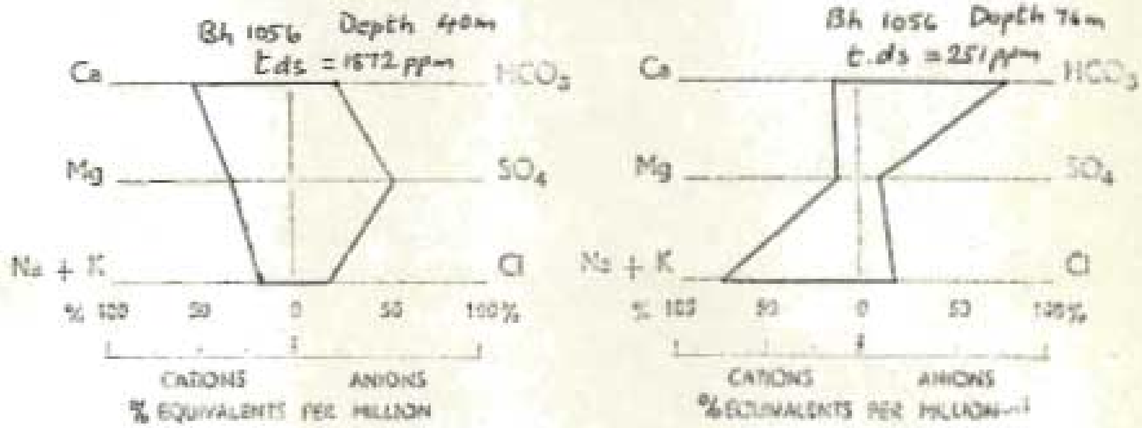


Fig 106
Showing Chemical Depth Stratification in Bh 1056

This borehole first encountered water in a southward dipping dolerite dyke from 40m onwards, and it is possible that the two deep samplings tapped fresh recharge water moving through fissures in the sandstone adjacent to the dyke. Typical chemical analyses from borehole 1056 are given below in Table 58.

TABLE 58

TYPICAL CHEMICAL ANALYSES FROM BOREHOLE 1056
WITH TWO SAMPLES SHOWING UNUSUALLY LOW TDS VALUES*

Depth	43m	54m	52m	76m*
Date	19.10.70	19.10.70	17.2.71	17.2.71
pH	7,20	7,20	7,20	7,85
CO_3^{--}	40	33	13	13
HCO_3^{-}	504	518	586	123
Cl^{-}	167	164	180	21
SO_4^{--}	471	471	218	21
F^{-}	1	1	1	1
Total anions	1183	1187	998	179
K^{+}	8	9	6	1
Na^{+}	113	110	114	57
Ca^{++}	232	236	229	9
Mg^{++}	93	87	65	5
Total cations	446	442	414	72
Sum total	1629	1629	1412	251
Tds	1732	1712	1384	240
Theor tds	1373	1366	1124	191

Depth	43m	49m	76m*
Date	15.6.71	15.6.71	15.6.71
pH	7,40	7,40	8,00
CO_3^{--}	-	-	-
HCO_3^-	577	593	142
Cl^-	160	160	28
SO_4^{--}	150	144	31
F^-	1	2	1
Total anions	828	899	215
K^+	7	7	1
Na^+	110	114	55
Ca^{++}	219	232	12
Mg^{++}	97	89	13
Total cations	433	442	81
Sum total	1261	1341	396
Tds	1116	1224	240
Theor. tds	1007	1050	226

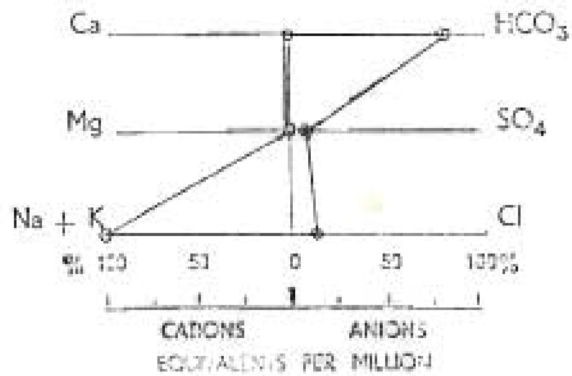
Water quality variations with depth

Three boreholes sampled at different depths viz, 1510, 1539 and 1929 show chemicalstratification with depth. Tables 59 , 60 and 54 show this increase in dissolved solids content with depth, while Fig. 107 depicts this difference diagrammatically. Table 54 (Borehole 1929) indicates that good quality, high tritium recharge water

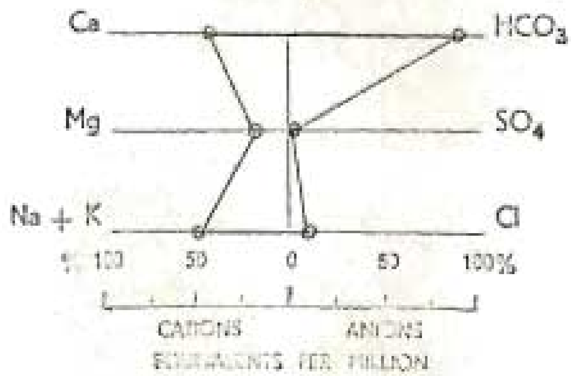
Fig 107

Chemical Depth Stratification in Bh 1510, Serowe

Bh 1510 Depth 15 & 45 m 17-6-70



Bh 1510 Depth 75 and 107 m 17.6.70.



mixes slowly downwards through the aquifer resulting in some chemical mixing but nevetheless retaining some stratification. (See Table 53 which shows a similar stratification in tritium concentration.)

TABLE 59

SHOWING CHEMICAL STRATIFICATION IN BH 1510

(Total dissolved solids in ppm)

Depth:		50'		150'		250'		350'
23.3.69	0,8$\pm$0,3	180			1,1$\pm$0,3	471	0,7$\pm$0,3	462
15.5.69	0,6	185		185	0,4$\pm$0,2	479	0,2$\pm$0,2	480
13.3.70		175	3,0$\pm$0,6	153		478		-
17.6.70		166		170		494		501
8.10.70	0,5$\pm$0,3	175	0,2$\pm$0,2	175	0,5$\pm$0,3	490	0,8$\pm$0,3	505
19.10.70		187		186		454		453
17.2.71	6,3	188	0,5	196	(1,9)	352		356
25.4.71	0,4	201	0,3	191	0,6	454	0,9	486
15.6.71		203		194		493		540
23.8.71		186		-		-		474
20.10.71		203		208		213		261
13.12.71		203		233		567		503
16.4.72		245		248		440		399
11.6.72				367				
10.8.72		278		258		476		398
Average tds		198		212		470		461

TABLE 60

SHOWING DEPTH STRATIFICATION IN BOREHOLE 1539

Borehole 1539

Depth	350'	400'	No significant T changes with depth
Date	17.2.71	17.2.71	
pH	7,80	7,75	
CO_3^{--}	13	13	
HCO_3^{-}	102	129	Slight increase with depth
Cl^{-}	29	54	Very slight increase with depth
SO_4^{--}	11	107	Note increase with depth
F^{-}	1	1	
Total	156	304	
K^{+}	2	2	
Na^{+}	53	120	Note increase with depth
Ca^{++}	11	15	
Mg^{++}	2	2	
Total cations	68	139	
Sum total	224	443	

Borehole 2446 (See section on geology), is a deep borehole which showed an improvement in water quality when water was encountered in the deep Middle Ecca grit aquifer. This quality improved even further after a nine hour pump test, thus indicating that the lower aquifer is probably stronger than the upper (lower Cave Sandstone and Ecca Shale aquifers). See Table 61.

TABLE 61

SHOWING IMPROVED WATER QUALITY IN THE DEEP MIDDLE ECCA AQUIFER

Borehole 2446

Depth:	43m	183m	215m (start of test)	215m (end of test)
Date	24.2.72	2.3.72	19.6.72	19.6.72
pH	6,90			
CO_3^{--}	-	-	-	-
HCO_3^-	341	432	501	412
Cl^-	217	214	212	116
SO_4^-	750	910	104	116
F^-	1	1	3	4
Total anions	1309	1557	820	648
K^+	3	2	2	3
Na^+	83	75	90	265
Ca^{++}	189	284	190	71
Mg^{++}	176	180	284	27
Total cations	451	541	566	366
Sum total	1760	2098	1386	1014
Tds	1708	2684	2456	1200
Theor. Tds	1587	1878		
K	2750	2800	2800	1610
Geology	Shale (Stormberg)	Shale (Ecca)	Middle Ecca Grit	

SUMMARY AND CONCLUSIONS

Serowe is at present completely dependent on ground water for township water supply. Ground water abstraction has been estimated at 30 000 m^3 per month but, at this rate, there appears to be no depletion of the main Cave Sandstone aquifer. Hydrographs indicate that recharge occurs in most years with an estimated recharge of 14,4 per cent of rainfall infiltrating to the ground-water table. This is substantiated by generally very high ^{14}C and moderately high tritium values, both of which indicate recent recharge. The evidence provided by isotope studies is corroborated by changes in the ground-water chemistry, which shows minor seasonal fluctuations in most boreholes and, in some cases, even marked chemical fluctuations. Boreholes in the unconfined aquifer near Serowe Hill, show a seasonal increase in total dissolved solids coinciding with the rainy season, indicating that rapid solution of salts present in the unsaturated zone takes place. Very low tritium and carbon -14 values are found in boreholes tapping the confined aquifer some distance from the major known recharge points. The Cave Sandstone aquifer is estimated to have a very large capacity to store water and, when it is considered that recharge at least equals the amount being abstracted, then it is probable that Serowe will be able to be supplied with water from boreholes for many years to come.

APPENDIX 5

GOVERNMENT BOREHOLES DRILLED IN SEROWE

Locality	No.	Depth (m)	Yield litres per min.	Remarks
Hospital	11	85	45	Deepened as Bh 1645
Government camp	13	120	34	
Tribal Offices	14	47	68	
" "	17	73	Blank	
Camp	60	116	38	
Tribal	70	95	68	
"	140	77	114	
"	159	81	91	Private Bh for A. Pagewood
Camp	178	68	45	
Hospital	180	84	48	Deepened as Bh 1623
Basimane	485	91	Blank	
"	489	102	15	
Botalaote	494	91	228	
Ratshosa	521	67	228	
Newtown	644	91	11	
Hospital	668	82	55	
"	670	76	228	Yield later dropped to 38 l/min.
Palamaokuwe	1049	111	137	
Mooketsi	1054	83	91	
Konyana	1056	58	15	
Mokwena	1062	91	68	
Camp	1065	98	34	
Kgotla	1087	107	6	
Teachers Training College	1373	62	121	
" " "	1378	62	152	
Masakola	1387	46	80	
Secondary school	1509	107	205	
" "	1510	[illegible]	[illegible]	

Camp	1520	122	137	
Metsemasweu	1538	107	22	
Anglican Mission	1539	133	137	BhZ342 deepened
Metsemasweu	1608	42	3	
Tribal W. of T.T.C.	1622	122	190	
Hospital	1623	122	182	Bh 180 deepened
Boltalaote	1643	91	205	
Hospital	1645	122	106	Bh 11 deepened
Roads Dept nr. Palmers house	1663	71	228	
Abattoir, Konyana	1684	43	114	
Blackbeard's house	1678	36	22	
Masakola dyke	1684	43	137	
Roads Dept E of Serowe	1929	141	11	
" " "	1930	91	304	
Observation bh nr. Wright's house	1976	91	304	
W. of Watson's Store	2162	91	137	
W. of Show Ground	2446	215	167	
W. of Tribal Workshop	2450	70	190	
Rametsana (Masakola Dyke)	2453	107	137	

SAND RIVER STORAGE

INTRODUCTION

A glance at Fig. 3 shows that the eastern portion of Botswana is apparently well drained with numerous rivers having a combined catchment area of 179 020 km^2. These rivers are, however, in actuality broad sandy river beds which flow only for a short period each year and, in rare years, not at all. Because of the intense thunderstorms that fall, with a consequent high rate of run-off, these rivers can, on occasions, carry immense quantities of water (Plate 31), a large amount of which rapidly percolates through the sandy bottom and sides to replenish the ground water aquifers lying in proximity to the river course (see section on Recharge and Ground Water Fluctuations). Very often, however, the bottom of the river bed may be an impermeable base and, where there is a reasonable depth of sand, considerable amounts of water are held in this important aquifer. Appreciable sub-surface flow often takes place in this aquifer. This aquifer has traditionally formed a most valuable source of water for the cattle industry and is often exploited by digging shallow wells in the river bed and manually hoisting the water to a nearby drinking trough or by allowing the cattle to have direct access to this water. (See Plates 3, 7).

In recent years the value of this aquifer, which is rapidly replenished, has come to be appreciated and a number of more detailed studies have been made in an attempt to assess the potential of these rivers as a source of water for mining (Selebi-Pikwe copper-nickel mines due to commence production at the end of 1974) and for irrigation (A detailed study of the Mahalatswe River has been carried out by the Food and Agricultural Organisation Scheme. (U.N.D.P.(S.F.)).

Sand rivers thus form one of the few primary ground water aquifers in Botswana. These aquifers are moreover regularly recharged; have a large storage capacity and have sufficiently large coefficients of transmissivity to produce high yields for large scale abstraction schemes.

The major sand rivers in eastern Botswana from north to south are: Ramokgwebane, Ntshe, Tate, Shashe, Motloutse, Thune, Lotsane, Mahalatswe, Metsemotlhaba and portions of the Limpopo River. (See Plates 63 (p 400), 64).

Cornellisen (1970) has described the exploitation of water in the Buffels Sand River in Namaqualand (N.W. Cape) for use in the Okiep Copper Mines.

GEOLOGY

The river beds consist mainly of recent, course-grained, granite-derived sands with complexly interbedded clay, silt, and gravel beds filling recent erosion channels cut into the older bedrock.

Pl. 64 Dolerite dyke on edge of Motloutse Sand River. Some surface water remaining after recent flow.

Pl. 65 Dense network of rootlets on edge of Motloutse Sand River.

INVESTIGATION OF THE POTENTIAL OF SAND RIVERS

The ground-water resources in sand rivers in Botswana are recharged virtually every rainy season (i.e. October to March). In the Mahalatswe River for example the river has failed to flow only once (1967/1968 season) in the past 89 years (Pike, 1970). This annual recharge has to be balanced against discharge by evaporation; transpiration; losses laterally and vertically to recharge of the deeper, fractured crystalline rocks; by sub-surface downstream flow and by abstraction from watering points in the sands. An idea of the transpiration potential of vegetation growing on the river banks can be gauged from Plate 65, which shows a dense network of fine rootlets growing into the river bed.

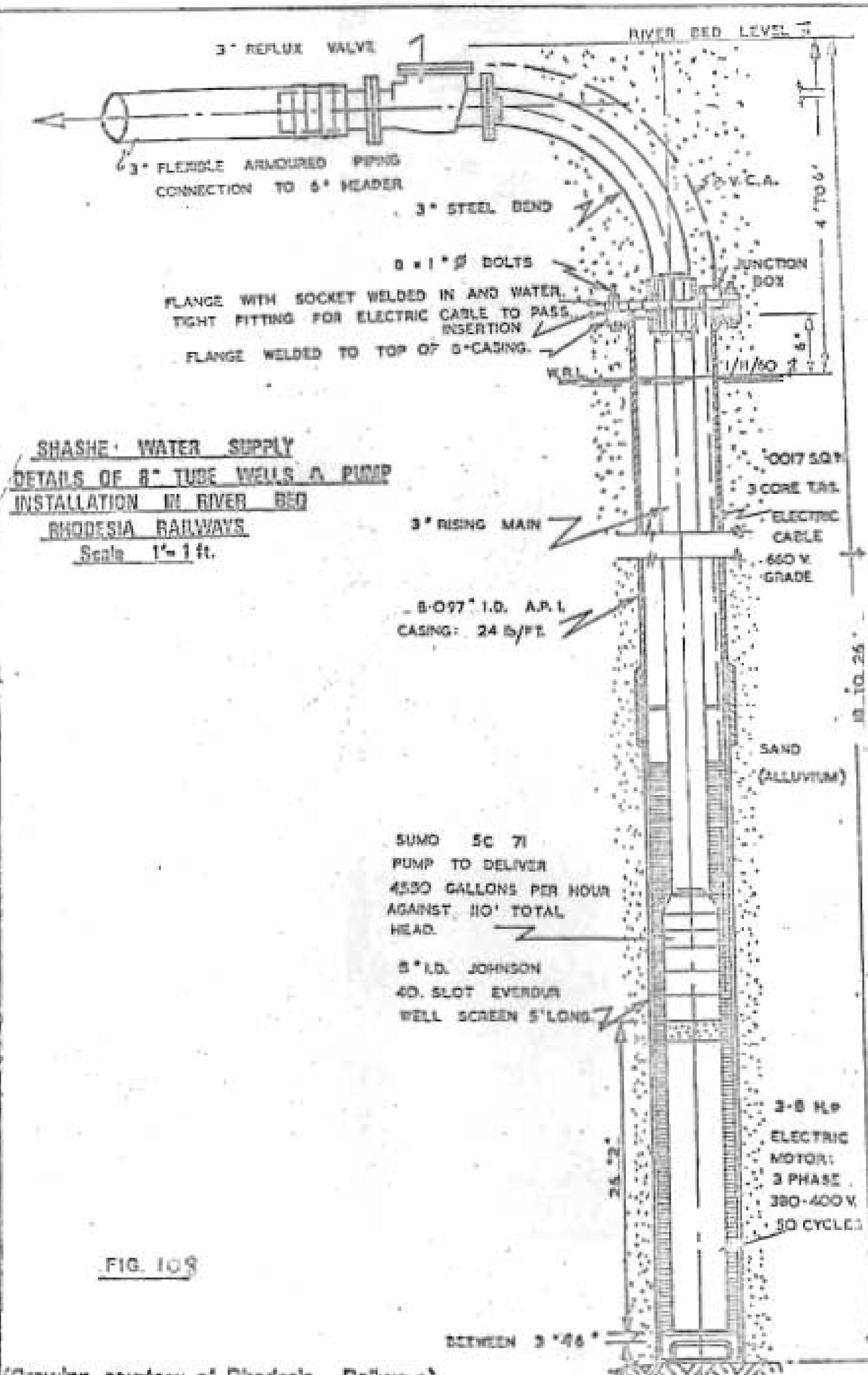
Shashe River

Surveys were carried out in 1968 using hand-driven probes to determine the depth of sand along a 7,5km strip in the Shashe River between the confluences of the Tate and Ramokgwebane Rivers by Bamangwato Concessions Limited. The results were summarised by Hyde (1969) who estimated that this section of the river contained $1,9 \times 10^6 m^3$ of saturated sand or $0,19 \times 10^6 m^3$ of extractable water or $0,025 \times 10^6 m^3$ per km, i.e. for an average width of river of 102 metres and an average saturated depth of 2,4 metres of sand and a 10% extraction rate Thomas and Hyde (1972) estimated a total of 6,818 x $10^6 m^3$ of extractable water between Shashe Siding and the confluence with the Limpopo River (274km). In the lower 145km of this river, the average width is at least two and a half times that higher up and the writer has calculated that 9,06 x $10^6 m^3$ of extractable water would be present with an overall total of 15,54 x $10^6 m^3$ present for the Shashe and its western tributaries. From the experience gained in the Mahalapswe River, where it was found that power augering indicated that the saturated sand thickness was considerably more than had previous hand probings, it may be safely concluded that the above figures are somewhat conservative.

The Rhodesian Railways are currently extracting an average annual amount of 0,42 x 10^6, of water from six 20cm diameter extraction points (Johnson well screens) developed in a section of sand, 5,5 to 7,9 metres in depth, in the river bed at Shashe Siding. Fig. 108 depicts this type of extraction point.

Motloutse River

The Motloutse River was also probed by Bamangwato Concessions Limited over a 13km section and the average width and depth of the river sand was found to be 100 and 3 metres respectively. Judd (1969) and Hyde (1969) estimated the full length of the Motloutse sand river (177km) to contain 5,324 x $10^{6,3}$ of extractable water. Of this 3,85 x $10^6 m^3$ are short term (shallow) resources which are lost rapidly to evaporation,



(Drawing courtesy of Rhodesia Railways)

Details of Shashe River tube wells and pump installation.

transpiration and drainage. An additional 0,887 x $10^6 m^3$ of mid-term resources (which could be developed by pumping) were estimated to be present while 0,590 x $10^6 m^3$ were estimated to be present as long-term (deep) resources.

Mahalatswe River

Extensive investigations of this river bed were made by the United Nations Development Programme (Special Fund) team. They estimated (Thomas and Hyde, 1972) that the lower 82km of the river contained 4,8 x $10^6 m^3$ of extractable water (i.e. 0,0585 x $10^6 m^3$ per km). Of this 1,6 x $10^6 m^3$ of water is in short-term storage; 2,28 x $10^6 m^3$ is in mid-term storage and 0,92 x $10^6 m^3$ of water is in long-term (deep) storage. Present extraction by the Rhodesia Railways and Mahalapye village is estimated to be 255 500m^3 per annum.

Other Sand Rivers

Minor amounts of water are extracted by Rhodesia Railways from the upper reaches of the Ramokgwebane River near Tsamaya (58 000m^3 per annum). Large quantities of water (up to 829 000m^3 per annum) are extracted using conventional boreholes from recent sands adjacent to the Limpopo River near Pont Drift not far from the Limpopo-Shashe confluence. No resources evaluation of the other large sand rivers in Botswana has been carried out.

Total Sand River Resources

By using recent satellite photography, the writer has calculated that a total of 1468km of major sand rivers are present in Botswana. Using the mean calculated value of 0,038 x $10^6 m^3$ water present per km of major river, the total extractable sand river ground water resources in Botswana is estimated to be:

$56,11 \times 10^6 m^3$ (See Table 62)

The total estimated current ground water usage from sand rivers is given below in Table 63.

TABLE 63

ESTIMATED CURRENT WATER ABSTRACTED FROM SAND RIVERS

Sand River	User	Annual abstraction m^3
Ramokgwebane	Rhodesian Railways	58 000
Ntshe	Rhodesian Railways	66 000
Shashe	Rhodesian Railways	414 000
Motloutse	Selebi-Pikwe Mine	166 000
Mahalatswe	Rhodesian Railways	132 000
	Mahalapye Township	66 000
Limpopo		829 000

TOTAL: 1 731 000 m^3

(= $380,80 \times 10^6$ gallons)

It is thus obvious that this valuable source of water is considerably underutilised.

TABLE 62

ESTIMATED SAND RIVER STORAGE IN BOTSWANA (USING ERTS PHOTOS)

River	Length km	Total extractable water = km x 0,038* in $m^3 \times 10^6$
Ramokgwebane	120	4,57
Shashe and tributaries	400	**$(145 \times 2,5 \times 0,025 \times 10^6) + (255 \times 0,025 \times 16^6) = 15,54$
Tate	125	4,75
Ntshe	55	2,09
Motloutse***	177	5,32
Thune	114	4,33
Lotsane	80	3,04
Selika	30	1,14
Machaneng	30	1,14
Limpopo	225	8,55
Mahalatswe****	82	4,80
Metsemotlhaba	30	1,14

TOTAL: $56,11 \times 10^6 m^3$ (± 12 344 000 000 gallons)

* Mean of calculated storage for middle reaches of Shashe, Motloutse and Mahalatswe Rivers

** Lower 145 km of Shashe estimated at $2\frac{1}{2}$ times average because of great width of sand river.

*** After Hyde (1969)

**** After Thomas and Hyde (1972)

METHOD OF ABSTRACTION OF WATER FROM SAND RIVERS

Water abstraction schemes in sand rivers should be based on the hydraulic properties of the aquifer determined by careful studies of gradient of the river bed, depth of sand and aquifer evaluation tests to determine coefficients of transmissivity and storage. Pumping rates and spacing of pumping points should be planned to draw water down to a point which will cut evapotranspiration losses but which will not be so great as to draw down below the top of the screened intake area. Mutual interference between pumping boreholes should be avoided.

An example of a typical abstraction point used by Rhodesia Railways at Shashe is given in Fig. 108 while technical details of the six tube wells are given in the letter from the Acting Chief Engineer, Rhodesia Railways, to the Geological Survey. (Courtesy Rhodesia Railways). This letter also gives partial chemical analyses of the water encountered in the sand in the Shashe River bed. (See Appendix 6).

Details of a typical longitudinal- and cross-section for the Ramokgwebane River near Tsamaya are shown in Figures 109 and 110. Figure 110 shows the initial arrangement of pumping points (and water levels at different dates during the abstraction of a total of 35 832 m^3 water between May and December 1964 (Fig. 111)).

Fig. 109 KAMAQUABANE RIVER

SECTION ACROSS RIVER AT B-R (Courtesy Rhod. Rai...

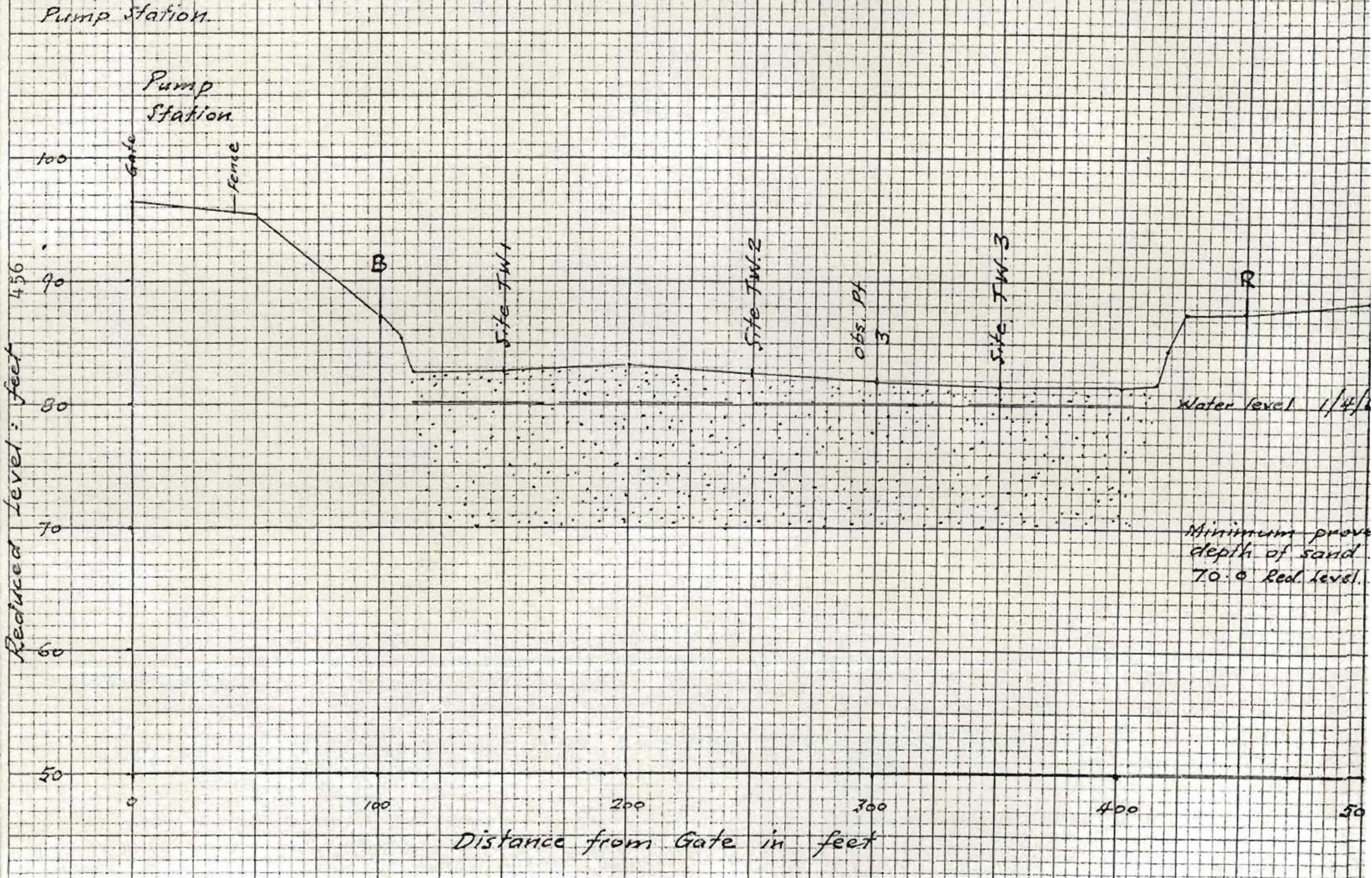


Fig. 110 TSAMAEA WATER SUPPLY: RAMAQUABANE RIVER

LONGITUDINAL SECTION SHOWING WATER LEVELS IN TUBE WELL AREA

Note: Observation points comprise ½" I.D. perforated tubes driven into the river bed and numbered as shown.

(Courtesy Rhod Railways)

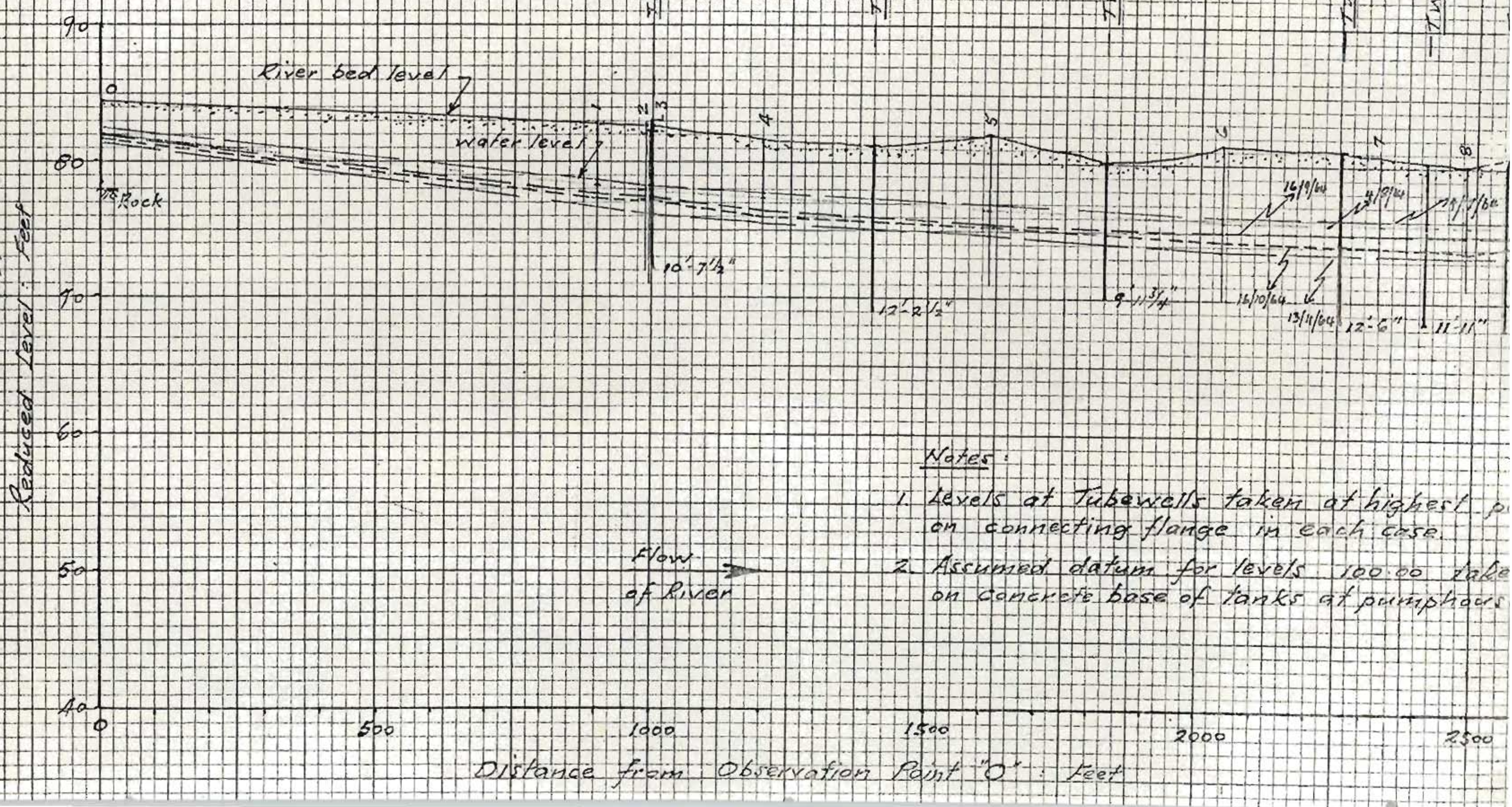


Fig. 11 TSAMAEA WATER SUPPLY: RAMAQUABANE RIVER
GRAPH SHOWING AVERAGE DAILY ABSTRACTION FROM TUBE WELL SYSTEM (Courtesy

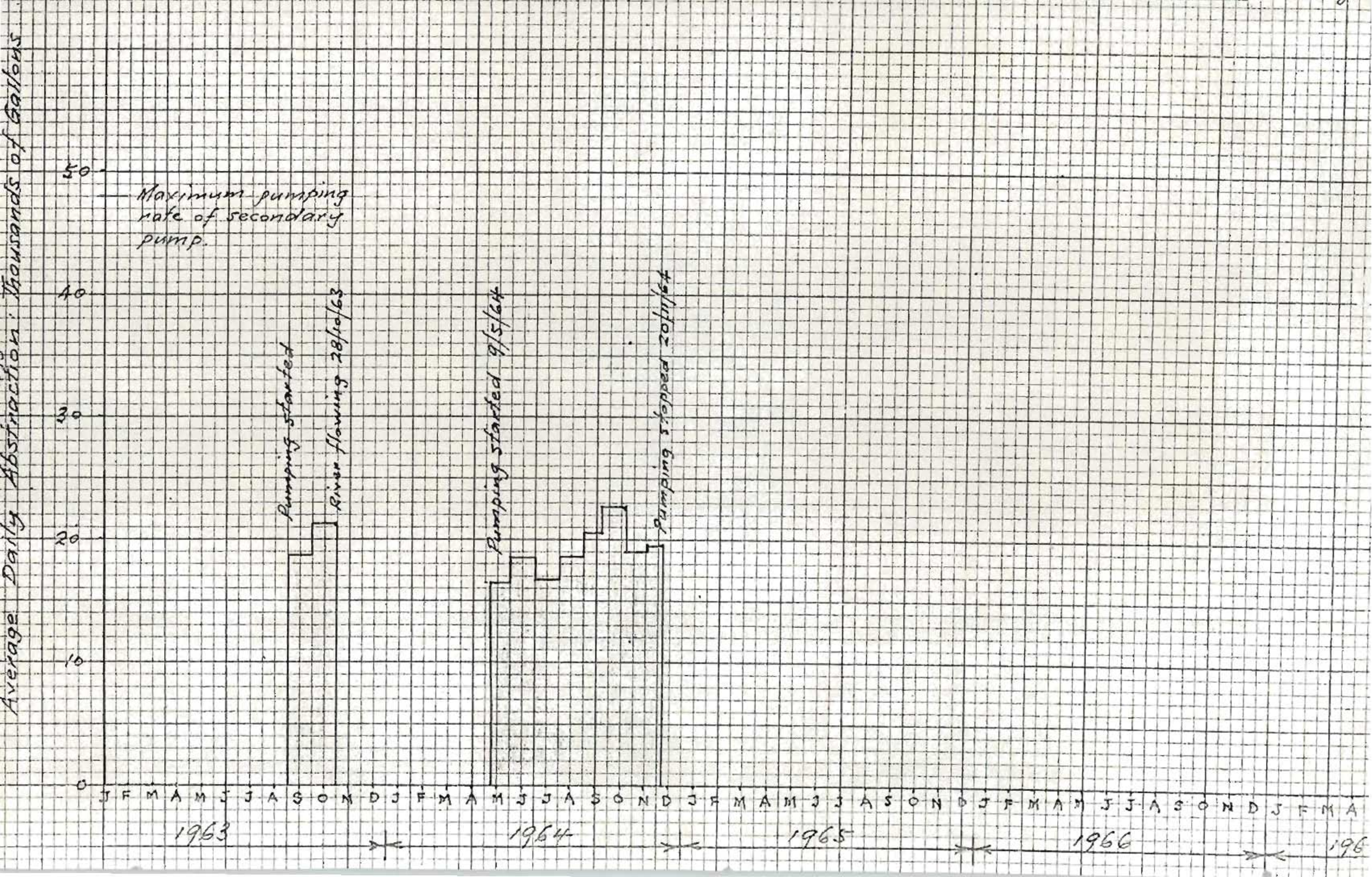


FIG: 112

TSAMAEA WATER SUPPLY : RAMAQUABANE RIVER

PLAN AT NEW TUBE WELL SITE.

Scale : 1" = 100'

Note : Water level observation points numbered 0 to 5 established at 500' intervals for 1500' upstream and 1000' downstream of tube well line B-R. (Courtesy Rhod. Railways)

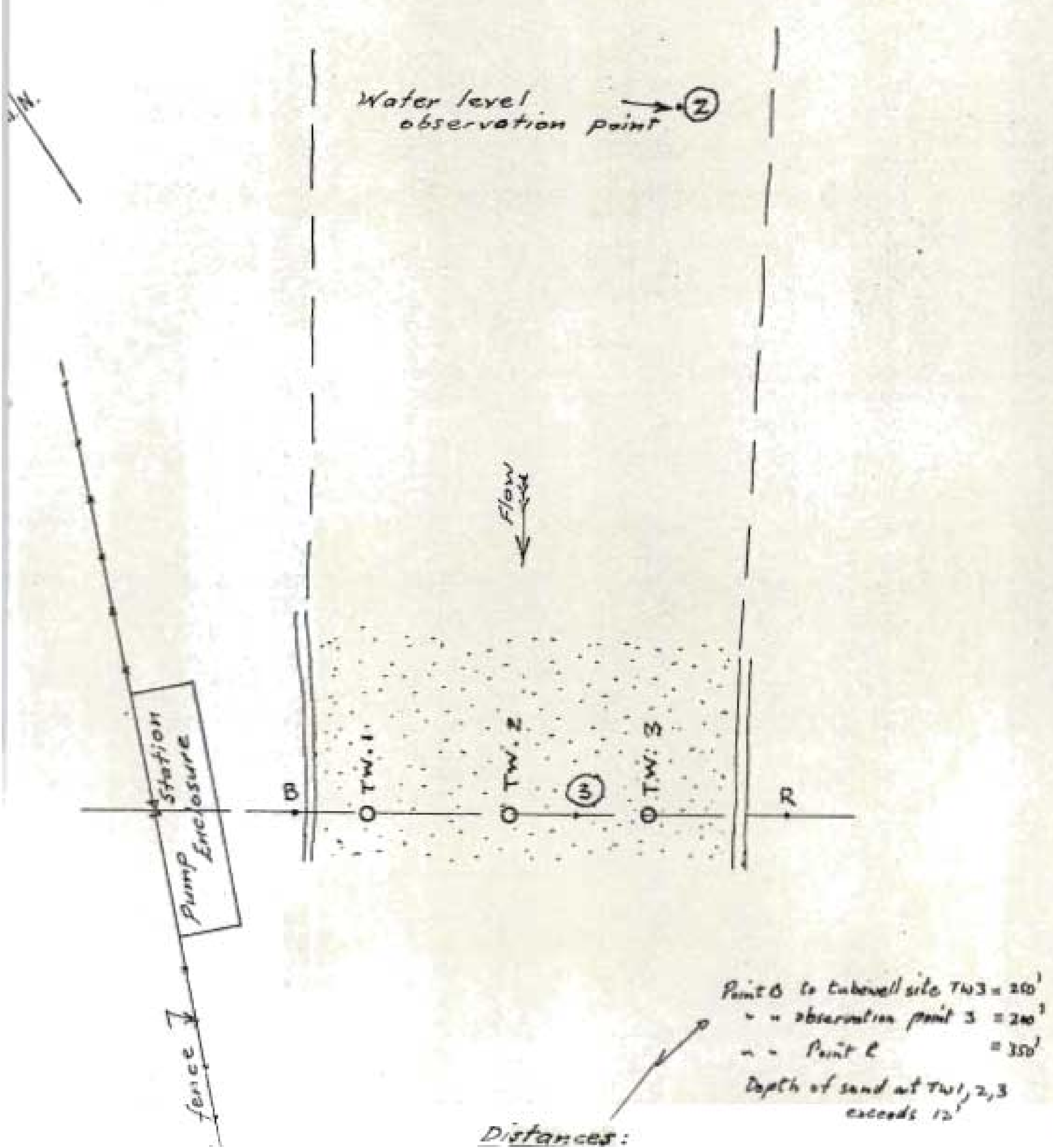


FIG 113

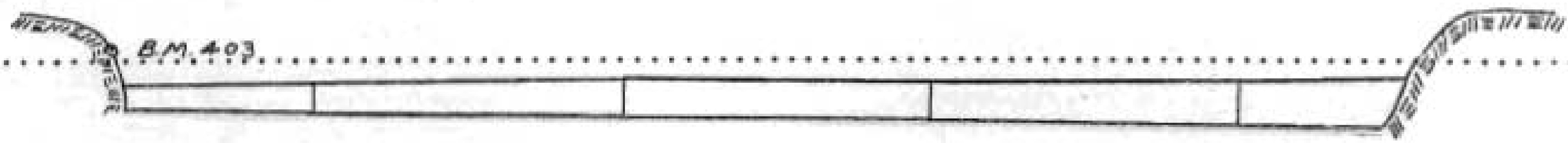
MAKLAUTSI RIVER - DEPTH PROBES

CROSS-SECTION AT BENCHMARK NO. 403 LOOKING WEST (Courtesy Bamangwato Con

DATE: 31-1-1969 SURVEYOR: F. J. R. NUNAN

DISTANCE FROM PUMP HOUSE TO BENCHMARK: 10,100' WEST BENCHMARK ELEVATION = + 2631·7

SCALE: 1:500



Average Width = 311 feet

Average Depth of Sand = 9·5 feet

Cross-Sectional Area of Sand = 2955 square feet

Effective Length East & West of Cross-Section = 1000 feet

Volume of Sand = 2,955,000 cubic feet

Sample No. = 403 %Permeability =

Water Potential = cubic feet x 6.25 = gallons

Progressive water potential between Pumphouse and Benchmark = gallons

Sand ... ... Black
Permeable Grey Clay ... Green
Impervious Red Clay ... Red
Bed Rock ... ... Blue

Checked:

BAMANGWATO CONCESSIONS LIMITED

FIG. 14

Graph of Screen Analysis

U.S. Sieve Series A.S.T.M.

Sample Number 403

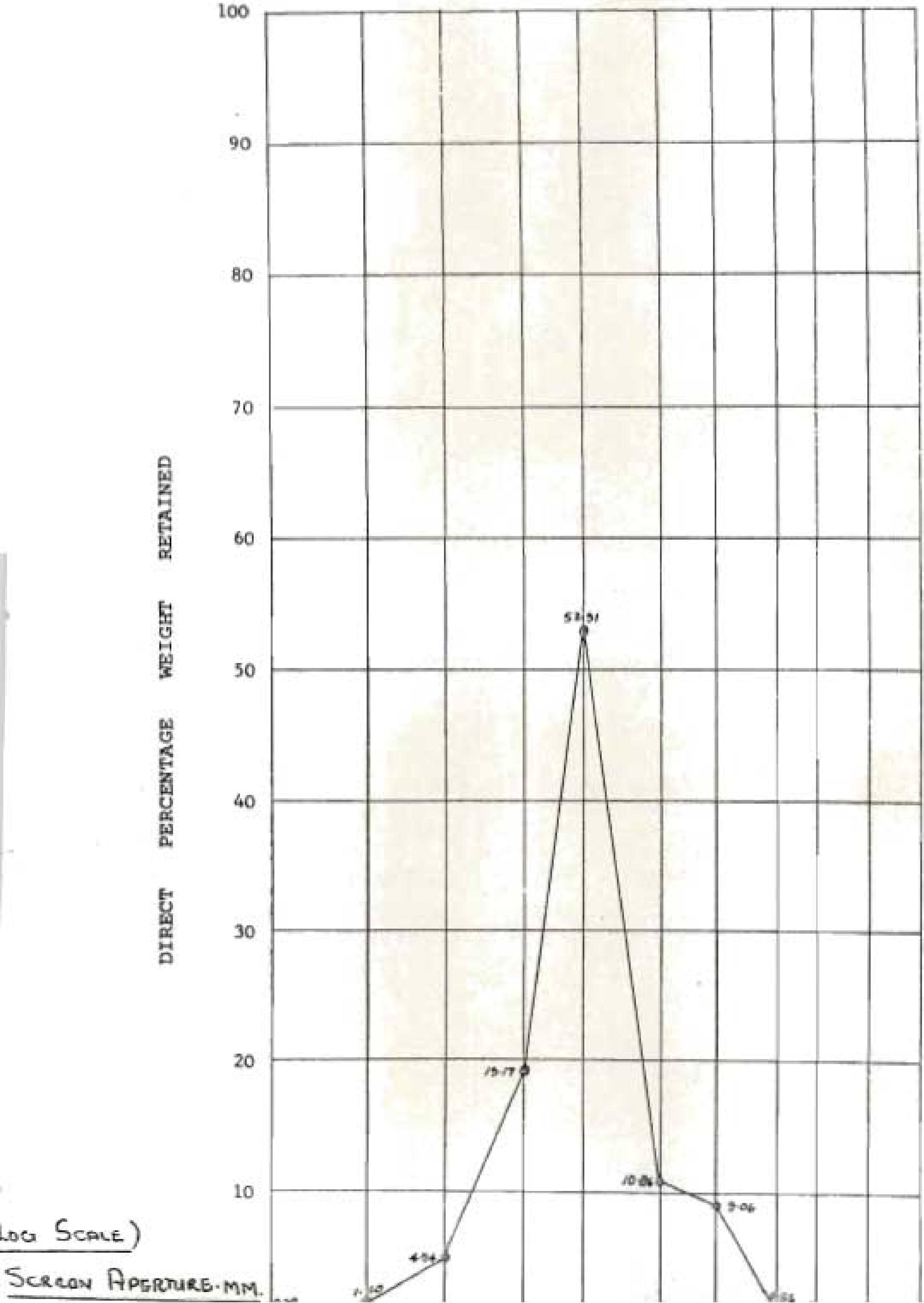


Fig. 115

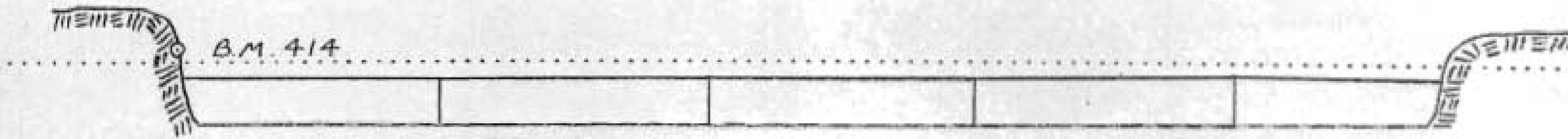
SHASHI RIVER - DEPTH PROBES

CROSS-SECTION AT BENCHMARK NO. 414 LOOKING WEST (Courtesy Ben. Concessions ...

DATE: 27-3-69 SURVEYOR: F. J. R. NUNAN

DISTANCE FROM ORIGIN TO BENCHMARK: 15,000' EAST BENCHMARK ELEVATION = +

SCALE: 1:500



Average Width = 354 feet

Average Depth of Sand = 13·2 feet

Cross-Sectional Area of Sand = 4684 square feet

Effective Length East & West of Cross-Section = 2500 feet

Volume of Sand = 11,710,000 cubic feet

Sample No. = %Permeability =

Water Potential = cubic feet x 6.25 = gallons

Progressive water potential between orijin and Benchmark = gallons

Sand	... Black
Permeable Grey Clay	... Green
Impervious Red Clay	... Red
Bed Rock ...	... Blue

Checked:

Figure 112 shows the geometry of new abstraction points installed early in 1965.

Details of a typical cross-section and sieve grading analysis of sand in the Motloutse River were given in Figures 113 and 114.
A typical cross-section across the Shashe River is shown in Figure 115 .

AQUIFER PROPERTIES

Detailed aquifer tests in the Motloutse Sand River gave a very high average coefficient of transmissivity of 1 216 m^2 per day (98 176 gallons per day per foot) and an average coefficient of storage of 0,249 or 24,9 per cent. This indicates an effective porosity(specific yield) of nearly 25 per cent. (See Chapter on Aquifer Tests). Sieving tests indicate that the sands in this river (and hence probably in most other Botswana sand rivers) has an excellent uniformity coefficient.

Houston (1972) in laboratory experiments calculated that permeabilities of the sands in the Mahalatswe Sand River range from 20 metres per day to 250 metres per day and estimated the specific yield to be between 15 and 30 per cent.

RECHARGE

Long term records at Mahalapye indicate zero flow in the Mahalatswe River during only one season over the past ninety odd years. Pike (1970) obtained a short term (two seasons) figure of 8 per cent of the inflow volume for the average recharge of the sand river over a 10 km stretch of the Mahalatswe River.

SUB-SURFACE FLOW

Pike (1970) also obtained a figure of 100 m^3 per day or 36 500 m^3 per annum of sub-surface flow for the same stretch of the Mahalatswe River.

ARTIFICIAL RECHARGE

Artificial recharge of sand rivers can be promoted by the systematic raising of concrete weirs across the rivers which then retain the coarse sand fraction during floods. This method was described by Wipplinger (1953 and 1958) in South West Africa, while Burger and Beaumont (1970) reviewed this method more recently.

FOSSIL VALLEYS

Enslin (1971) has described fossil valleys in the Northern Cape up to 200 metres deep and 5 km wide, which were filled 6 million years ago by Kalahari Beds gravel and sand, followed by red clay; then marls, limestone and sand and finally the whole area was covered by aeolian sands. These ancient sand rivers now constitute important deep aquifers both in the Northern Cape, and along and north of the Molopo River in southern Botswana. Recent tritium datings of water from a borehole in this area (Mazor et al, 1974) indicate that these aquifers are currently being recharged by ephemeral flood waters flowing down the Molopo River.

A similar pre-Kalahari valley has been proved in the Kweneng area beneath a post Kalahari fossil valley at Tsoto (See Fig. 10). In this case, however, water was not encountered in the Kalahari Beds but in the deeper Ecca Subgroup aquifer.

CONCLUSIONS

Sand rivers (including fossil sand filled river channels) form an extremely important and, as yet, largely untapped source of ground water for domestic, agricultural, industrial and mining supply in Botswana. An initial rough estimate, using ERTS-1 satellite photographs, has shown that approximately $56 \times 10^6 m^3$ of extractable water are probably present in the sand rivers of eastern Botswana. Between 10 and 20 per cent of the above extractable water should be available as long term (deep) storage and a larger percentage as mid-term storage.

RHODESIA RAILWAYS

PLEASE QUOTE
W1/SS.1215
REFERENCE NO.

Chief Engineer's Office,
P.O. BOX 604,
Bulawayo, 16th December 1960.
Rhodesia.

Telephone:
Railway Exchange 2861.

The Director,
Geological Survey,
Lobatsi,
Bechuanaland Protectorate.

Dear Sir,

SHASHI : WATER SUPPLY : TUBE WELLS.

With reference to your discussions with the Water Engineer in Mafeking recently, I subjoin particulars of six tube wells completed within the Railway Strip in the Shashi River by Rhodesia Railways Departmental Drill No.2 :-

Site No.	TW.515	TW.516	TW.517	TW.518	TW.519	TW.520
Depth	21'	21'	26'	20'	21'	18'
Dia.	8"	8"	8"	8"	8"	8"
AP.1 Casing 8"	17'	17'	22'	16'	17'	14'
Screen Length	5'	5'	5'	5'	5'	5'
Water Level	4'	5'	6'	6'	6'	6'
Yield Test g.p.h.	8400	8400	8400	8400	8400	8400
Pump setting	19'	19'	20'	16'	18'	16'
Drawdown	4'	2'	1'	3'	2'	2'
Quality of water (in p.p.m.):-						
H	60	64	56	66	60	64
P	-	-	-	-	-	-
M	78	82	74	78	80	82
NaCl	10	8	14	18	8	8
TDS	91	98	91	98	91	91
Ca	38	44	32	42	36	36
Mg	22	20	24	24	24	28
Date commenced	15/10/60	19/10/60	21/10/60	31/10/60	2/11/60	7/11/60
Date completed.	19/10/60	21/10/60	23/10/60	1/11/60	4/11/60	9/11/60

Geology: Coarse grained alluvium over granite bedrock.

The well screens are Johnson 40 slot (.040" opening) Everdur metal, 8" internal diameter, and have a 5' screen length screwed on to the 8" A.P.1. casing as illustrated on the accompanying print of plan CE.91/VB.207.

Yours faithfully,

GROUND WATER MOVEMENT, WELL HYDRAULICS AND AQUIFER EVALUATION TESTS IN BOTSWANA

INTRODUCTION

Pump testing of boreholes in Southern Africa is generally carried out with the sole objective of obtaining information on the performance and efficiency of the borehole, while from the drawdown, yield and calculated specific capacity suitable equipment can be ordered for long term use on the borehole.

More sophisticated testing of boreholes for the determination of the main aquifer characteristics such as coefficients of storage and transmissivity is seldom carried out, largely because the requirements of homogeneous aquifers of infinite extent do not generally pertain in South Africa (Enslin, 1956). However, recent detailed aquifer testing of boreholes in Botswana by the writer and other workers has shown that valuable data can be obtained by detailed aquifer tests even where ostensible geological indications are that the aquifer is of a heterogeneous nature. Venter (1969) has independently come to a similar conclusion that "the non-equilibrium formula may be applied with success to aquifers consisting of fissures in impermeable rocks."

PREVIOUS WORK

In South Africa, pump tests have been described by Enslin (1956), Venter (1969), Boehmer (1970), and Olivier (1970). In Rhodesia tests were carried out by Hindson and Wurzel (1963) in the Sabi Valley alluvium. In Botswana aquifer tests have been described by Jennings (1969 and 1970), Jones (1969), Anon. (1969) and Robins (1971 and 1972).

AQUIFER TESTS AND WELL HYDRAULICS

A fairly detailed description of the techniques employed in aquifer tests has been given in this thesis as these methods are relatively unknown in Southern Africa. Liberal reference has been made to the following in this section:- Theis (1935), Jacob (1946) and Johnson (1966).

Hydraulic properties of rocks

The porosity of a rock is a measure of the interstitial space of the rock and is expressed quantitatively as the percentage of the total volume of rock occupied by the interstices (Meinzer, 1959).

Because of the forces of molecular attraction, adhesion and cohesion, not all water in the interstices of a saturated rock can be withdrawn by boreholes or wells and hence the term specific yield is used to express the quantity of water that a unit volume of the material will give up when drained by gravity. Conversely, the quantity of water that a unit volume retains when subjected to gravity drainage is called the <u>specific retention</u>. Thus, specific yield plus specific retention will be equal to the porosity.

Factors affecting Ground Water Flow

<u>Permeability</u> (K) is the capacity of a porous medium for transmitting water. It may be measured by investigating the amount of water that will flow through a sample of sand in a certain time and under a given difference in head. The pioneer in the field of ground water movement was Darcy (1856). He derived a formula known as Darcy's Law, which showed that the flow of water through a column of saturated sand is proportional to the difference in hydraulic head at the ends of the column and inversely proportional to the length of the column. This may be expressed as -

$$V = K \frac{(h_1 - h_2)}{l}$$

where V is velocity of flow, (h1 and h2) is the difference in hydraulic head, l is the distance along the flow path between the points where h1 and h2 are measured and K (coefficient of permeability) is a constant depending on the characteristics of the water-bearing material through which the water flows. Darcy's Law remains the fundamental equation governing the flow of water in a porous medium and hence in ground-water flow.

The hydraulic gradient

$$I = \frac{h1 - h2}{1} = \frac{dh}{dl}$$

then $V = KI$ by substituting $I = \frac{dh}{dl}$

and $V = \frac{Q}{A}$ (from velocity equation)

Because water moves only through intergranular pore spaces and not through the whole cross-sectional area, the equation $V = KI$ should be corrected by dividing by the porosity α. In order to convert to feet per day the equation should also be divided by the number of gallons in a cubic foot i.e. 10.

$$\therefore \quad V = \frac{KI}{10\alpha}$$

Where A is the cross-sectional area through which the water moves and Q is the quantity of flow per unit of time $A = bW$ where b is the saturated thickness of the aquifer and W is the width. Now from the velocity equation $V = \frac{Q}{A}$ or $Q = AV = KIA$.

The <u>hydraulic conductivity</u> (coefficient of permeability) K, is the quantity of water that will flow through a unit cross-sectional area of a porous material per unit of time under a hydraulic gradient of one at a specified temperature.

The <u>storage coefficient</u>, S, of an aquifer may be defined as the volume of water an aquifer releases or takes into storage per unit surface area (i.e. per unit prism of the aquifer) of the aquifer per unit change in head. For practical purposes S is equivalent to the specific yield for a water-table aquifer. S for water table aquifers ranges from 0,01 to 0,30, while it is much smaller for artesian aquifers (0,00001 to 0,005). Thus water drained from a watertable aquifer, greatly exceeds that from an artesian aquifer. The volume of water taken up or released from storage (Vw) equals the product of the volume of rock through which the change in water level occurred (Vr) and the storage coefficient, i.e. Vw = Vr x S.

Related to the hydraulic conductivity, K, is the term transmissivity (coefficient of transmissibility), T, which is defined as the rate at which water will flow through a vertical strip of aquifer of unit width through the full saturated thickness of the aquifer under a hydraulic gradient of unity at the prevailing temperature of the ground water. Transmissivities of 10 000 gallons per day per foot (124m^2 per day) are regarded in the United States as being adequate for municipal, industrial or irrigation purposes. The transmissivity T is equal to the hydraulic conductivity K multiplied by the saturated thickness of the aquifer, b.

i.e. $T = Kb$

When the transmissivity, T, is introduced in the Darcy equation, the flow through any vertical section of an aquifer may be expressed as

$$Q = T.I.W.$$

where W is the width of the vertical section through which the flow occurs and I is the hydraulic gradient.

As will be shown later, T can be determined from aquifer pumping tests, thus overcoming the problem of obtaining reliable values for the hydraulic conductivity from laboratory tests.

General definitions relating to aquifer tests

Radius of influence R is the distance from the centre of the borehole to the limit of the cone of depression. Cones of depression for artesian boreholes are larger than for water-table boreholes.

Drawdown is the drop in level in a pumped borehole.

Static Water Level is the level of water in a borehole when no water is being taken from the aquifer.

Pumping Level is the level at which water stands in a borehole when pumping is in progress. Also known as "dynamic water level".

<u>Residual drawdown</u> is the distance between the original static level in a borehole and the level of water in a borehole during the recovery period after pumping is stopped.

<u>Specific capacity</u> of a borehole is the yield per unit of drawdown e.g. if pumping rate is 150 g.p.m. and the drawdown 20 feet, then specific capacity = 8 g.p.m./ft of drawdown at the time the measurements are taken.

<u>Cone of depression</u> is the form of the lowered water surface caused by a pumped borehole.

<u>Objectives of pump tests</u>

A borehole is generally tested for either of two main purposes. The usual objective is to obtain information on the performance and efficiency of the borehole from the yield, drawdown and calculated specific capacity so that suitable pumping equipment can be selected.

The second objective is to provide data from which the principal factors of aquifer performance can be calculated and hence the test may be styled an "aquifer test".

An aquifer test consists of the pumping of one borehole and by recording drawdown and yield in the pumped borehole and in other observation wells, the data can be analysed and the hydraulic characteristics of the aquifer determined. These characteristics can serve as an extremely valuable aid in practical ground water investigations.

Among the usual hydraulic characteristics which can be calculated are the average permeability, the coefficients of storage and transmissivity, the interference between boreholes at different spacings and for different pumping rates or the expected drawdown in the pumped borehole at various distances from the pumped borehole after any desired period of time. Other parameters which can be determined are the existence of impermeable boundaries limiting the extent of the aquifer or the existence of unsuspected sources of recharge to the aquifer.

Flow from Aquifer into Borehole

When a borehole is pumped, water is derived from storage in the aquifer immediately surrounding the borehole. As pumping continues, more water must be derived from storage from greater distances and a circular-shaped cone of depression expands outwards around the borehole so that water can move from greater distances to the borehole. In other words, the radius of influence of the borehole increases as the cone continues to expand. The drawdown also increases as the cone deepens at a decreasing rate as with each metre of horizontal expansion a larger volume of stored water is available than from the preceeding one. Eventually, when the expanding cone intercepts sufficient water from the aquifer to counterbalance the pumping rate, the cone becomes stabilised and equilibrium is established. Where intermittent recharge occurs, water levels will continue to be drawn down until a recharge event occurs or when overpumping takes place a net loss in storage may occur.

For an artesian aquifer in which equilibrium conditions have been obtained

$$Q = \frac{Pm\ (H - h)}{528\ \log R/r} \qquad \text{———} \qquad (1)$$

where P = permeability of the water-bearing sand, in gallons per day per square foot.

Q = borehole yield in gallons per minute.

h = depth of water while pumping, in feet.

R = radius of the cone of depression, in feet.

r = radius of well, in feet.

m = thickness of aquifer, in feet.

H = static head at bottom of aquifer, in feet.

For a water table aquifer

$$Q = \frac{P(H^2 - h^2)}{1055\ \log R/r} \qquad \text{———} \qquad (2)$$

where H = saturated thickness of the aquifer before pumping, in feet. All other terms are defined above.

If P. H, m and R are known then for a water-table aquifer

$$P = \frac{1055 \, Q \log r_2/r_1}{(h_2^{\,2} - h_1^{\,2})}$$

where r_1 = distance to the nearest observation well in feet.

r_2 = distance to the farthest observation well in feet.

h_2 = saturated thickness in feet at farthest observation well.

h_1 = saturated thickness in feet at nearest observation well.

For artesian conditions

$$P = \frac{528 \, Q \log r2/r1}{m(h2 - h1)}$$

h2 = head, in feet, at the site of the farthest observation well measured from the bottom of the aquifer.

h1 = head, in feet, at the site of the nearest observation well measured from the bottom of the aquifer.

H and m can generally be determined from borehole logs. From equation (2) Q varies as $\frac{K}{\log R/r}$ where K represents all the constant terms and thus calculations can be made as to how the radius of a well affects the yield e.g. for artesian boreholes (where R is large) the percent increase resulting from doubling the borehole diameter is ± 7 per cent.

It can also be seen from equation (1) for artesian aquifers that the yield is directly proportional to the drawdown H - h provided the water level does not drop below the top of the aquifer and is also directly proportional to the aquifer thickness.

Non-equilibrium formula

The derivation of this formula by Theis (1935) was a major advance in groundwater hydraulics and was the first to take account of the effect of time of pumping on the yield.

The Theis formula is

$$S = \frac{114,6\ Q\ W(u)}{T}$$

where s = drawdown in feet, at any point in the vicinity of a borehole discharging at a constant rate.

Q = pumping rate in g.p.m. (U.S. gallons)

T = coefficient of transmissibility of the aquifer, in g.p.d. per foot.

$$W(u) = \text{well function of } u = \int_{\frac{1,87r^2 S}{Tt}}^{\infty} \frac{e^{-u}}{u}\, du$$

S = coefficient of storage

r = distance, in feet, from centre of pumped borehole to point where drawdown is measured.

t = time since pumping started in days.

The main advantages of the Theis formula are that drawdown can be predicted any time after the commencement of pumping; the transmissivity and average permeability can be determined from the early stages of a pump test before equilibrium has been obtained; the aquifer coefficients can be determined from time-drawdown measurements in a single observation borehole rather than two for the equilibrium formula.

T and S can be calculated graphically by matching a curve plotted from the pump test with a type curve and T calculated using the equation $T = \frac{114,6\ Q\ W(u)}{s}$. After determining T, S can be calculated from $S = \frac{u\ T\ t}{1,87r^2}$

Modified Non-Equilibrium Formula

Where u is less than 0,05 i.e. with large t and small r Jacob (1946) showed that Theis' equation can be simplified to $S = \frac{264\ Q}{T} \left(\log \frac{0,3\ T\ t}{r^2 s}\right)$

Data from the pump test is then plotted on semilogarithmic paper with time t plotted horizontally on the logarithmic scale and drawdown s plotted vertically on the arithmetic scale.

The coefficient of transmissibility T is calculated from $T = \frac{264\ Q}{\Delta s}$ where Δs = slope of time-drawdown graph expressed as the change in drawdown between any two values of time on the log scale whose ratio is 10.

Once T has been calculated, S may be obtained from $S = \frac{0{,}3\ T\ t_o}{r^2}$ where t_o = intercept of the straight line at zero drawdown, in days and r = distance, in feet, from pumped well to observation well.

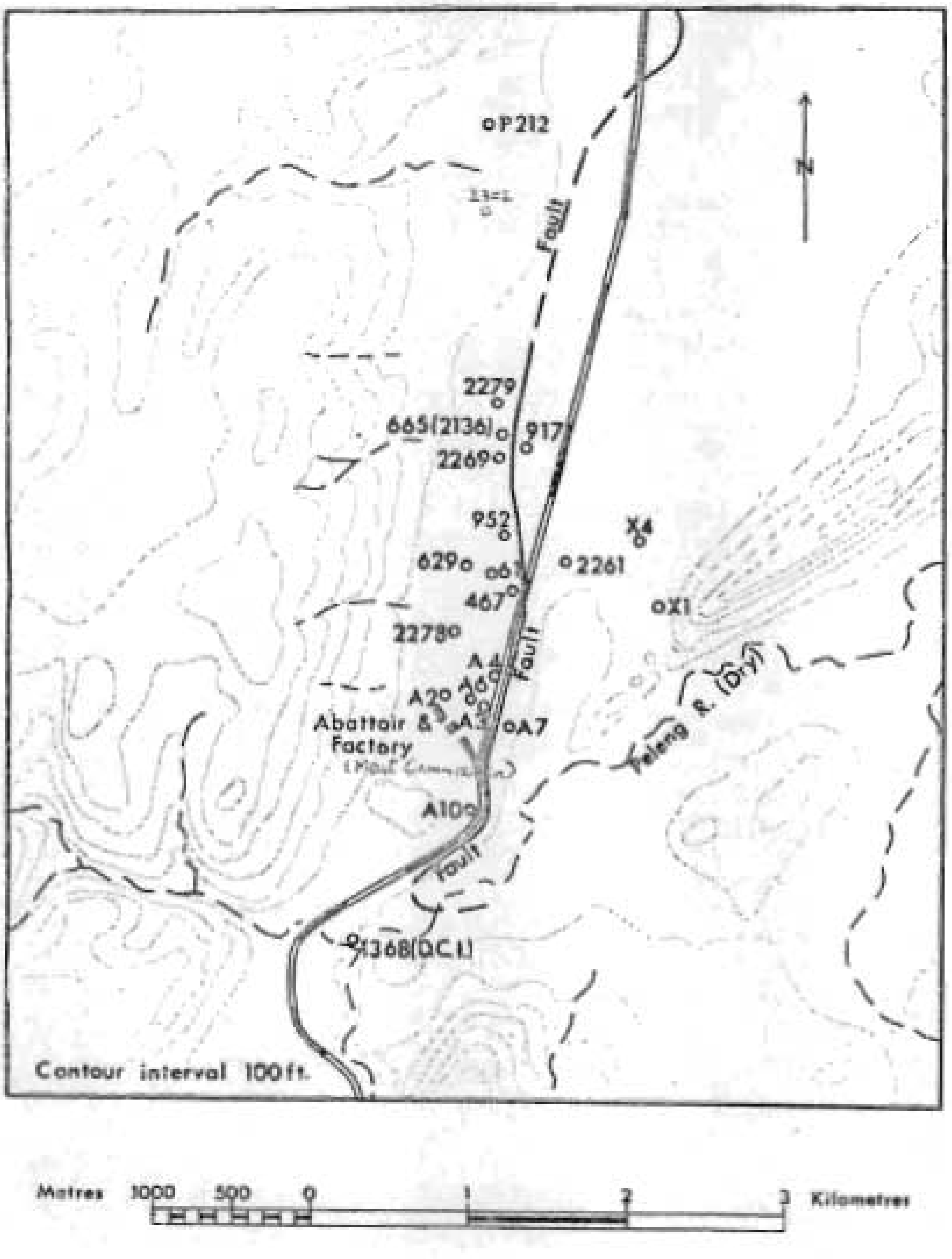
This time-drawdown diagram, in addition to its use for calculating T and S, is particularly useful for predicting future drawdown at any time in the future for a constant pumping rate.

CASE HISTORIES OF AQUIFER TESTS IN BOTSWANA

Because of the paucity of primary aquifers in Southern Africa, it had long been considered that detailed aquifer evaluation tests to determine the transmissivity and coefficient of storage of aquifers could not be carried out because of an apparent lack of homogeneity in the secondary aquifers generally present. In order to determine whether certain aquifers in Botswana did in fact, because of their intricate interconnecting system of fissures and joints, behave on a large scale as a homogeneous aquifer, a series of detailed pump tests were commenced by the writer on a variety of aquifers. Results of these tests are given below:-

LOBATSE WESTERN BASIN

Detailed aquifer tests were carried out on borehole A2 at the Botswana Meat Commission (Fig. 116) with water level observations being carried out simultaneously on boreholes A5 (353 feet or 107,62m away), A6 (364 feet or 110,97m), A4 (848 feet or 258,53m) and A7 (1052 feet or 320,73m) during the period 29th April - 2nd May 1969.



Borehole Locations.
FIG 11b Map: Lobatse western basin.

Geology

The Western Lobatse ground-water basin is underlain by a thick development (up to 30m) of colluvial soil and gravel overlying decomposed, waddy dolomite (Transvaal Supergroup) of variable thickness. This, in turn, overlies fresh, hard dolomite with interbedded chert horizons.

The aquifer test

Prior to the detailed aquifer evaluation test measurement of fluctuations in boreholes caused by barometric changes and tidal effects were noted. Slight barometric fluctuations were noted on boreholes A4, A10 and A7. In borehole A4 these fluctuations amounted to a maximum of 0.05 ft (15mm). The excellent correlation between the daily pressure maximum and the greatest depression of the piezometric water surface for borehole A4 can be seen in Fig.117.

Unfortunately no measurements could be made for boreholes A2 and A5, but as the water level fluctuations caused by pumping in the two boreholes far exceeds any possible barometric fluctuation, this should make no difference to the calculated results.

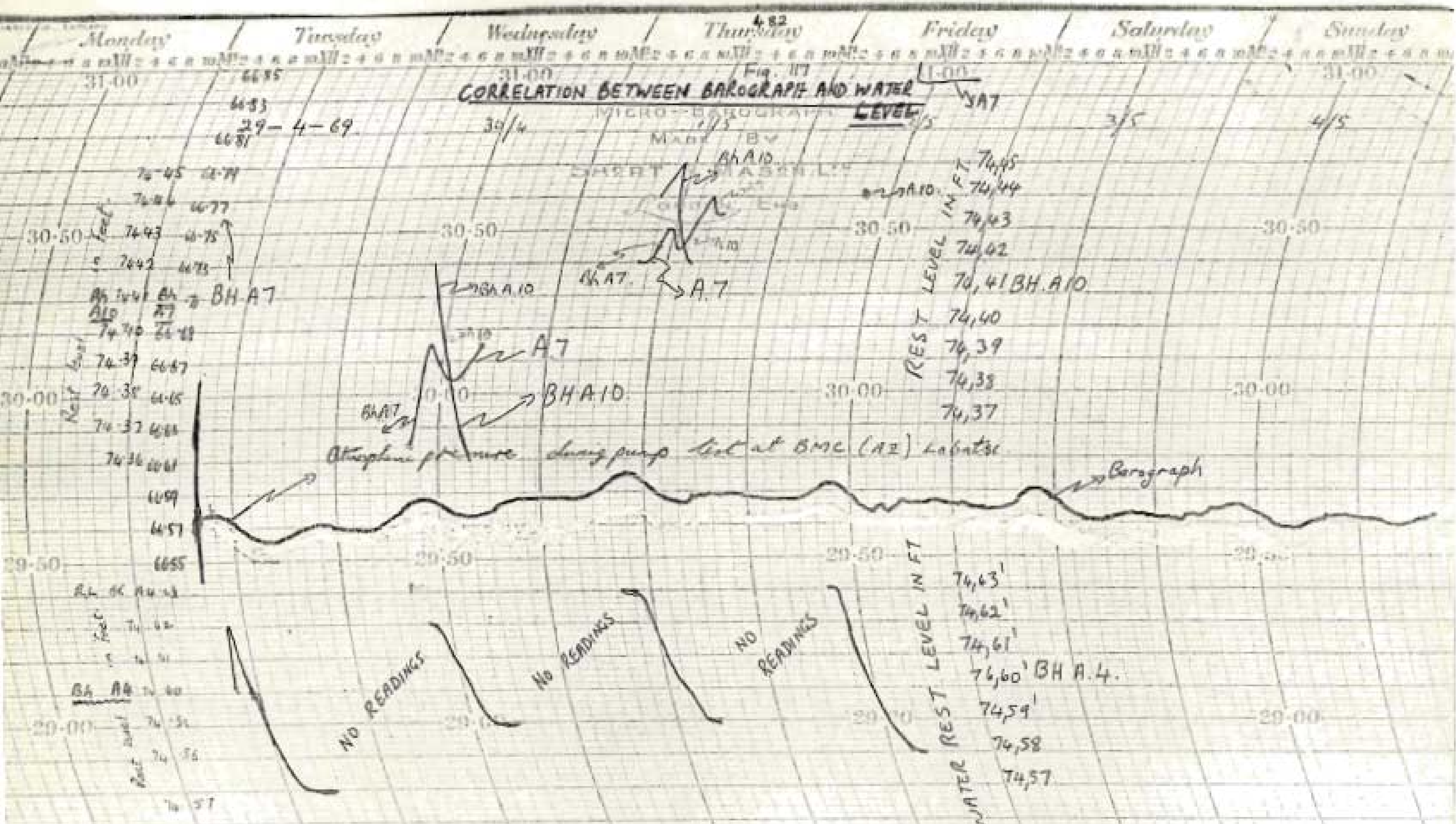

Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
CORRELATION BETWEEN BAROGRAPH AND WATER LEVEL
MICRO-BAROGRAPH
MADE BY
SHORT & MASON L^TD
LONDON, ENG
29-4-69
30/4
1/5
3/5
4/5
31.00
30.50
30.00
29.50
29.00
BH A7
BH A10
A7
BH A10
A.7
BH A.10
SAT
Atmospheric pressure during pump test at BMC (AZ) Lobatse
Barograph
REST LEVEL IN FT
74,45
74,44
74,43
74,42
74,41 BH.A10
74,40
74,39
74,38
74,37
NO READINGS
NO READINGS
NO READINGS
WATER REST LEVEL IN FT
74,63'
74,62'
74,61'
74,60' BH A.4.
74,59'
74,58
74,57

Fig. 117

Results of Pump Tests

Pumping commenced at 1117 hours on 29th April 1969 and continued until about 0700 hours on 1st May, when the power supply was accidentally switched off by a security guard. During this period 178,000 gallons of water ($809m^3$) were pumped at an average rate of 4,380 gallons per hour (331 litres per minute) until the morning of 30th April, when the pumping head was increased by about 50 feet (15m) when water was pumped directly into the storage tank. This resulted in a drop in the pumping rate to 3,940 gallons per hour (298 litres per minute). Drawdown during this initial pumping period reached a maximum of 9,11 feet (2,77m) at 4,380 g.p.h. and recovered to a maximum drawdown of 8,28 feet (2,52m) at 3,940 g.p.h.

Time-drawdown Graphs

The drawdown results were first plotted (See Fig.118)as a time-drawdown graph on log - log paper and then matched with a type curve and T calculated using the Theis non-equilibrium formula -

Borehole A2 Time-drawdown graph

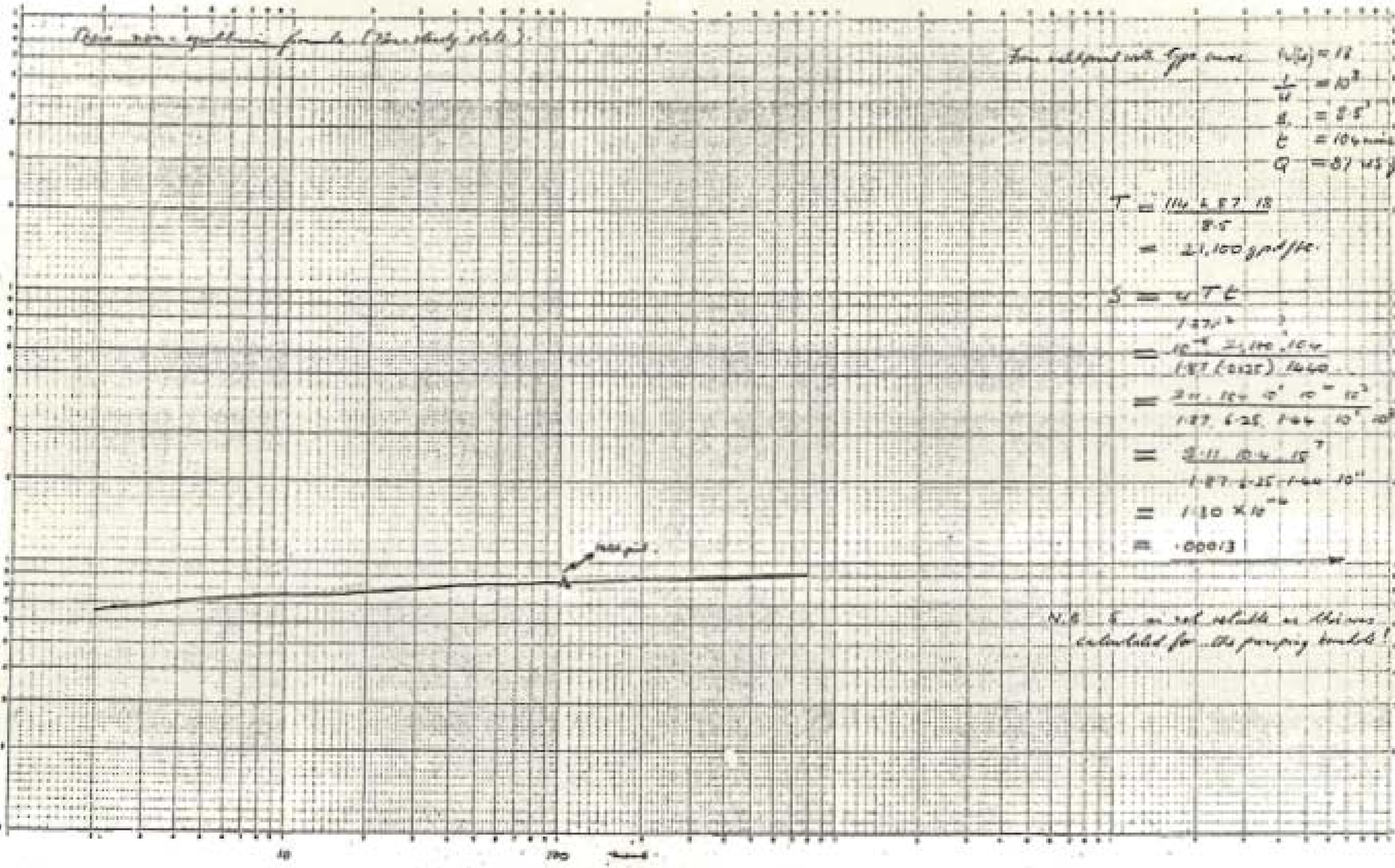


Fig. 118

$$S = \frac{114,6\ Q\ W(u)}{T}$$

where S = drawdown in feet for constant Q.

Q = pumping rate in gallons per minute (U.S. gallons).

$W(u)$ = well function of u.

$$= \int_{1,87\ \frac{r^2 S}{Tt}}^{\infty} \frac{e^{-u}}{u}\ du$$

t = time since pumping began in days.

r = distance in feet from centre of pumped borehole to point where drawdown is measured.

Using the Theis formula T = 21,000 gallons per day per foot (260,8m^2/day). Similarly, by matching with a nonsteady state leaky artesian type curve a value of 18,400 g.p.d. per foot was obtained (228,2m^2/day).

A second time-drawdown graph was plotted for the second pump test which commenced at 1123 hours on 1st May.

T (See Fig.119) from this test = 24 900 g.p.d./ft. (308,76m^2/day). The type curve for the matching of the curves on Figs. 118 and 119 is shown in Figs.120 and 121.

Borehole A2 Time-drawdown graph.
Test commenced 1123 hrs on 1/5/69.

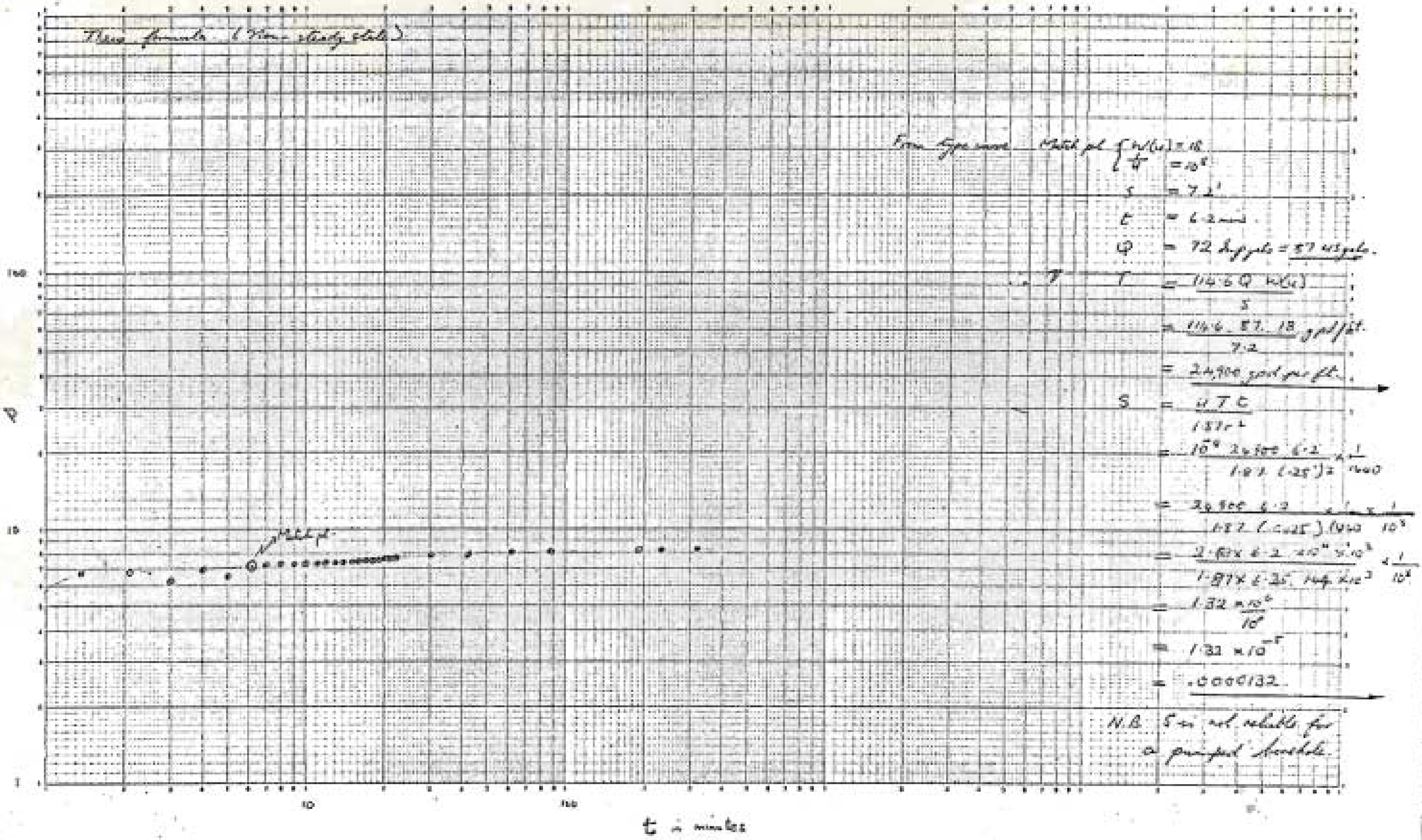


Fig. 119

Type Curve $W(u)$ vs $\frac{1}{u}$

Fig 120

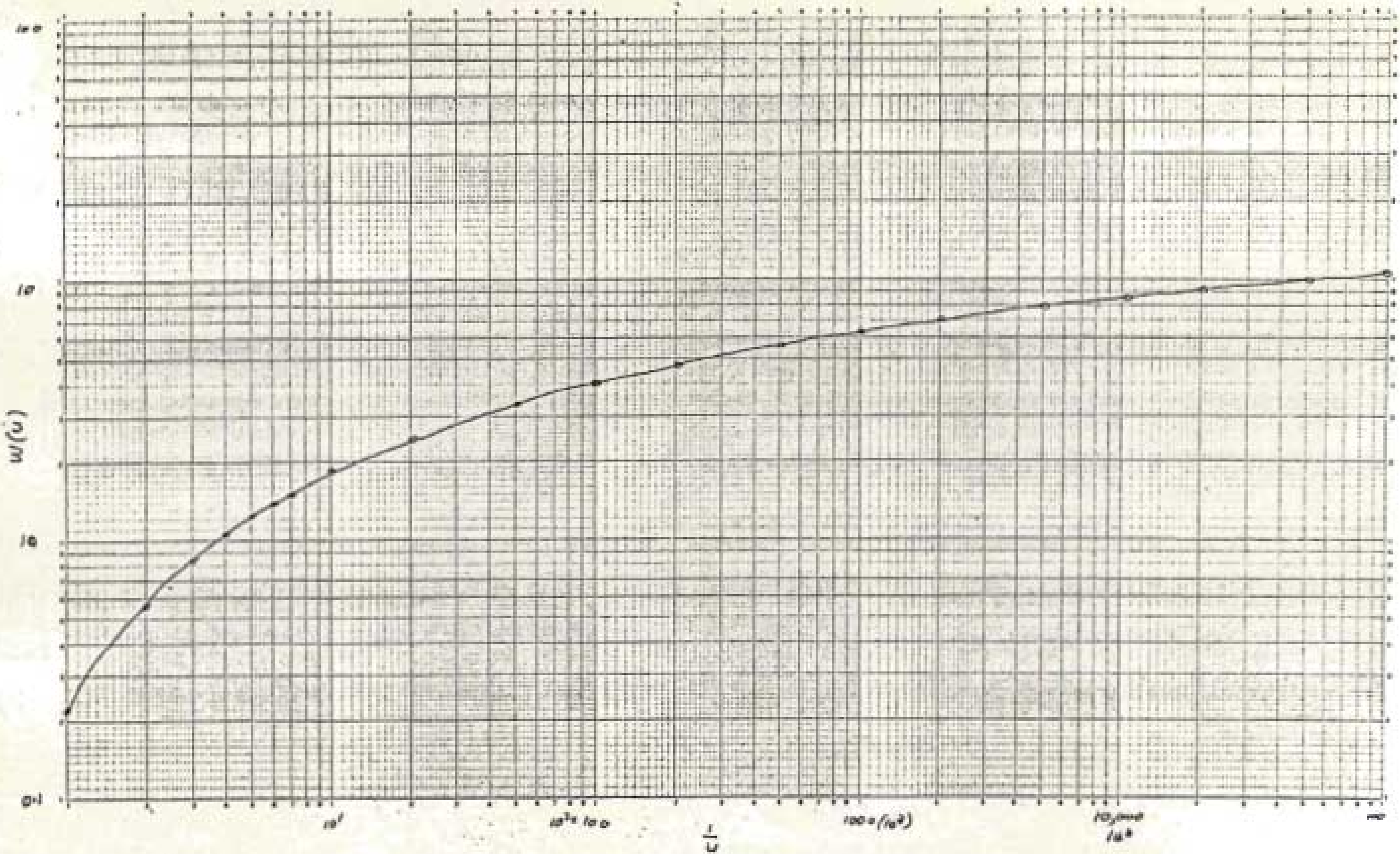
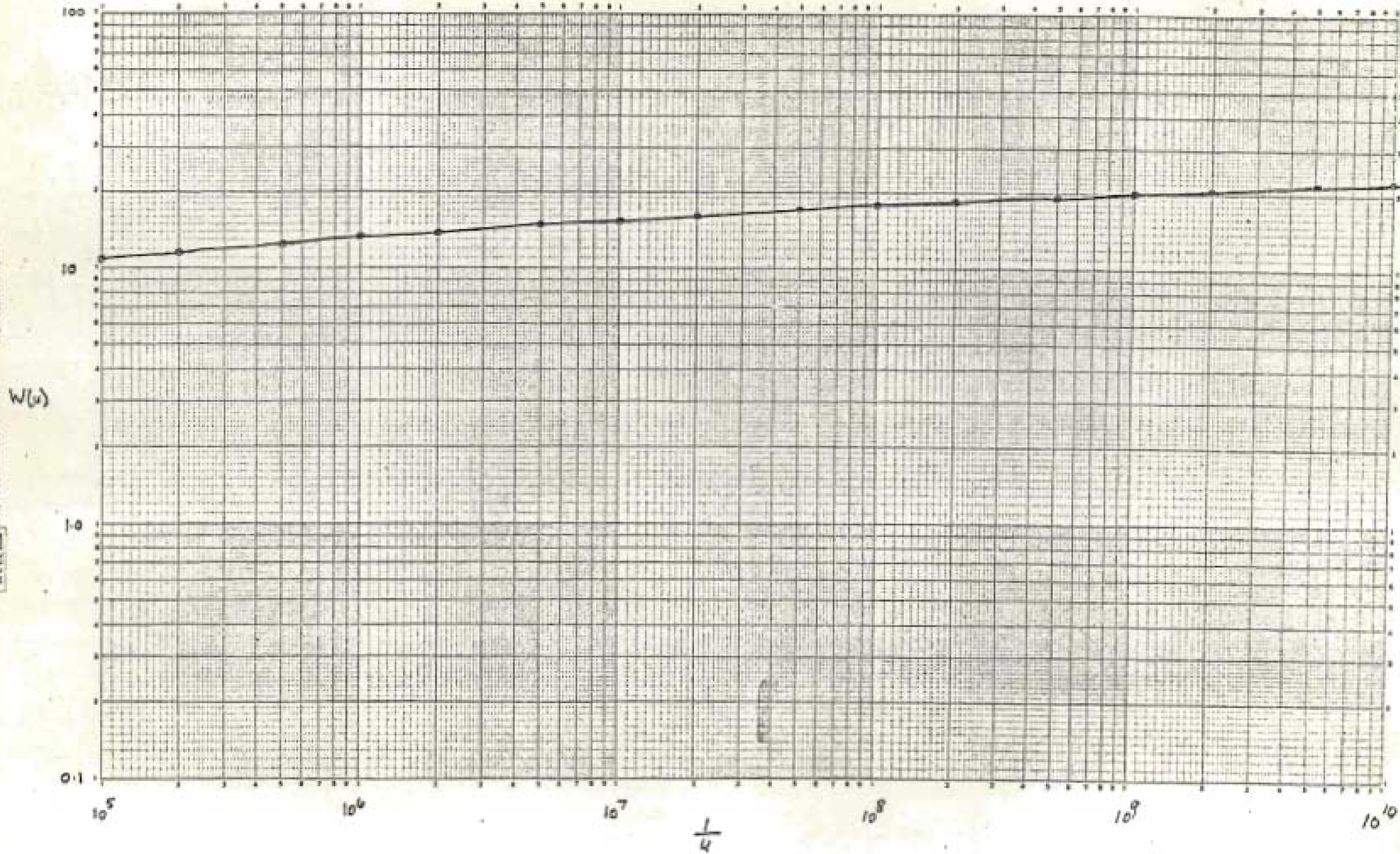


Fig 120

Type Curve $W(u)$ v $\frac{1}{u}$

Fig. 121



As it is easier to make calculations using semilogarithmic graph paper, the results were then plotted with the drawdown s plotted on the arithmetic scale and time plotted on the log scale. Calculations of T were then made using Jacob's modified non-equilibrium formula

$$S = \frac{264\ Q}{T} \left(\log \frac{0{,}3\ Tt}{r^2 S}\right)$$

or

$$T = \frac{264\ Q}{\Delta s}$$

where Δs = change in drawdown between any two values of time on the log scale whose ratio is 10.

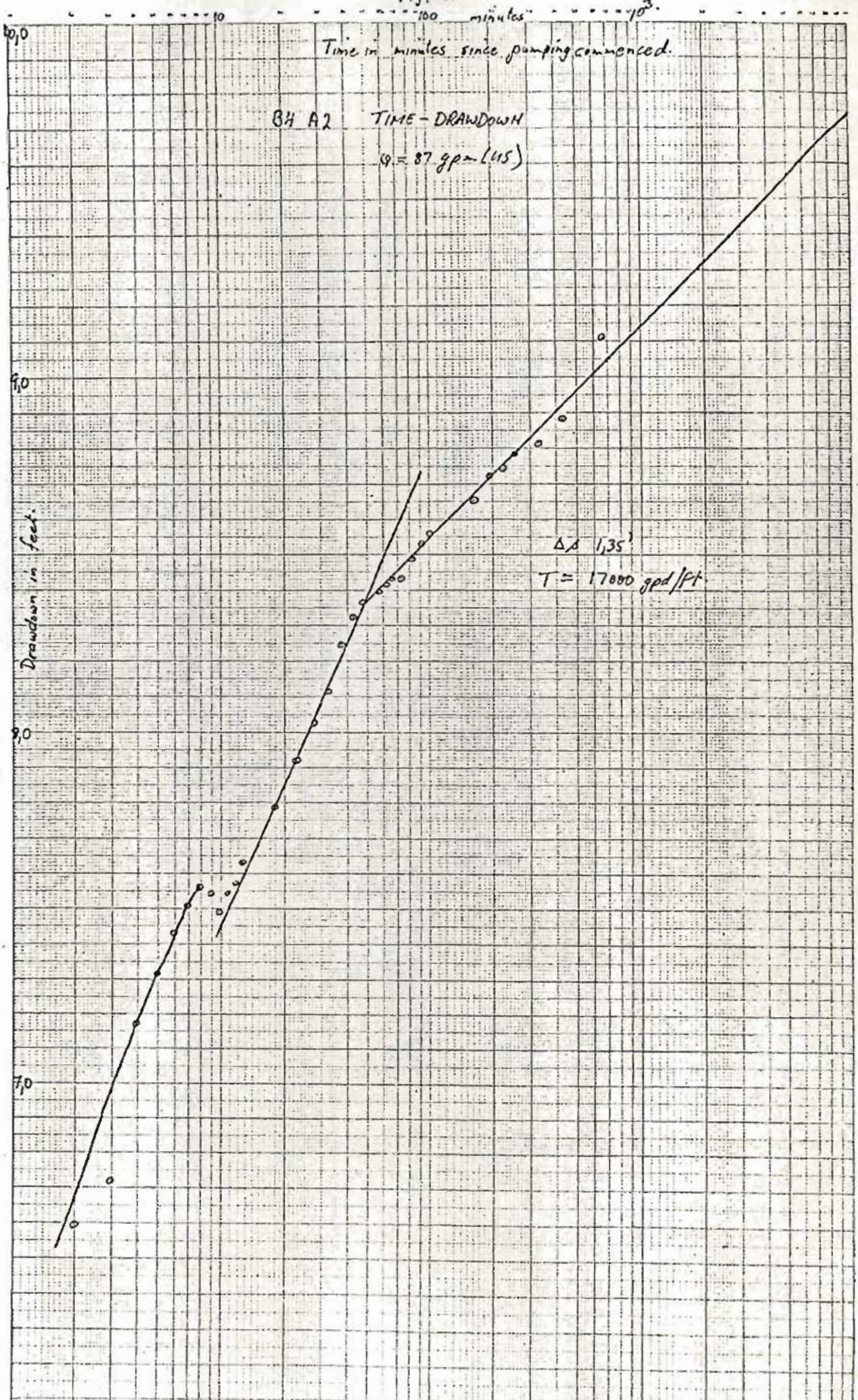
Figures 122 and 123 clearly show that there is a marked decrease in the rate of drawdown due to an additional source of recharge or a zone of higher transmissibility being encountered. Values from these two graphs are T = 17 000 and 20 200 g.p.d per foot (211,1m^2/d and 250,88m^2/d) respectively.

Time-drawdown graphs for boreholes A5 and A6 were also drawn. These gave values of 47 800 (593,67m^2/d) and 59 700 (741,47m^2/d) g.p.d. per foot for T and values for S of .32 and .0000113 respectively. (See Figs. 124 and 125).

Distance-drawn graphs

Graphs were then plotted, on semilogarithmic paper, of the distance of the observation borehole from the pumped borehole versus the drawdown

Fig. 122


10
100 minutes
10^3
Time in minutes since pumping commenced.
B4 A2 TIME - DRAWDOWN
Q = 87 gpm (US)
Δs 1,35'
T = 17000 gpd/ft
Drawdown in feet.
10,0
9,0
8,0
7,0
6

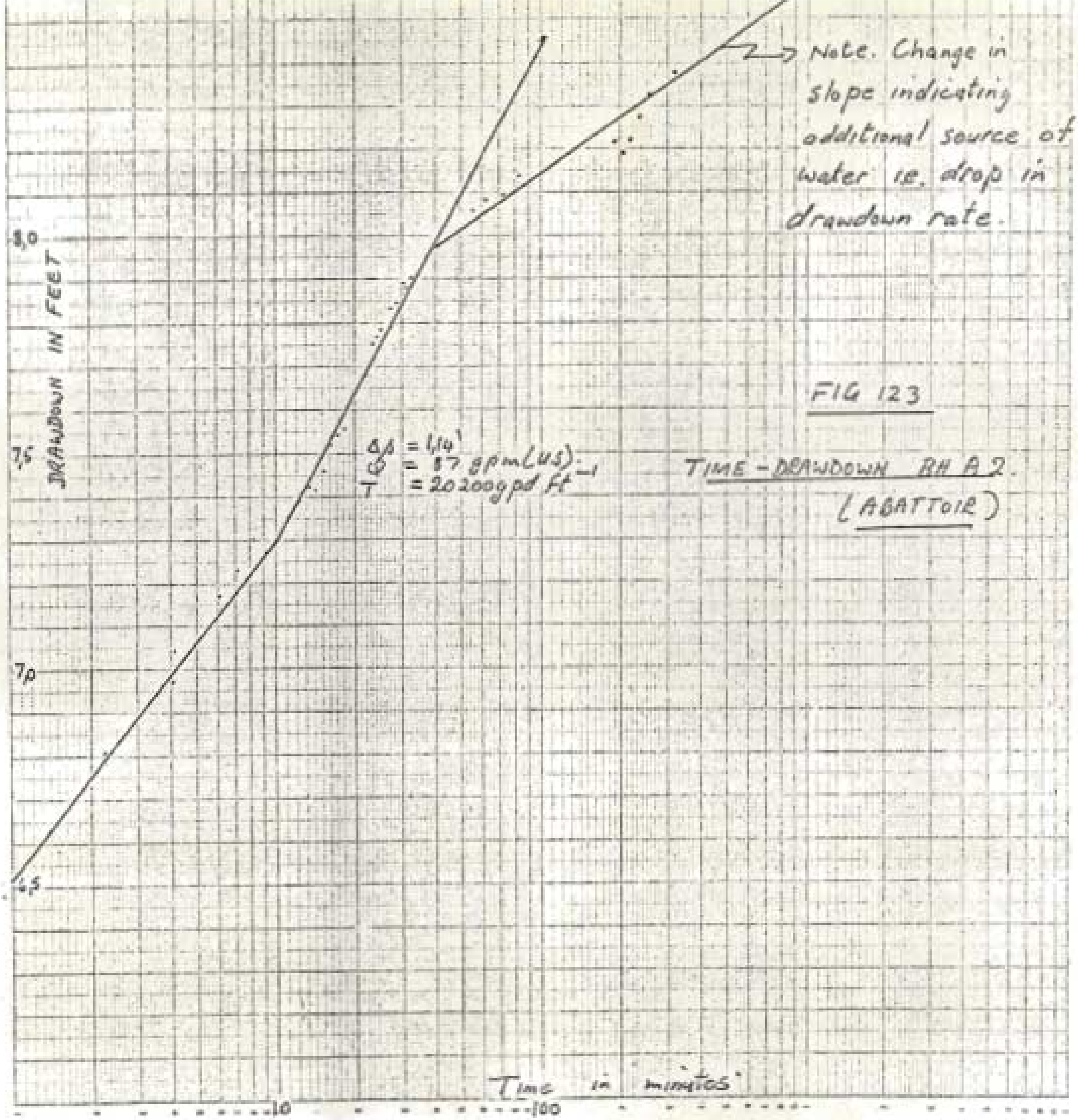
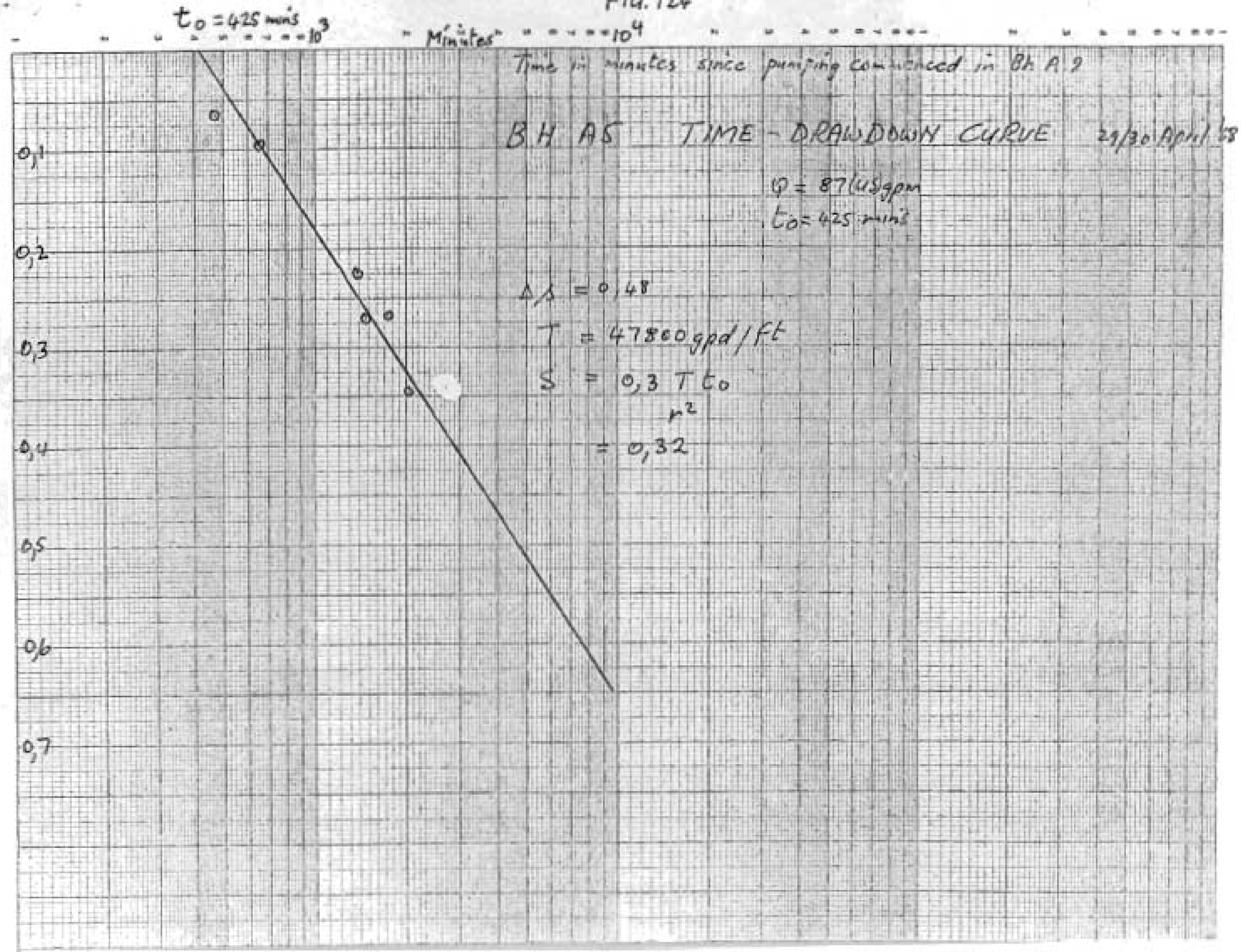


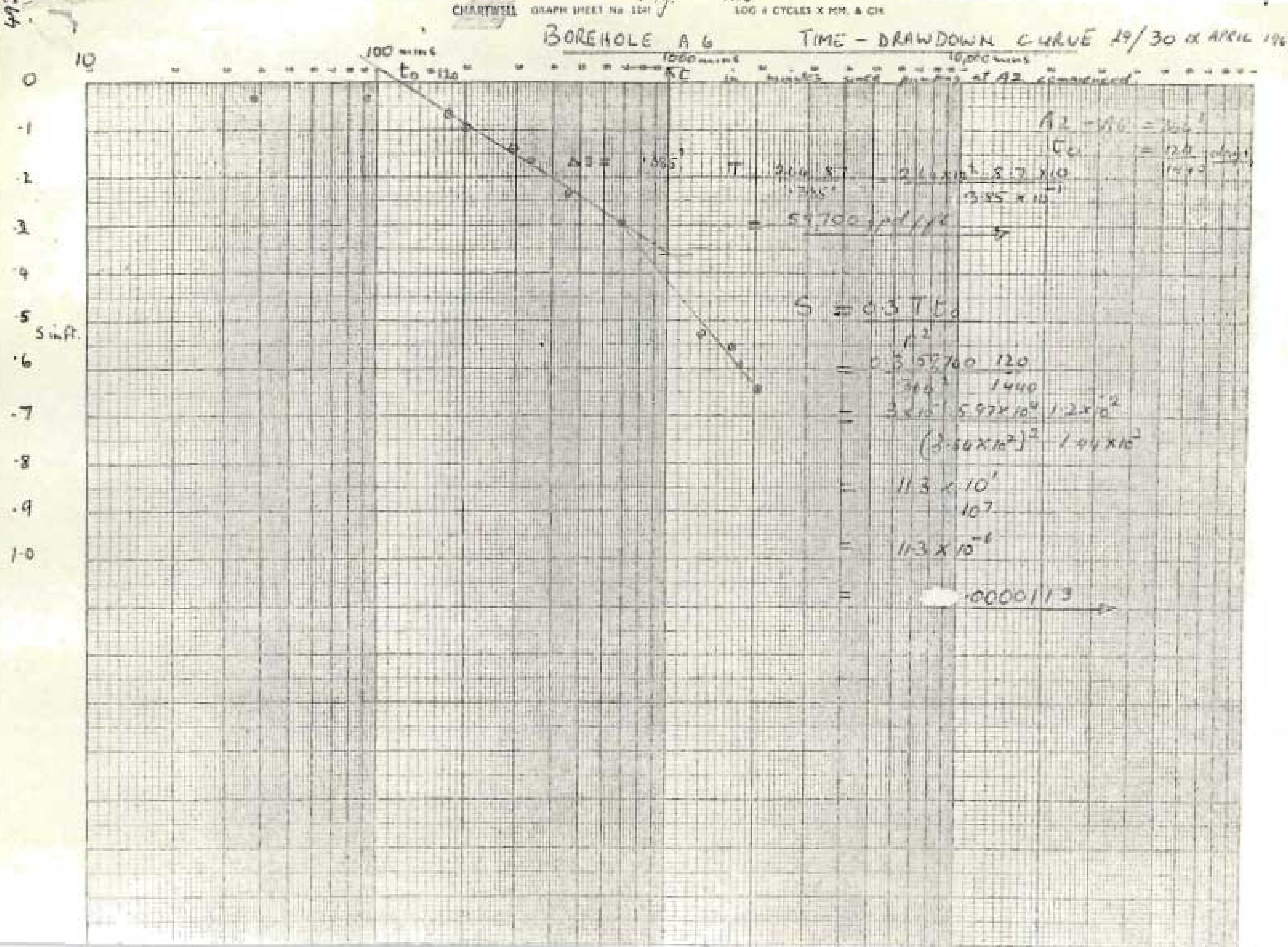
FIG 123

TIME - DRAWDOWN BH A 2.
(ABATTOIR)

FIG. 124



t_0 = 425 mins
10^3
Minutes
10^4
Time in minutes since pumping commenced in Bh A 9
B.H. A5 TIME - DRAWDOWN CURVE 29/30 April 58
Q = 87 (US) gpm
t_0 = 425 mins
$\Delta s = 0{,}48$
$T = 47860$ gpd/ft
$S = \frac{0{,}3\,T\,t_0}{r^2}$
$= 0{,}32$
0,1
0,2
0,3
0,4
0,5
0,6
0,7


CHARTWELL GRAPH SHEET No. 5241 LOG 4 CYCLES X MM. & CM
BOREHOLE A 6 TIME - DRAWDOWN CURVE 29/30 of APRIL 1969
100 mins
1000 mins
10,000 mins
t₀ = 120
t in minutes since pumping at A2 commenced
s in ft.
0
·1
·2
·3
·4
·5
·6
·7
·8
·9
1·0
Δs = ·385
T = 264 × 87 / ·385
= 57,700 gpd/ft
S = 0·3 T t₀ / r²
= 11·3 × 10⁻⁶
= ·0000113

at a fixed time since commencement of pumping. Two graphs, one at t = 1780 minutes since commencement of pumping, and one at 302 minutes since the commencement of the second test were plotted (See Figs.126 and 127), for boreholes A5, A6 and A3. Average values for T were 21 000 (260,8m^2/d) and 14 166 (175,65m^2/d g.p.d. per foot, respectively. The lower values for Fig. 11 are probably due to the fact that equilibrium conditions had not been restored prior to the commencement of the second test.

Time-Recovery Curve

A time-recovery curve was plotted (See Fig.128) for the water-level recovery following the cessation of the second pump test. Results from this gave the rather high value for T of 90 000 g.p.d. per foot (1116,0 m2/d). Once again the rather untimely accidental cessation of the first test probably caused the erroneously high value for T.

Discussion on Results

Values for T appear to be of the order of 20 000 g.p.d. per foot (248,4m2/d) which is surprisingly high. A series of "strong" boreholes recently tested near Orapa gave average values of 500 to 1 000 g.p.d. per foot. Values of S are also high.

Fig 126

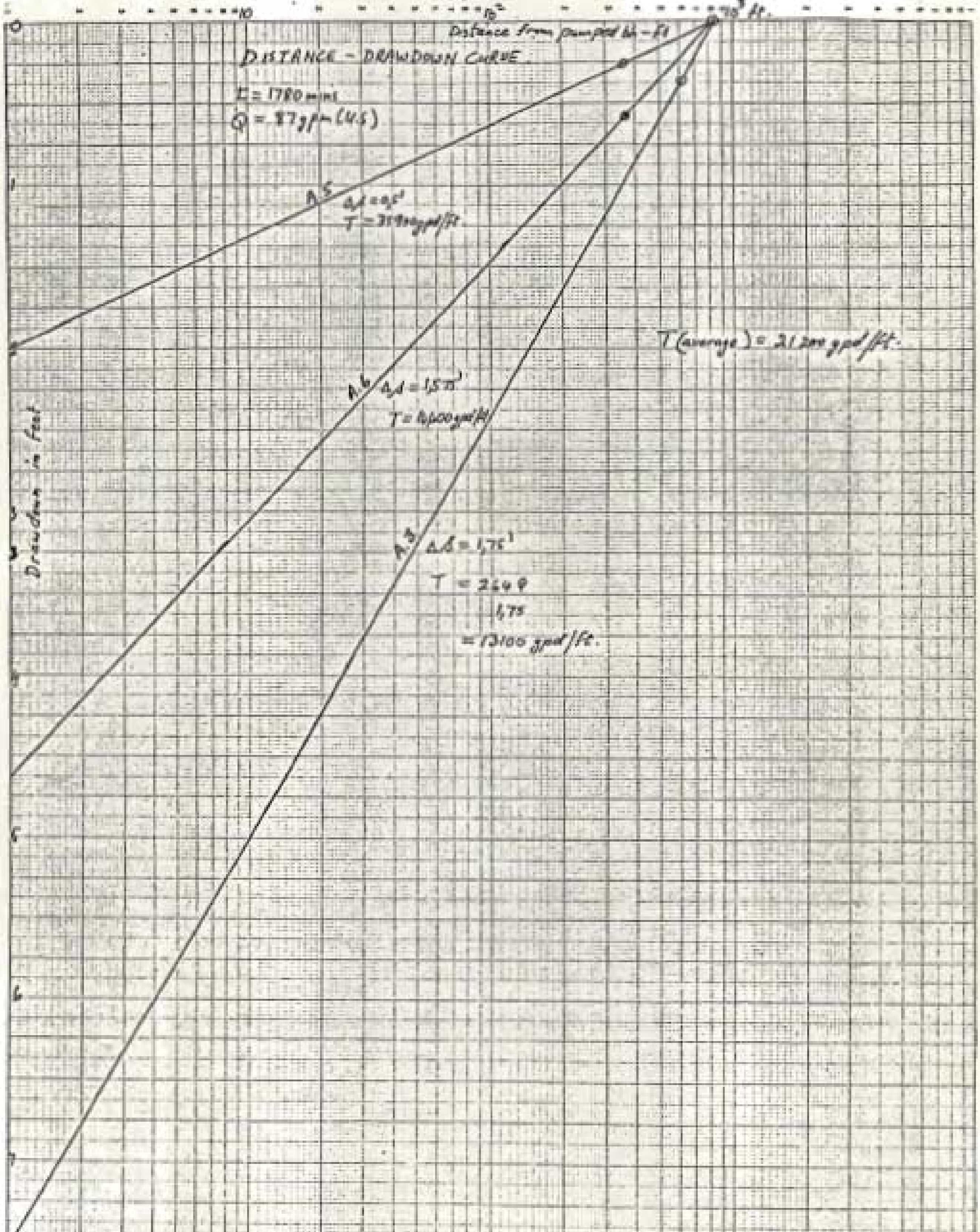
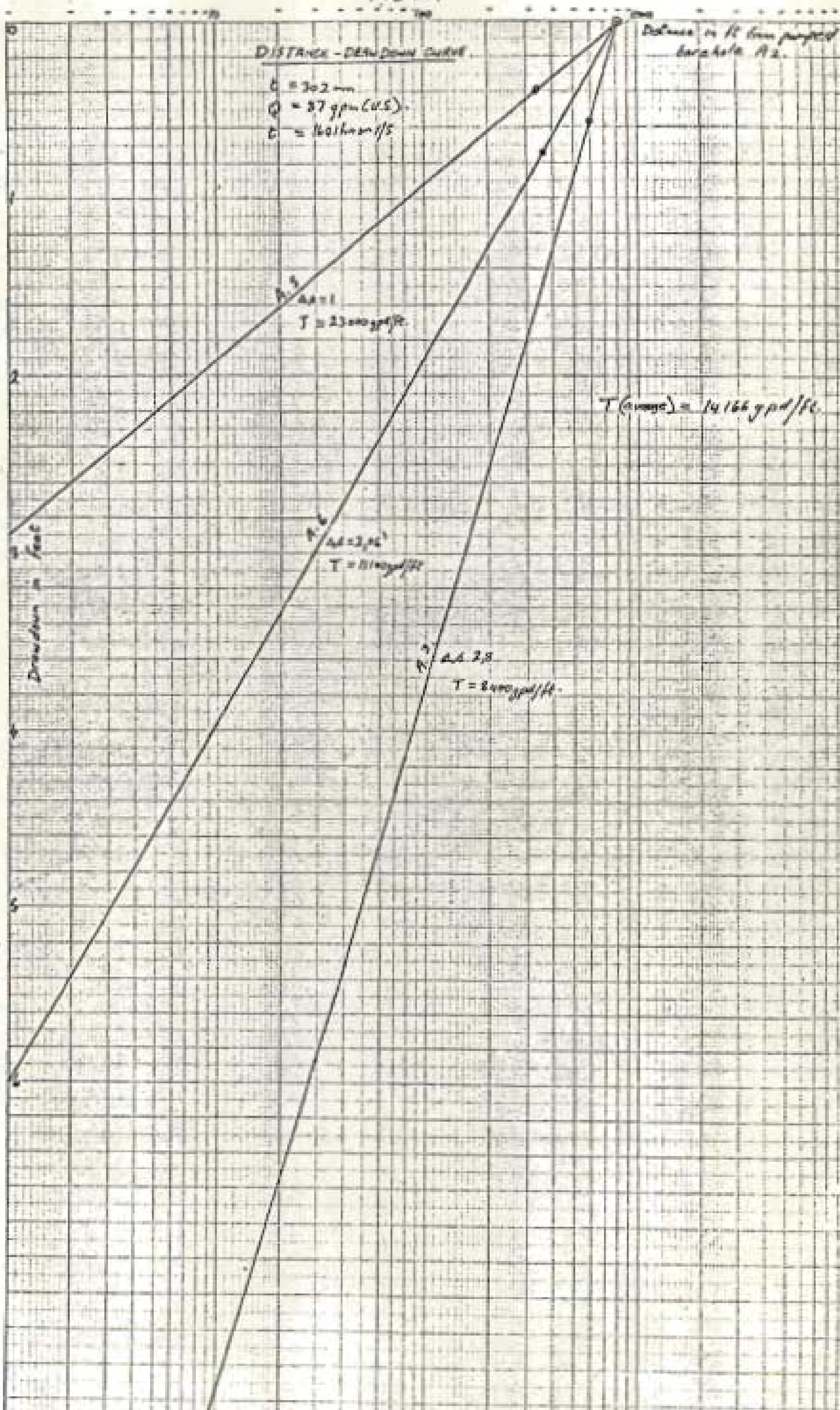

10
10²
10³ ft.
Distance from pumped hole – ft
DISTANCE – DRAWDOWN CURVE.
t = 1780 mins
Q = 87 gpm (U.S)
A5
Δs = 0.5'
T = 35900 gpd/ft.
T (average) = 21200 gpd/ft.
A6
Δs = 1.55'
T = 16600 gpd/ft
A3
Δs = 1.75'
T = 2640 / 1.75
= 13100 gpd/ft.
Drawdown in feet
0
1
2
3
4
5
6
7

FIG 127


DISTANCE - DRAWDOWN CURVE.
t = 302 min
Q = 37 gpm (U.S).
Distance in ft from pumped borehole A2.
T (average) = 14166 gpd/ft.
Drawdown in feet
0
1
2
3
4
5
6
A5
T = 23000 gpd/ft.
A6
T = 8400 gpd/ft.

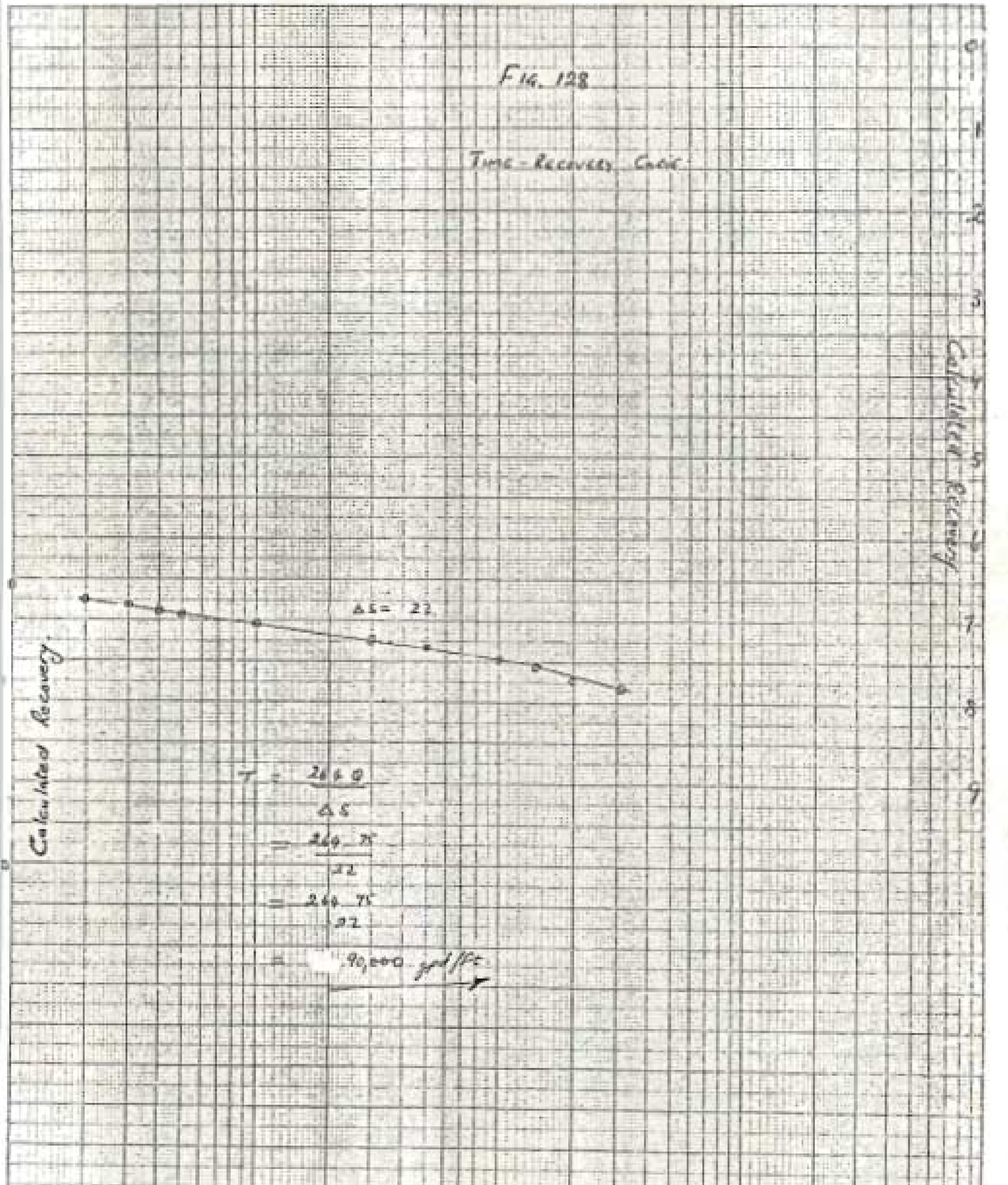


FIG. 128
TIME - RECOVERY CURVE
ΔS = 22
Calculated Recovery
Calculated Recovery
T = 264 Q / ΔS
= 264 75 / 22
= 264 75 / 22
= 90,000 gpd/ft
0
1
2
3
4
5
6
7
8
9
0
10
t
100
1000
10,000

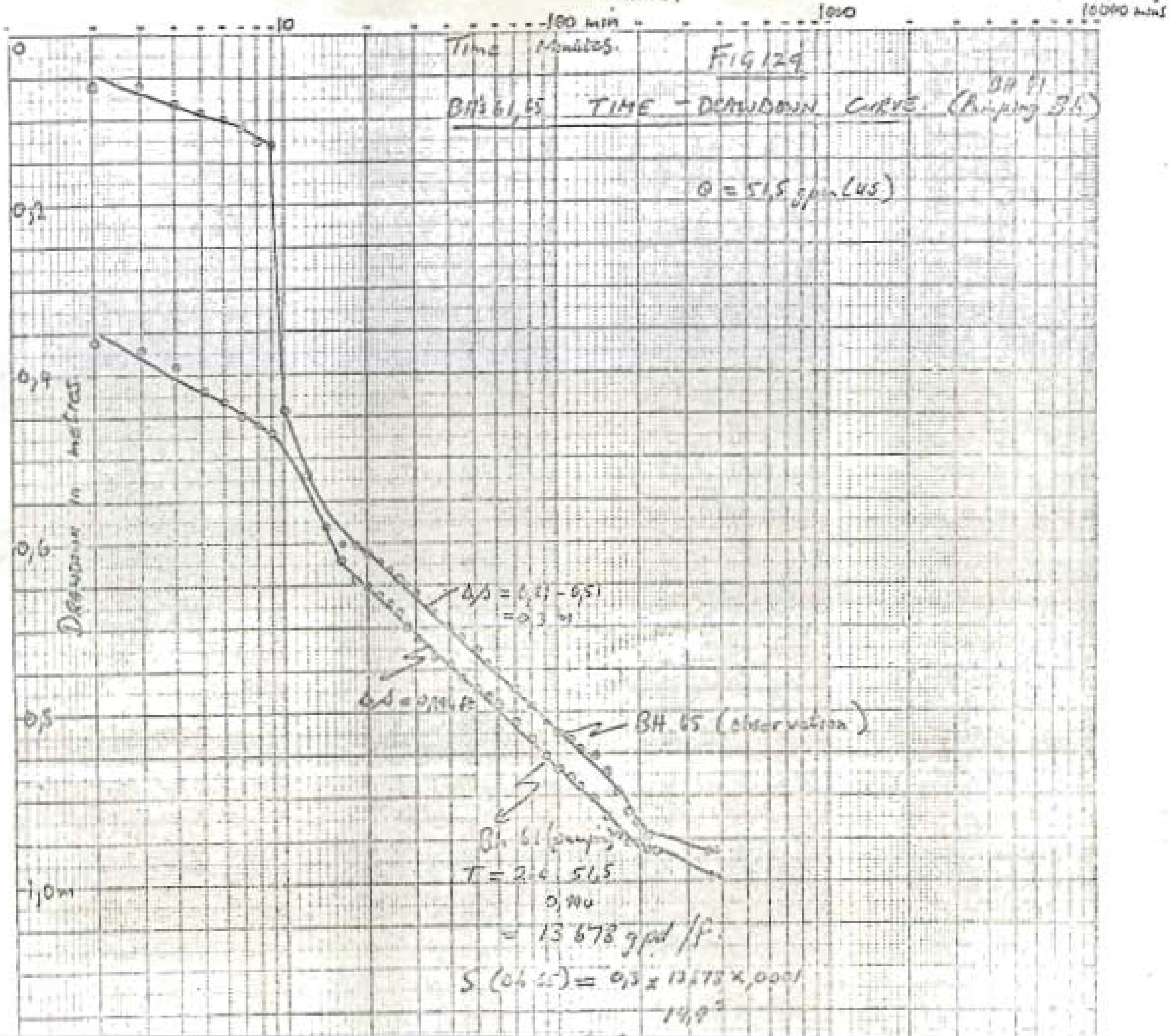
Using the above results, the drawdown, either in the pumped borehole or at any distance from the pumped borehole, can be calculated for any pumping rate and for whatever period of pumping is desired, e.g. by referring to Fig122, the drawdown in the pumped borehole after 10 000 minutes of continuous pumping at 4,380 g.p.h. (199,71/min) will only be 9.75 feet (2,97m). Thus drawdowns for a series of boreholes pumping from the same aquifer can be calculated. The fact that borehole A4 only 848 feet (258,5m) from A2 was completely unaffected during the test shows that the radius of influence of the cone of depression is also surprisingly small and hence for the optimum development of water from this basin a series of closely spaced boreholes would have to be drilled.

The aquifer tests thus confirm calculations that the storage capacity of the Western Basin is very large. (See Chapter on Hydrogeology of Lobatse).

<u>Other Pump Tests in the Lobatse Western Basin</u>

Results of further pump tests carried out on boreholes 61 and 665 using the nearby boreholes 65 (19,9 feet away) and 2135 (12 feet away) respectively as observation holes, are summarised in Table 64 below, while time-drawdown, distance drawdown and residual drawdown curves are shown in Figs. 129-132

FIG. 129



10
100 min
1000
6,94 days
10000 mins
Time minutes.
FIG 129
BH's 61, 65 TIME - DRAWDOWN CURVE (Pumping BH)
BH 61
Q = 51,5 gpm (US)
0
0,2
0,4
0,6
0,8
1,0 m
Drawdown in metres
BH. 65 (observation)
T = 264 × 51,5 / 0,90
= 13 678 gpd/ft

Fig 130

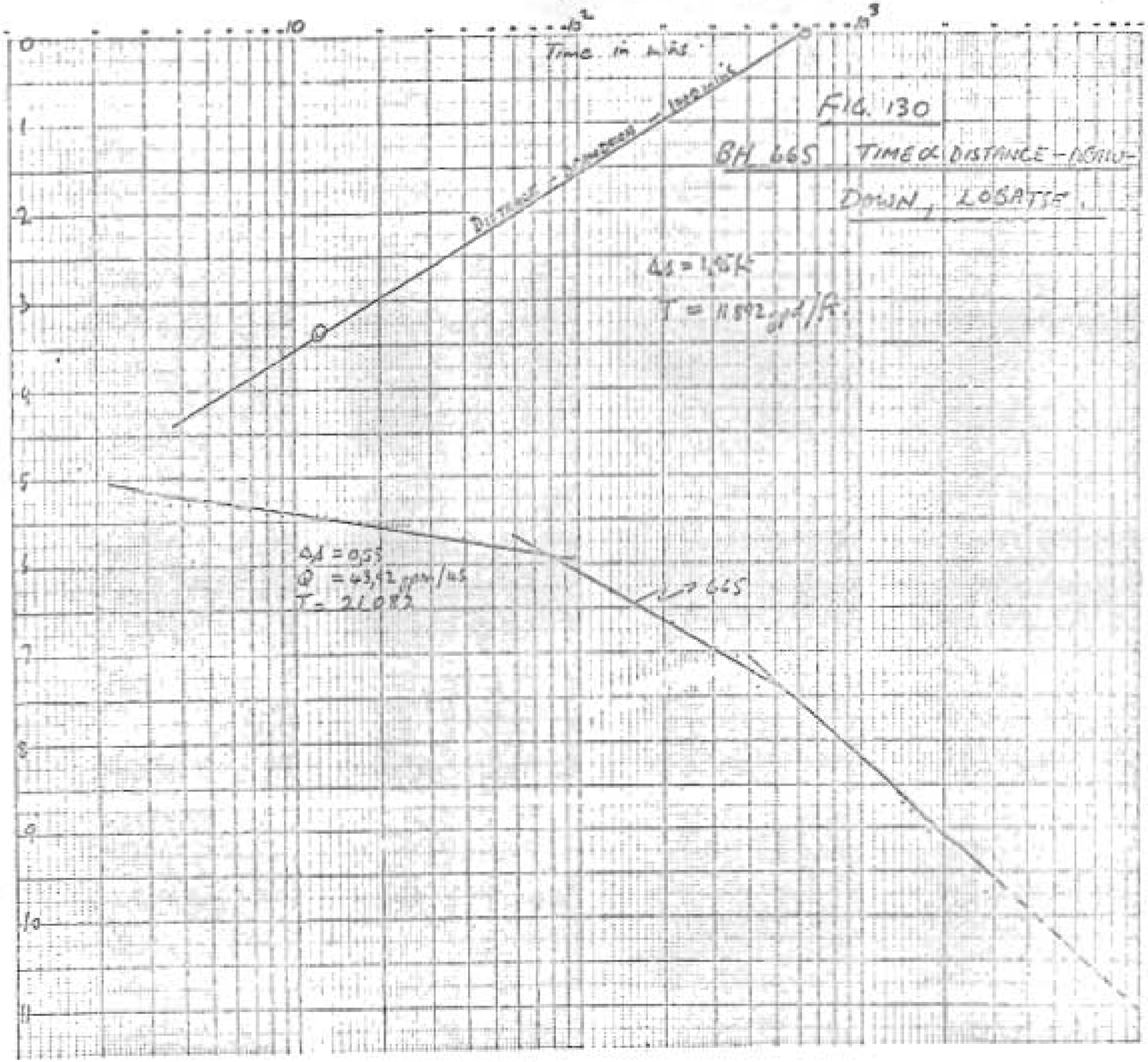


FIG. 130
BH 665 TIME & DISTANCE - DRAW-DOWN, LOBATSE
Time in mins
10
10^2
10^3
0
1
2
3
4
5
6
7
8
9
10
11
Δs = 0,55
Q = 43,42
T = 21082
665
T = 11892

Fig 131

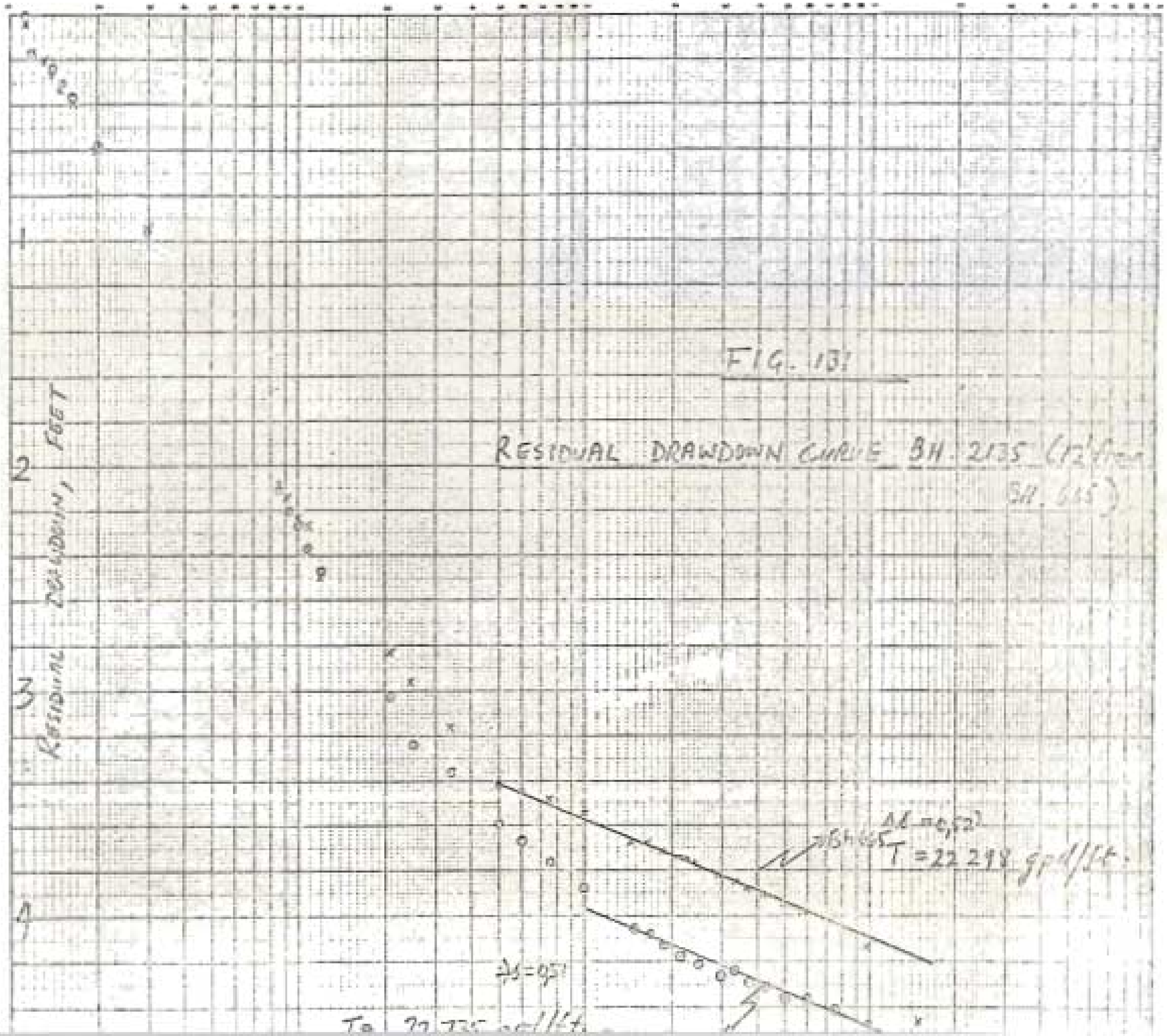


FIG. 131
RESIDUAL DRAWDOWN CURVE BH. 2135
RESIDUAL DRAWDOWN, FEET
1
2
3
4
T = 22 298 gpd/ft.

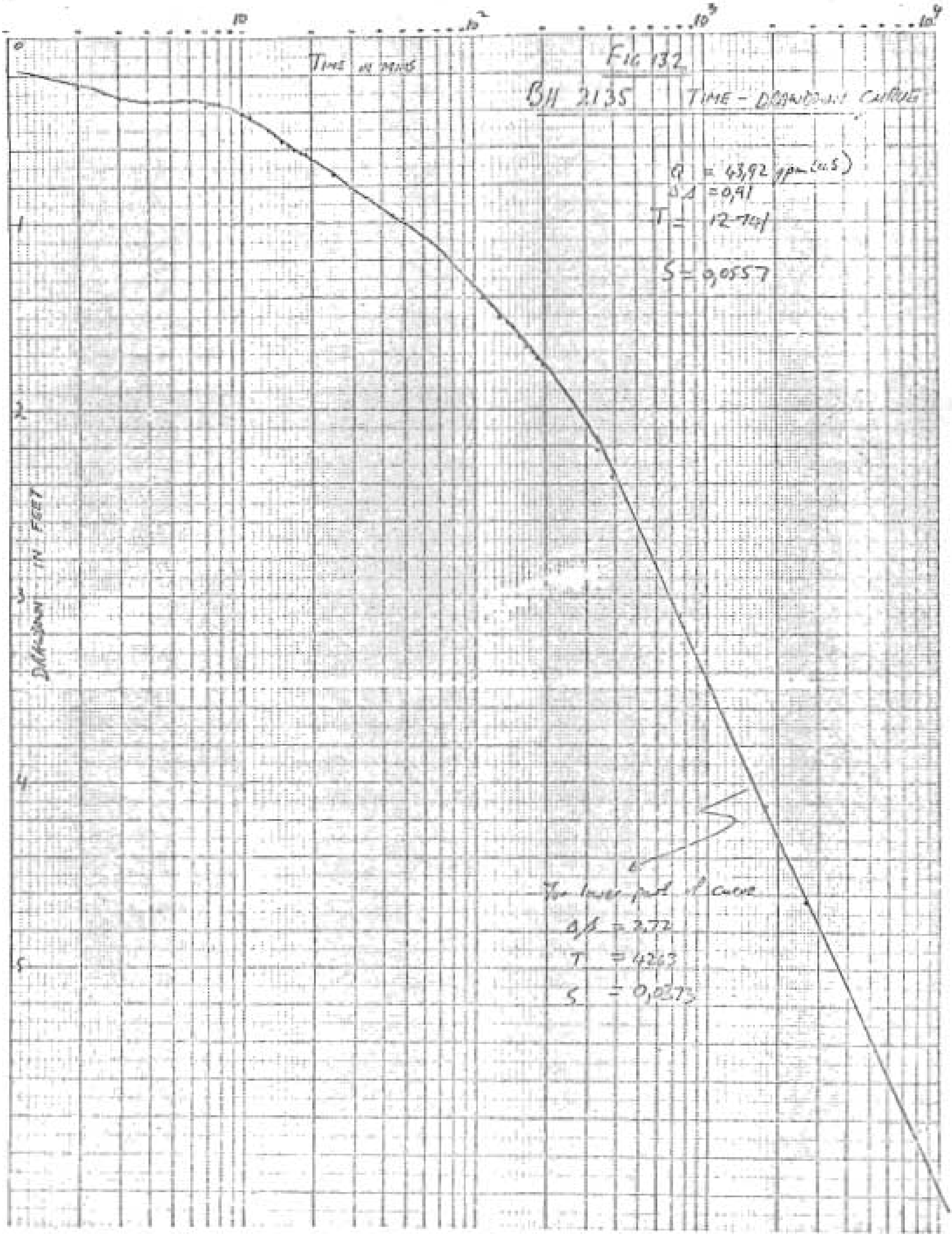

10
10^2
10^3
10^4
TIME IN MINS
FIG 132
BH 2135 TIME - DRAWDOWN CURVE
Q = 43,92 gpm (U.S)
Δs = 0,91
T = 12 701
S = 0,0557
For lower part of curve
Δs = 2,72
T = 4263
S = 0,0373
DRAWDOWN IN FEET
0
1
2
3
4
5

Table 64

VALUES FOR T & S   PUMP TEST LOBATSE WESTERN BASIN

	r	T		S
		gpd/ft	m^2/day	
TIME-DRAWDOWN				
*BH 665				
" 2135	12 ft	12741	158	0,0557
" 61		13678	170	
" 65	19,9ft			0,00104
DISTANCE-DRAWDOWN (BHS 917 & 2135)				
		11982	148,5	
RESIDUAL DRAWDOWN				
BH 665		22298	277	
BH 2135		22735	282,3	

*This test showed decreasing permeability of the aquifer with an expanding cone of depression indicating a boundary effect.

Lobatse Railway Basin (D.C.'s Office) Pump Test

(See Fig.116)

A number of closely spaced boreholes were used as observation holes during a pump test in the vicinity of the District Commissioner's office to determine the value for T and S for the dolomite aquifer.

Geology

The boreholes were drilled in decomposed dolomite with manganiferous wad. (Dolomite Group, Transvaal Supergroup).

Results of the pump test

Measurements were taken in the pumped hole and in 3 observation boreholes neaby.

The time-drawdown curve for the pumped hole is shown in Fig. 133 . This gave a value for T of 3465 g.p.d./ft (43m2/day)

The fluctuations in the curve were caused by an inability to keep the pumping rate absolutely constant. Time-drawdown curves for observation holes 2 and 3 are given in Fig. 134 and for D.C. No. 4 borehole in Fig.135. Values of T and S for the test are given in Table 65.

FIG 133

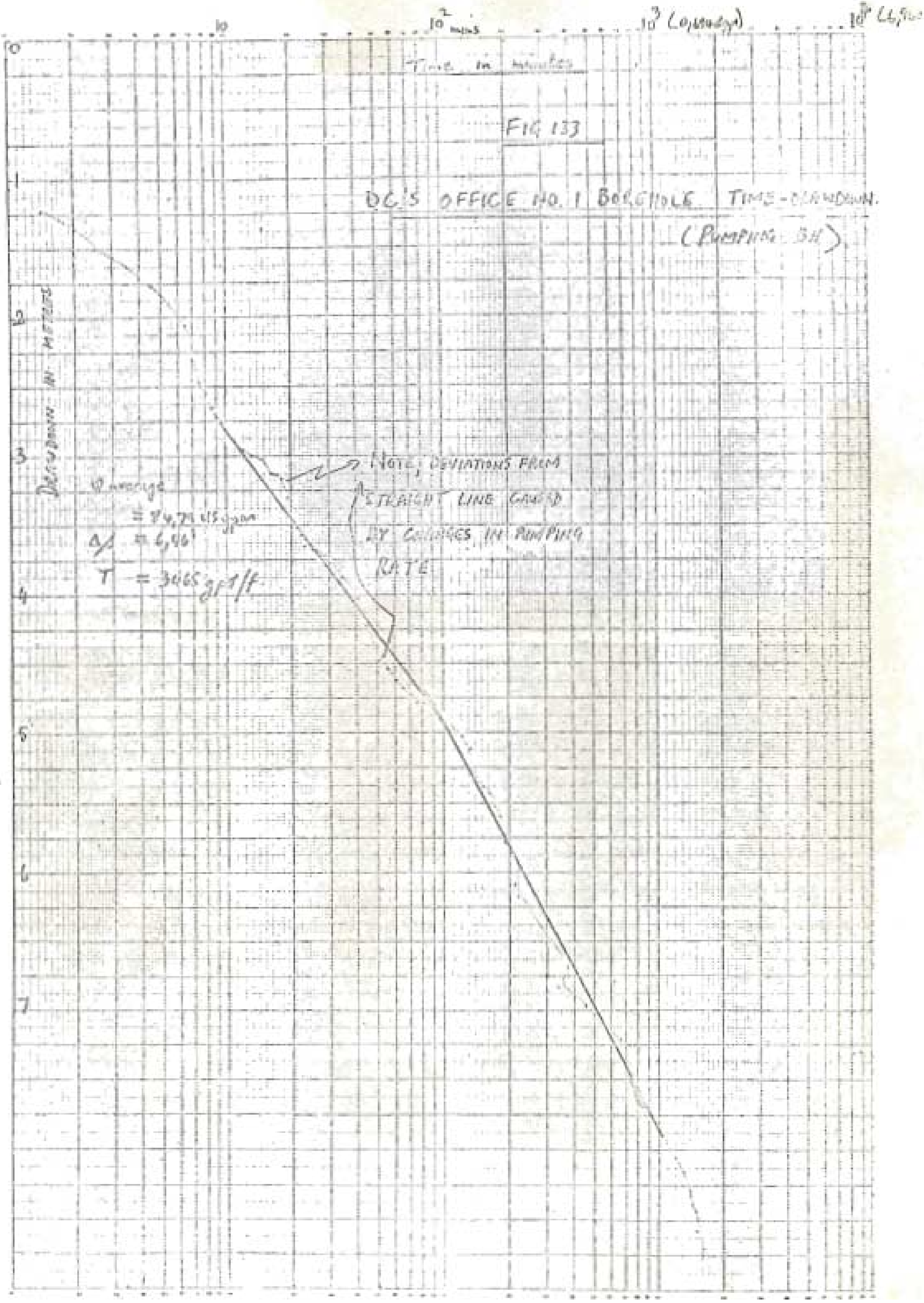
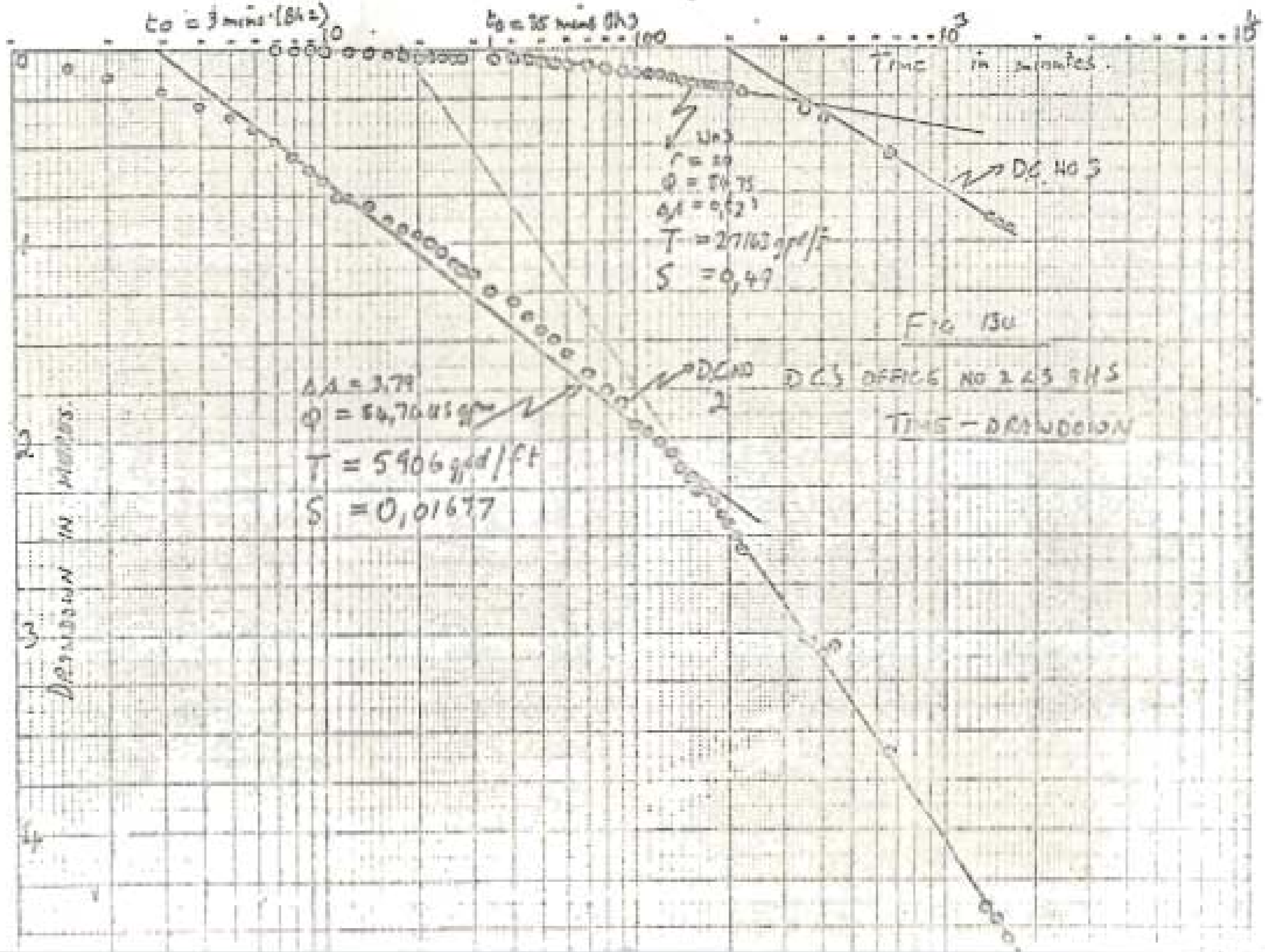

10
10² mins
Time in minutes
FIG 133
DC'S OFFICE NO. 1 BOREHOLE TIME-DRAWDOWN.
(PUMPING BH)
Drawdown in metres
0
1
2
3
4
5
6
7
NOTE; DEVIATIONS FROM STRAIGHT LINE CAUSED BY CHANGES IN PUMPING RATE
T = 3465

Fig 134


to = 3 mins (Bh 2)
to = 35 mins Bh 3
10
100
10^3
10^4
Time in minutes.
Drawdown in metres.
0
1
2
3
4
Bh 3
r = 20
Q = 54,75
Δs = 0,62
T = 27163 gpd/ft
S = 0,47
DC No 3
Δs = 3,79
Q = 54,74 usgpm
T = 5906 gpd/ft
S = 0,01677
DC No 2
Fig 130
DC3 OFFICE NO 2 & 3 BHS
TIME – DRAWDOWN

507

Fig 135

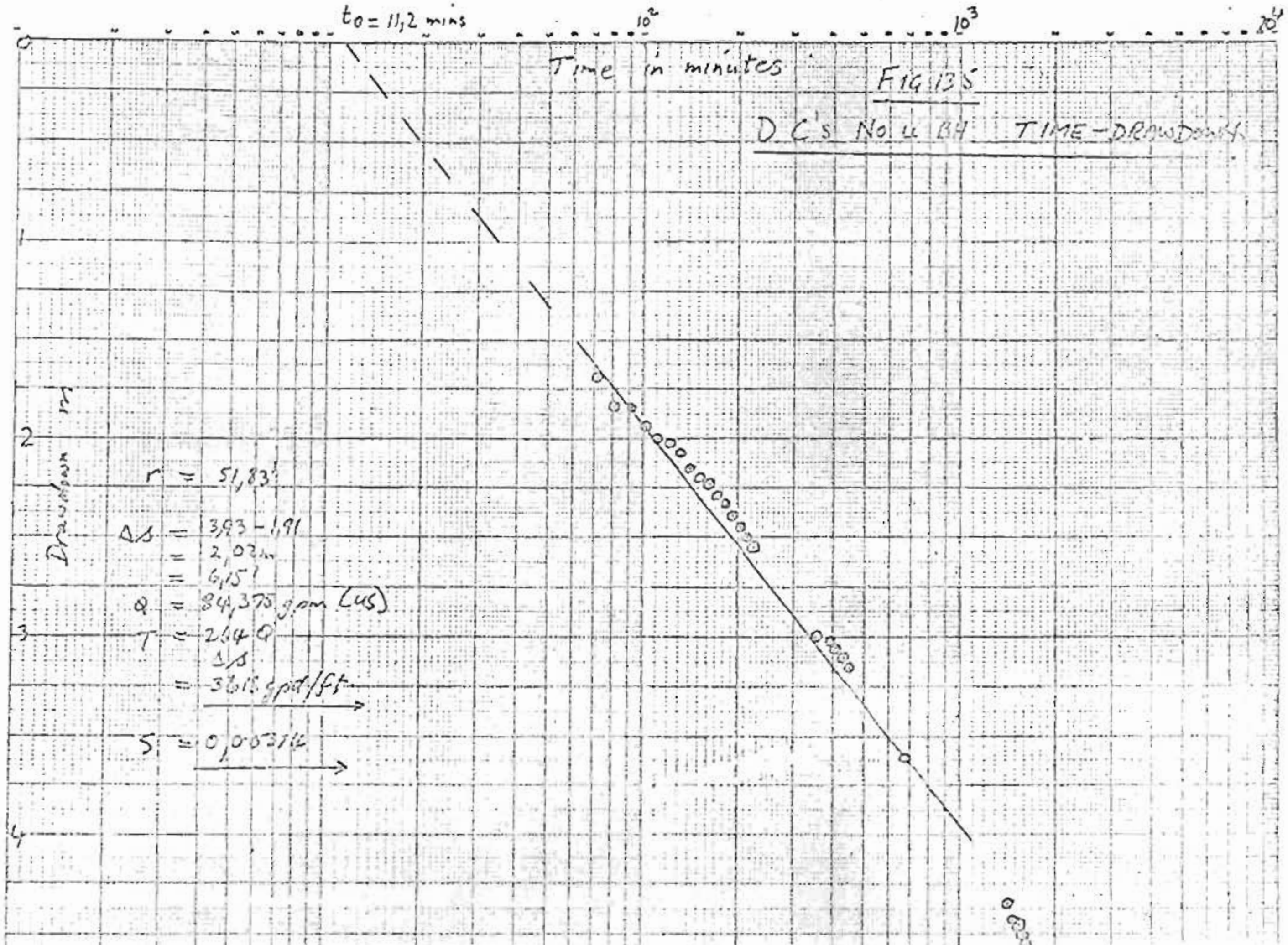

t0 = 11,2 mins
10²
10³
10⁴
Time in minutes
FIG 135
D C's No 4 BH TIME-DRAWDOWN
Drawdown m
0
1
2
3
4
r = 51,83'
Δs = 3,93 − 1,91
= 2,02m
= 6,57'
Q = 84,375 gpm (US)
T = 264 Q / Δs
= 3615 gpd/ft
S = 0,00376

TABLE 65

VALUES FOR T AND S PUMP TEST D.C.'s OFFICE BOREHOLES

BOREHOLE NO.	r	T		S
		g.p.d./ft	m^2/day	
D.C. 1 (Of no 1368)		3465	43	-
D.C. 2 (622)	14,83ft	5906	73	0,01677
D.C. 3 (?)	20,0 ft	27163	337,3	0,49
D.C. 4 (1276)	51,83ft	3618	44,9	0,00314
	Average:	10038	124,55	0,009955

All boreholes showed an increase in the gradient on the time-drawdown graph and hence less permeable zones in the dolomite are present in the vicinity of all four boreholes.

Lobatse Estates Southern Basin

The Lobatse Estates southern ground-water basin represents one of three basins on Lobatse Estates which, prior to the completion of the Nuane Dam, formed the mainstay of Lobatse water supply.

Geology

Boreholes in this basin penetrate black shale and shaly siltstone overlying Daspoort Subgroup ferruginous quartzite of the Pretoria Group (Transvaal Supergroup).

The Pump Test

A pump test was carried out on borehole 1077 and water level observations made on borehole 1041 situated 615 feet (187,5m) from borehole 1077. (See Fig. 510).

Results of the tests are given in Table below while the time-drawdown curves are shown in Figures 511 and 512 .

TABLE 66

VALUES FOR T AND S PUMP TEST LOBATSE ESTATES S. BASIN

BOREHOLE NO.	Q	r	T		S
			g.p.d./ft	m^2/day	
1077	35,4gpm(US)	-	150	1,86	
1041		615ft	1021	12,68	0,03239
		Average:	585,5	7,27	

Hildavale (± 30km south of Lobatse)

Geology

Fractured and decomposed dark fine-grained acid lavas (felsite) assigned to the Kanye Volcanic Group cut by younger diabase dykes. The felsites are overlain by a highly porous and permeable layer of nodular calcrete exceeding 3m in thickness.

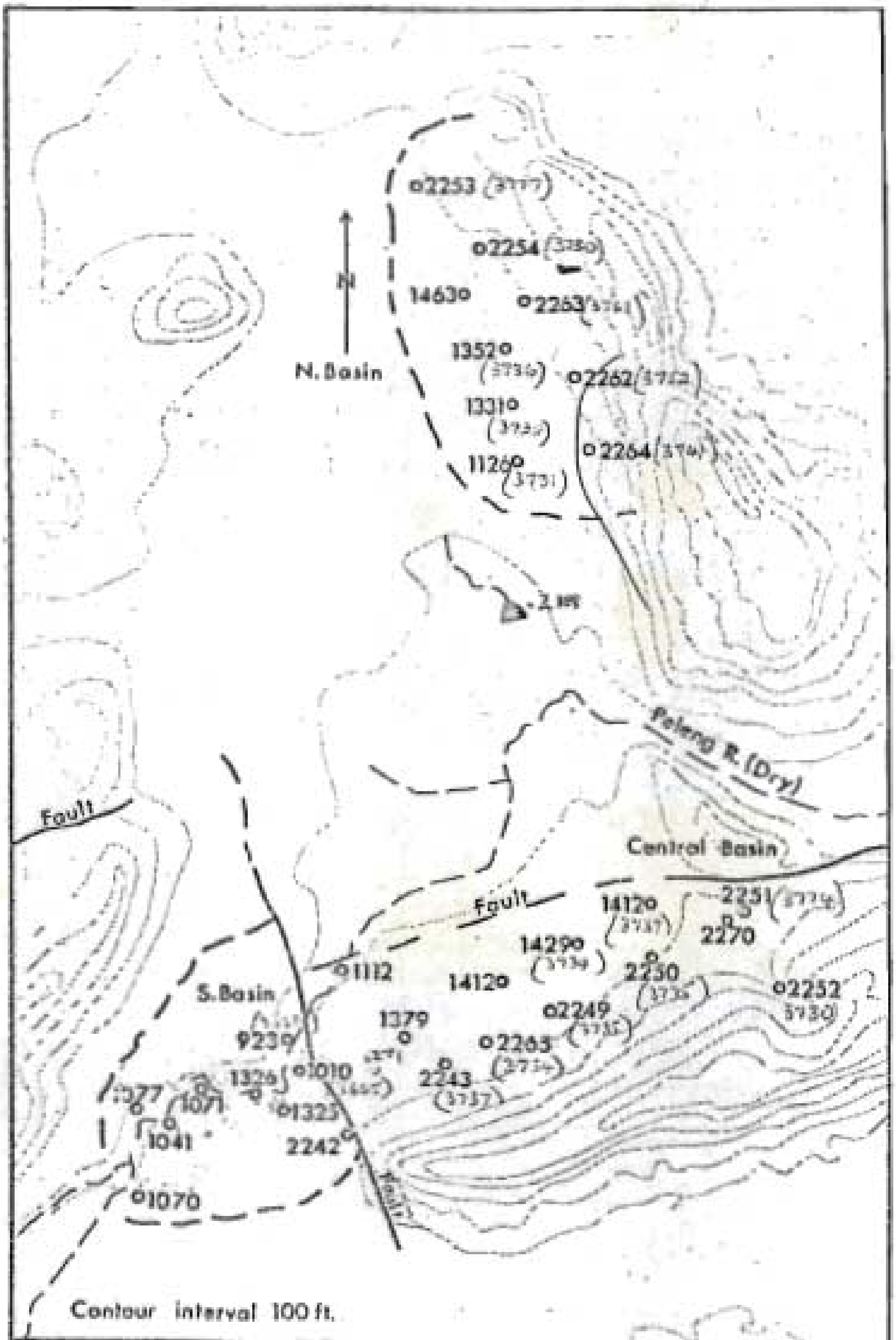


FIG. 136 Map: Lobatse Estates basins

x

FIG. 137

L-94

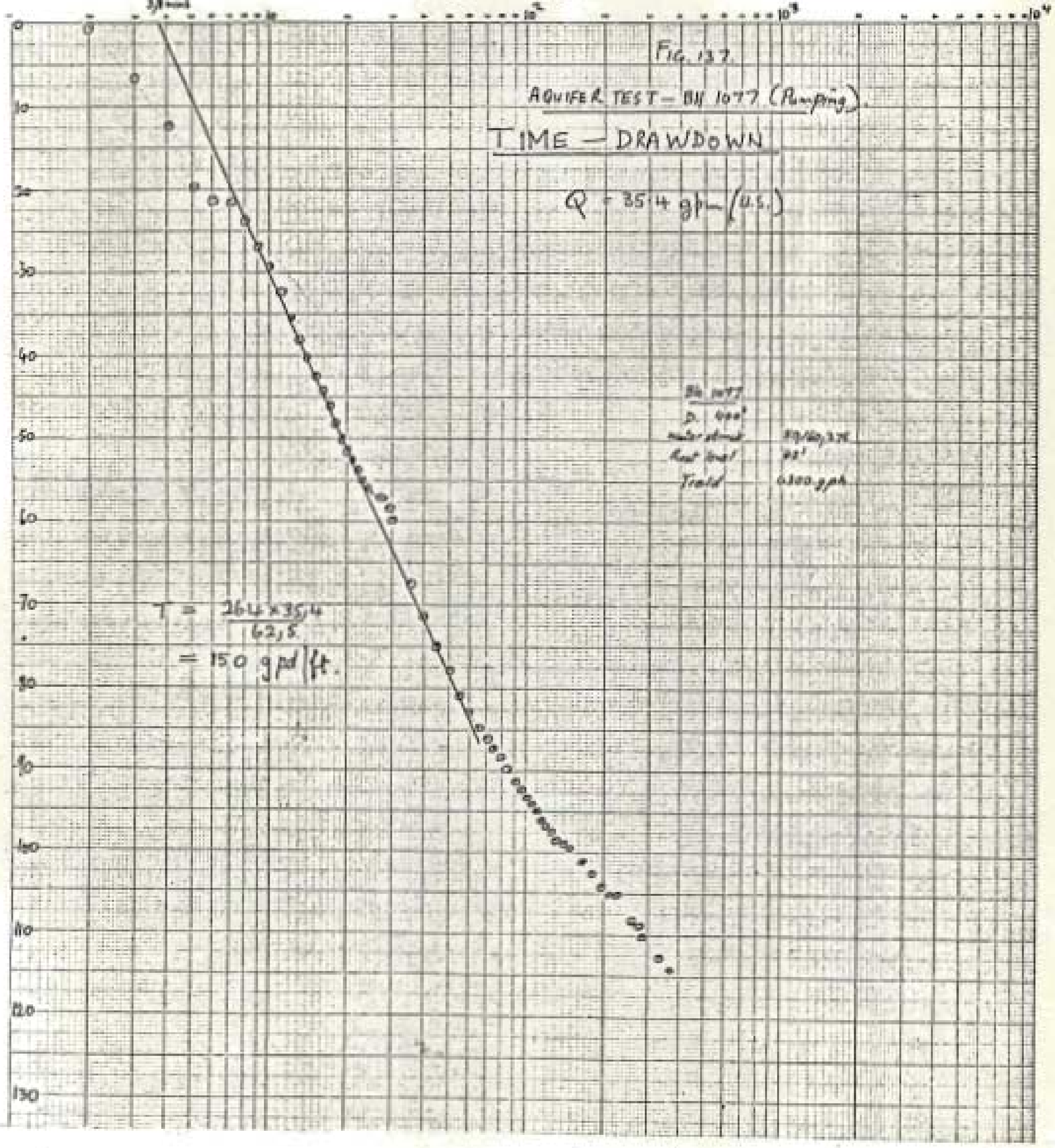


FIG. 137.
AQUIFER TEST – BH 1077 (Pumping).
TIME – DRAWDOWN
Q = 35.4 gpm (U.S.)
BH 1077
Rest level
Yield
T = 264 × 35,4 / 62,5
= 150 gpd/ft.
3 mins
10
10²
10³
10⁴
0
10
20
30
40
50
60
70
80
90
100
110
120
130

FIG 138

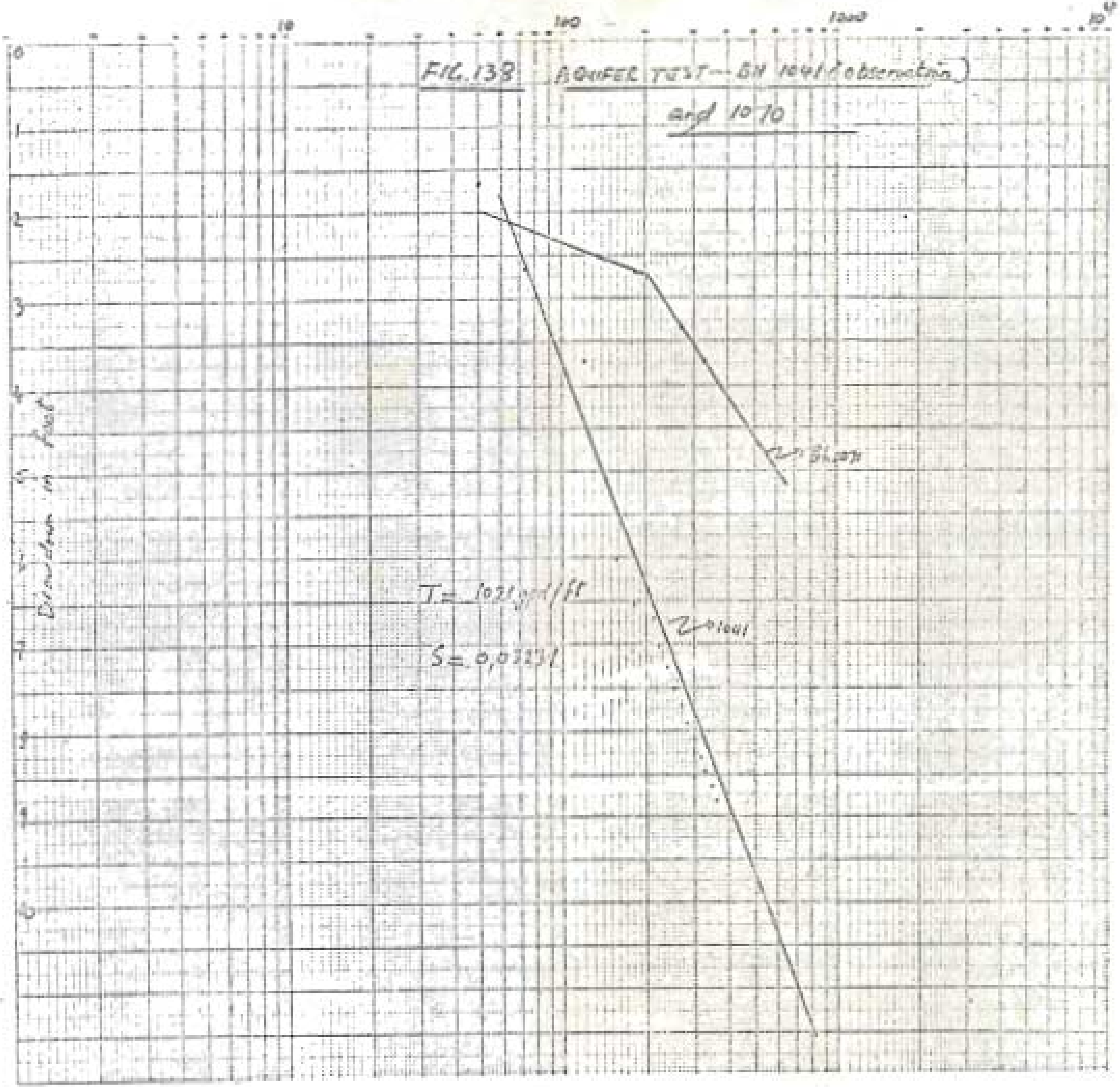


FIG. 138 AQUIFER TEST—BH 1041 (observation)
and 1070
T = 1031 gpd/ft
Drawdown in feet
10
100
1000

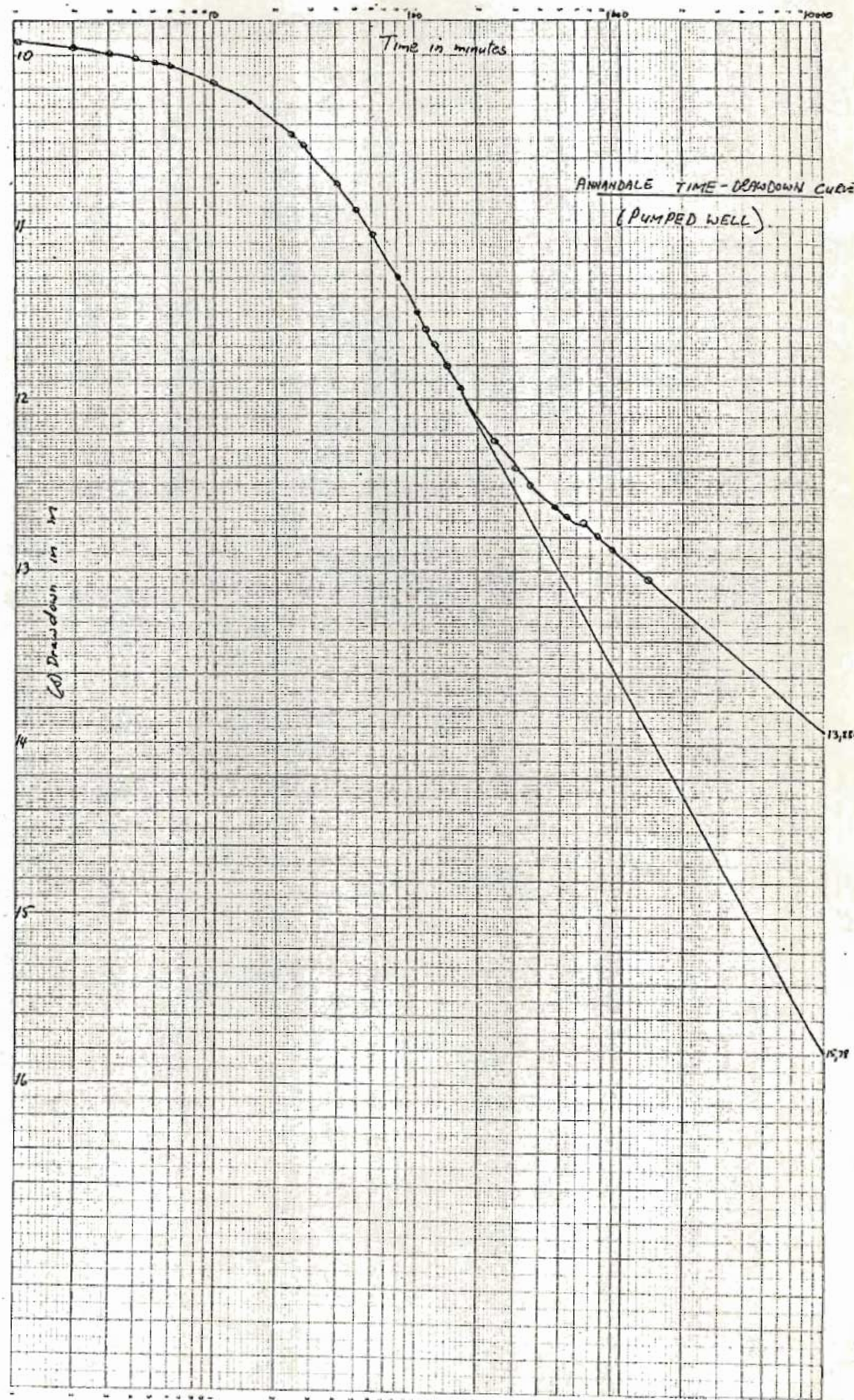
The Pump test

A pump test carried out in September 1970 on a hand dug well was carried out for 24 hours pumping at 15 g.p.m. (900 gph or 681/minute). Drawdown in the pumped well and in an observation borehole 6 feet away was carefully measured and plotted as shown in Figs. 139,140. A value for T of 716 gpd per ft or 8,89 m2 per day was calculated and a value of 0,0662 for S calculated i.e. an effective porosity for a water table aquifer of 6,6 per cent. It can be seen that, by extending the time-drawdown curve, a theoretical drawdown of either 15,9 or 20,1m after 10 minutes (694 days) at a pumping rate of 15 gpm would result depending on which curve is taken. Both curves were remarkably smooth, indicating close compliance with theoretical requirements for a pump test, but both showed the effects of the cone of depression encountering a zone of more permeable material after about 240 minutes.

Pump Tests at Orapa, Central District

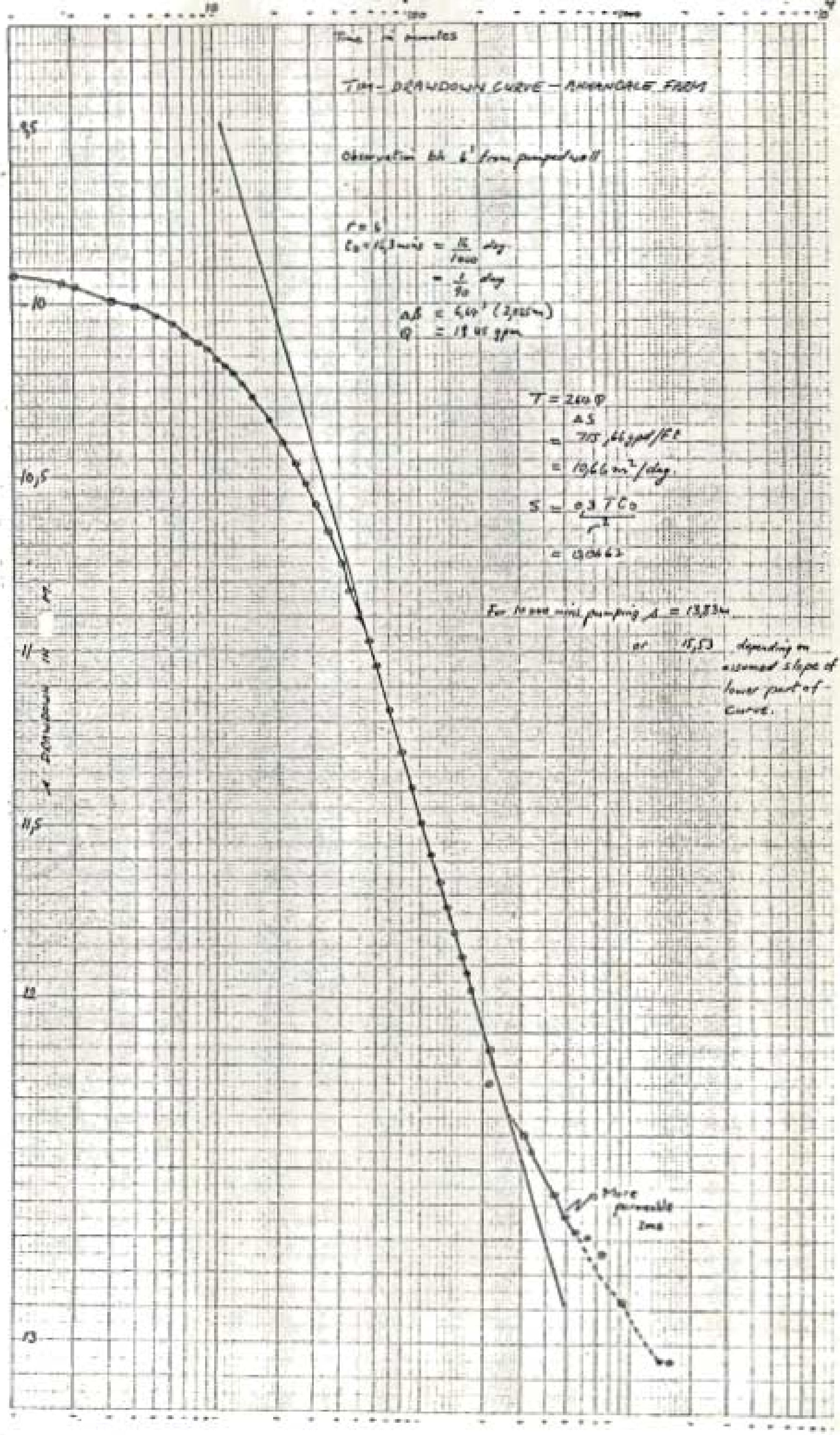
Extremely detailed pump tests were carried out at Orapa on the Cave sandstone aquifer. These tests have been briefly described in the Chapter on the Hydrogeology of the Orapa area.

Fig 139



10
100
1000
10000
Time in minutes
10
11
12
13
14
15
16
(s) Drawdown in m
ANNANDALE TIME-DRAWDOWN
(PUMPED WELL)

Fig 140


Time in minutes
10
100
1000
Observation bh 6' from pumped well
r = 6'
Q = 19,45 gpm
T = 264 Q / ΔS
= 10,66 m²/day
S = 0,3 T t0 / r²
For 10 000 mins pumping s = 13,83m
or 15,53 depending on assumed slope of lower part of curve.
More permeable zone
9,5
10
10,5
11
11,5
12
13

The results of the pump tests indicate that the Cave sandstone aquifer has a low transmissivity (T) averaging 1,000 gpd/foot (15m²/day) and an average value for the storage coefficient (S) of 0,0001.

Pump Tests at Sua Section - Makgadikgadi Salt Pan

Geology

Lacustrine sediments mainly clay and silt averaging about 30m thick overlying about 40m of Ecca sendstone.

Aquifer Tests

Detailed tests undertaken for Makgadikgadi Soda Limited (Anon, 1969 and Schicht, 1969), indicate that the artesian aquifer underlying the northwestern section of the Sua Pan has an average coefficient of transmissibility of 17 500 gpd/ft (217,35 m2/day) and a coefficient of permeability of 135 gpd/ft assuming an aquifer thickness of 130 feet. The average coefficient of storage was calculated at 0,0005. As a result of the tests, water levels in pumping wells were computed for different borehole spacings, pumping rates and pumping periods and recommendations made for a borehole extraction system capable of producing an assured supply of brine for commercial salt-soda production for a 25 year period and which would not exceed a maximum allowable drawdown of 112,5 feet.

Pump Tests in Letlhakane Fault Zone, Pikwe Area, Central District

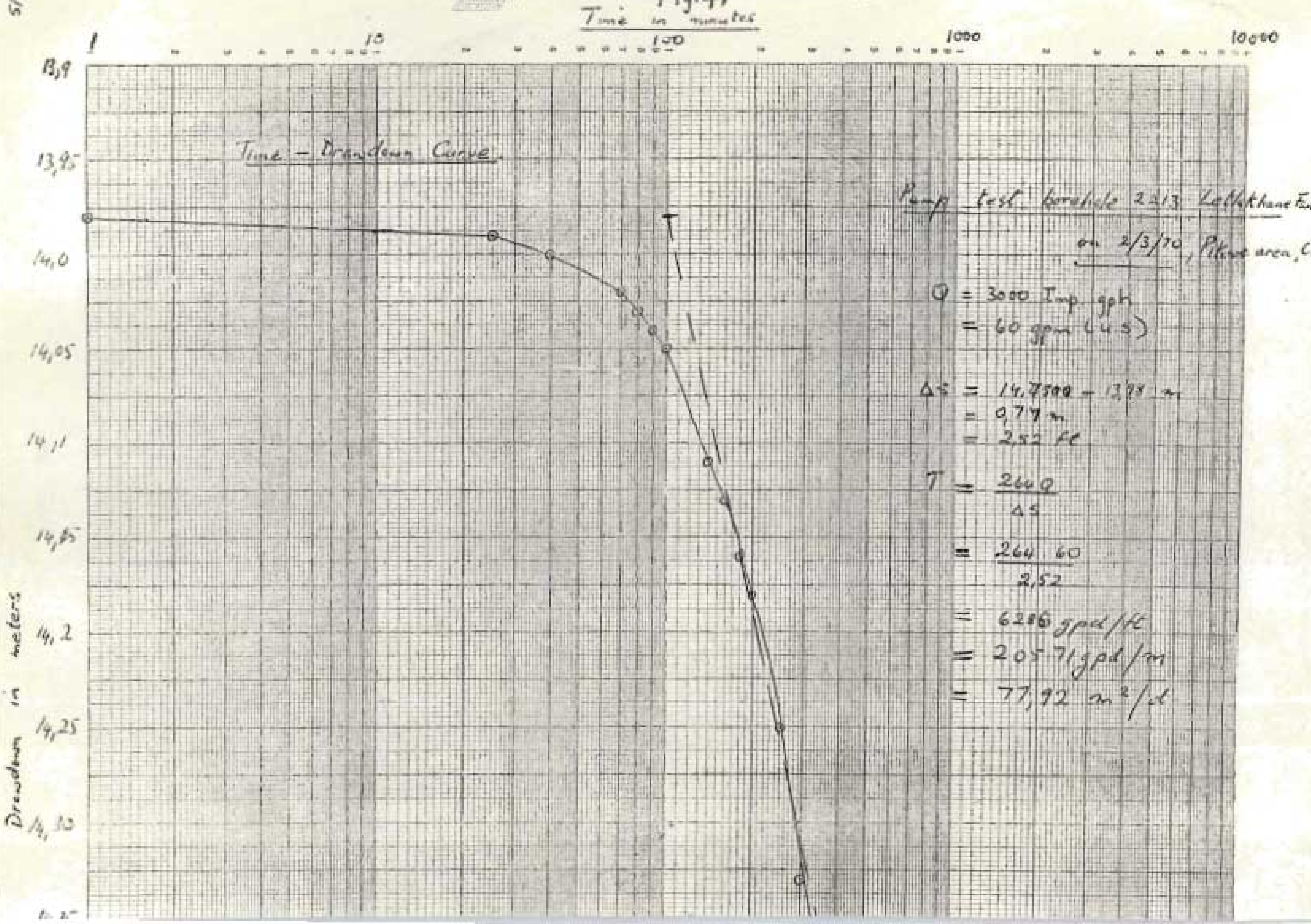
Following detailed geophysical surveys using a variety of integrated geophysical techniques, a number of high yielding boreholes were developed in sheared granitic, metavolcanic and metasedimentary rocks in the Letlhakane fault zone near Pikwe. A detailed pump test carried out over seven days in March 1970 on borehole 2213 gave a value for T of 77,92 m^2/d (See Fig. 141). Subsequently, Robins (1972) carried out further detailed pump tests and arrived at an average value for T of 105 m^2/day and an average value for S of 0,00003074.

SAND STORAGE

Introduction

Numerous large sandy river beds are present in northeastern and eastern Botswana. These river beds carry no surface flow for the larger part of the year (Plate 30) but can come down in spate following heavy rains (Plate 31). These sand rivers are generally found in areas underlain by Basement Complex igneous and metamorphic rocks.

Fig 41


CHARTWELL GRAPH SHEET No. 5341 LOG 4 CYCLES X MM. & CM.
Time in minutes
1
10
100
1000
10000
13,9
13,95
14,0
14,05
14,1
14,15
14,2
14,25
14,30
Drawdown in meters
Time - Drawdown Curve
Pump test borehole 2213 Lelfakhane Farm on 2/3/70, Pilanesberg area, C.E.
Q = 3000 Imp. gph
= 60 gpm (U.S.)
Δs = 14,7500 - 13,98 m
= 0,77 m
= 2,52 ft
T = 264 Q / Δs
= 264 60 / 2,52
= 6286 gpd/ft
= 20571 gpd/m
= 77,92 m²/d

These are largely unexploited at present and a quantitative assessment of the water stored in them should greatly assist long-term future socio-economic planning in Botswana.

Geology

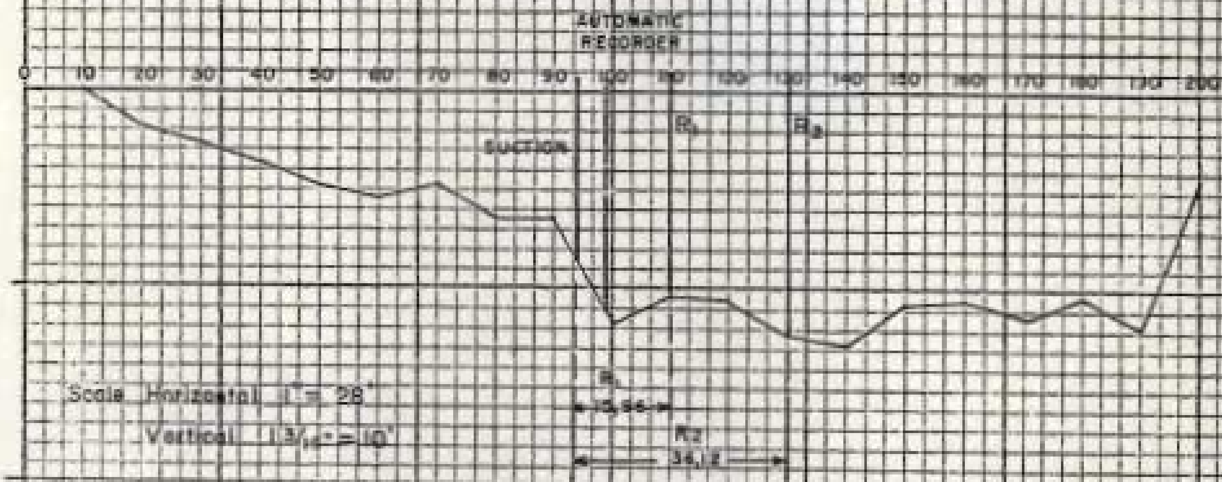
The recent unconsolidated sediments consist mainly of coarse sands with some clay, silt, gravel and boulder beds. The depth of these recent deposits is extremely variable and is generally less than 5m in thickness. The sand basins in the river beds are often separated by rock bars and hence a longitudinal section along a sand river consists of a series of sand basins separated by rock bars cropping out in the river bed. The margins of the sand rivers generally comprise impermeable banks and levees with a high clay content and hence the lateral extent of the sand aquifers is limited. Lund (personal communication) informed the writer that he drilled numerous dry shallow wagon drill holes along the banks of the Motloutse River opposite areas containing large quantities of water in the river bed.

A typical longitudinal section obtained by probing down the Motloutse River is shown in Fig. 142 while a cross section at the site of pump test (403) p.520

Fig. 14.2

MOTLOUTSE RIVER - PROBE ACROSS PUMP TEST SITE

50' DOWNSTREAM FROM MARK No 247



is shown in Fig 116 Typical grading analyses of sand from the pump test site are given in Figs. 143, 144 and 145. It can be seen that, by comparison with other curves, (Fig.146) the uniformity coefficient (average 2,33) is remarkably good and compares very favourably with the usual figure of 3,5 quoted by Mono Pumps (Africa) (Pty) Limited. A figure of over 5 is regarded as indicating a sand of poor permeability as the pore space between the larger particles has been filled with finer material at the expense of water.

<u>Pump test 1. Motloutse River</u> (Test carried out by Bamangwato Concessions Limited. All calculations and plotting by C. M. H. Jennings)

The pump test was carried out 717 feet below peg 403 in the Motloutse River bed (Fig.113) and corresponding to Government peg 145,000.

The test was commenced at 0738 hours on 26th September 1969 and stopped at 1430 hours on 27th September 1969. A diagrammatic sketch of the position of the test and observation holes is given below in Fig. 147.

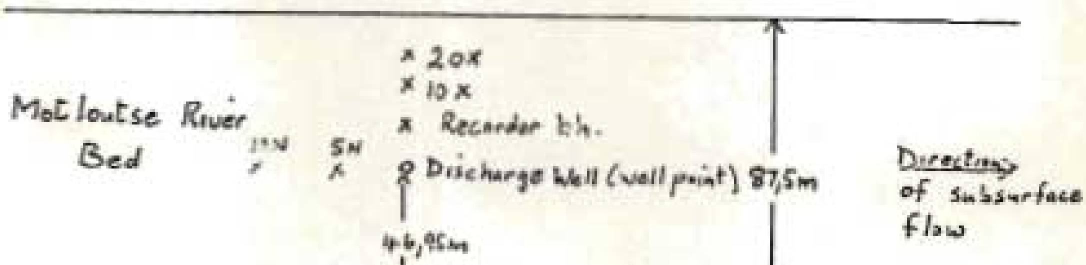


Fig. 147

Diagrammatic Sketch Test and Observation Bh's – Motloutse River Bed.

522

FIG. 143

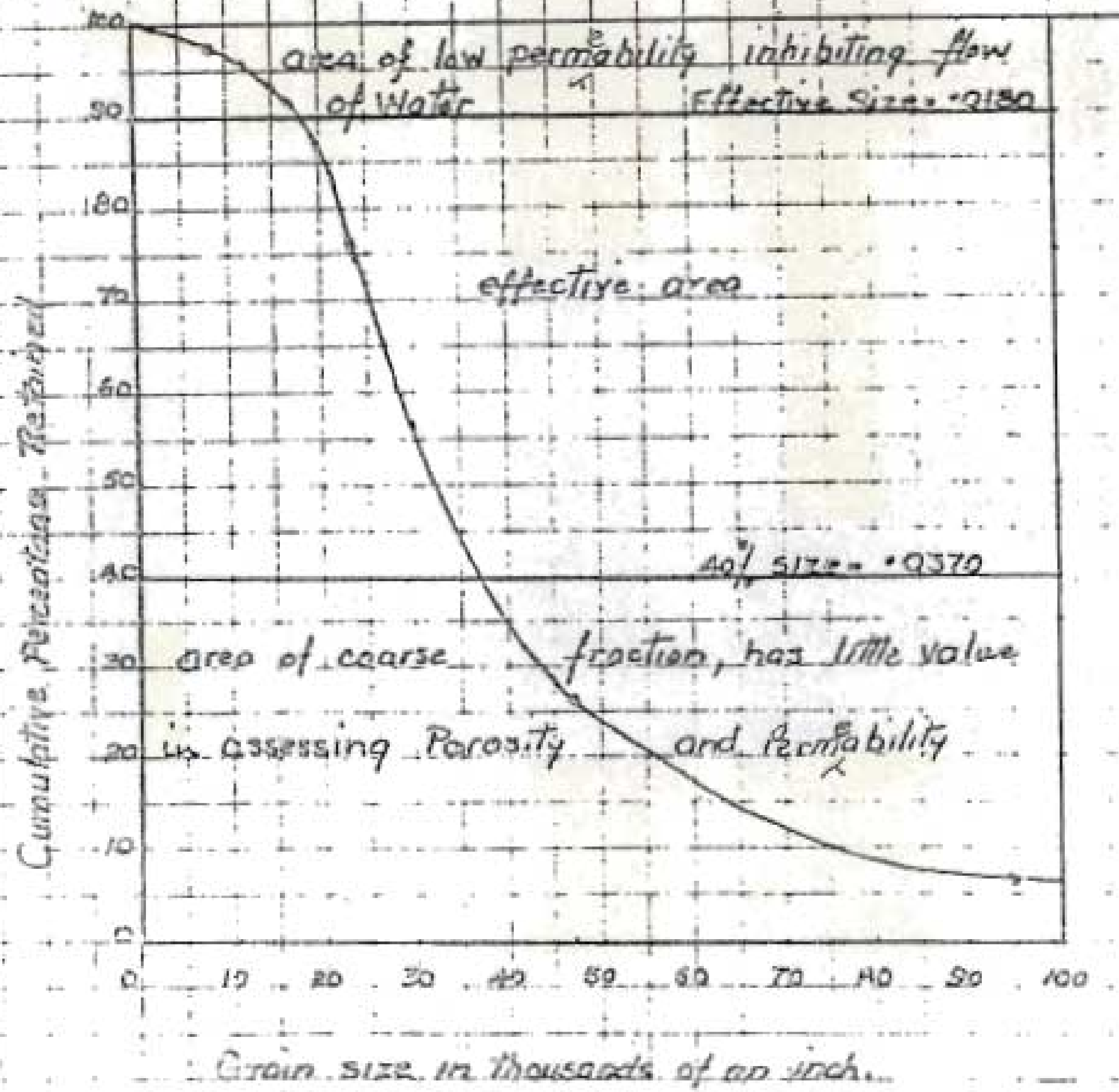
1 — 2-5-69

CLIENT Test Sample taken by

JOB Macloutsi River — Mr N. Mc Pherson

ght of
le
0 Gms

Size Screen opening	Weight Retained	Cumulative Weight Retained	Cumulative % age Retained
·0945	18·50	18·50	6·13
·0472	64·50	83·00	27·30
·0236	146·90	229·90	76·63
·0165	47·20	277·10	92·36
·0116	8·70	285·80	95·30
·0082	8·60	294·90	98·30
Pan	4·30	298·70	99·56
	298·70		



Uniformity Coefficient ·037 / ·018 = 2·06

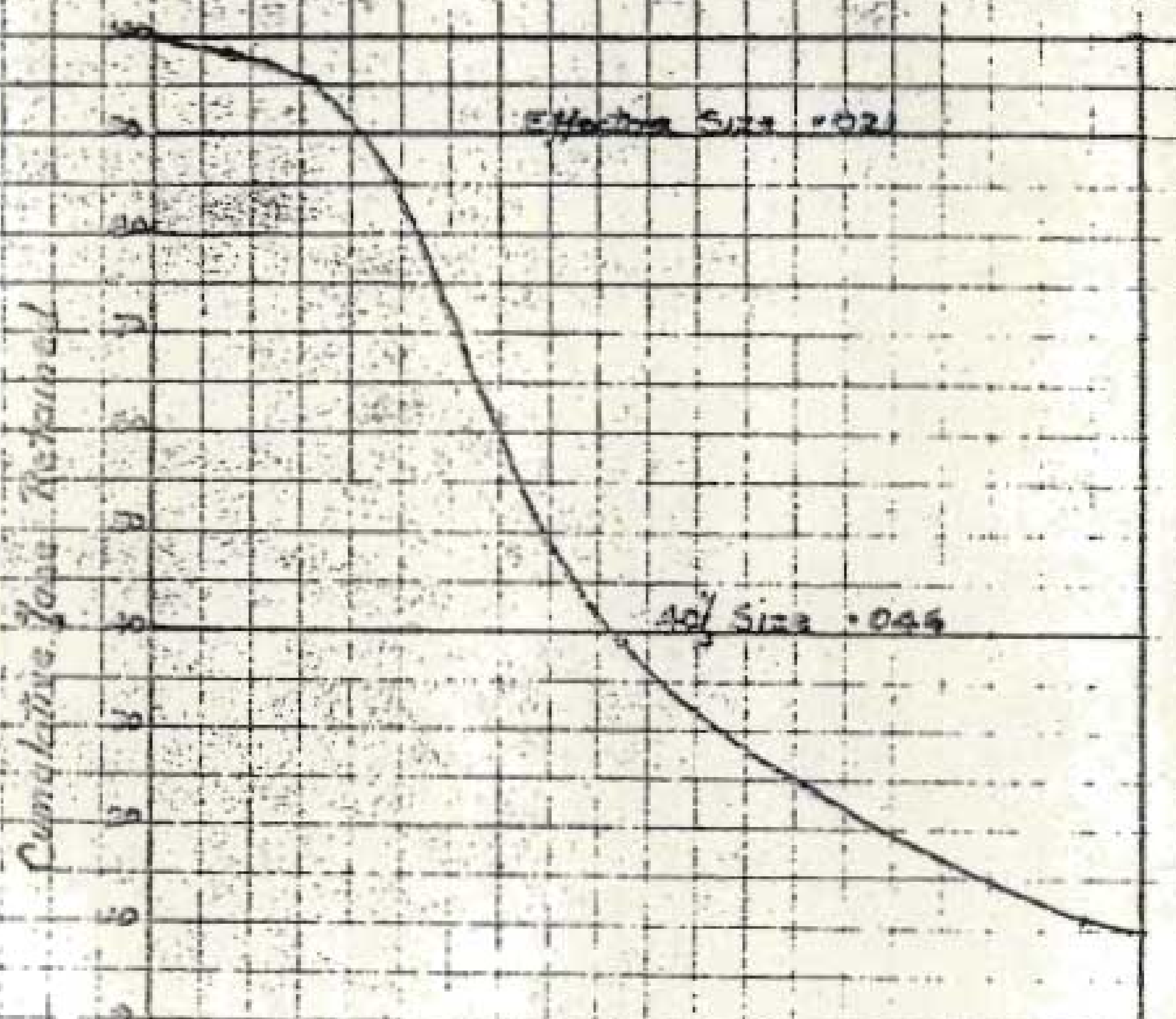
Fig 144

2-5-69

CLIENT. Test Sample taken by

JOB Maclautsi River _______ Mr H Mc Pherson

	Size Screen opening	Weight Retained	Cumulative Wt Retained	Cumulative % Retained
	·0394	35·1 Gms	35·1	10·20
·3 Gms	·0472	100·2	135·3	39·05
	·0234	150·4	294·3	85·14
	·0135	38·7	333·0	95·60
	·0116	7·2	340·2	97·70
	·0032	3·3	343·5	98·70
	Pan	2·4	345·9	99·39



Grain Size in thousands of an inch.

Uniformity Coefficient $= \frac{\cdot 046}{\cdot 021} = 2\cdot 19$

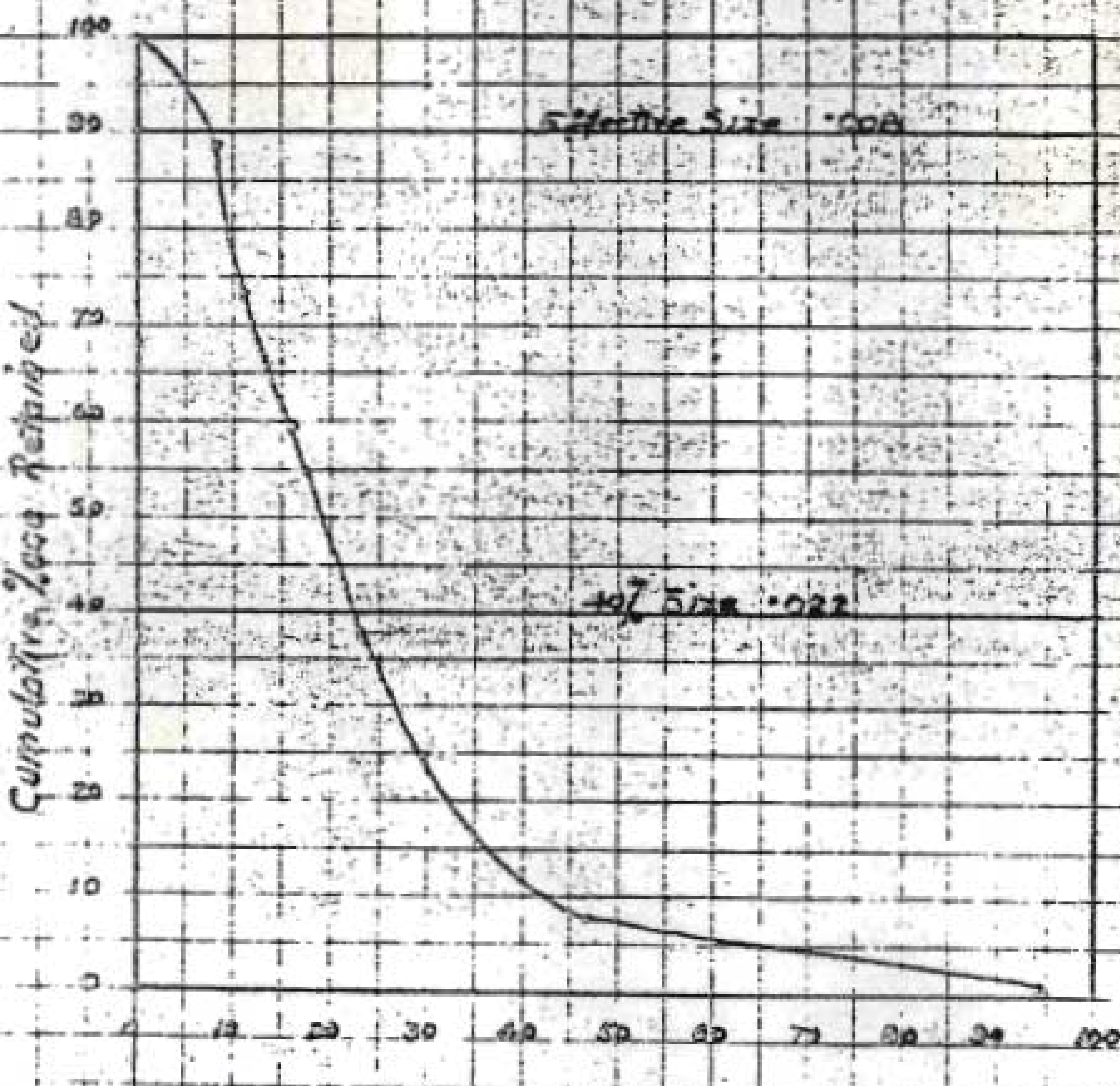
FIG 105

CLIENT Sample from Macloutsi River

JOB Opposite Peg 538 30-1-69

ht of
le
2 Gms

Size Screen Opening	Weight Retained	Cumulative Wt Retained	Cumulative %age Retained
·0945	2·4	2·4	0·8
·0472	19·5	21·9	7·3
·0236	89·6	111·5	37·17
·0165	67·5	179·0	59·7
·0116	41·8	220·8	73·6
·0082	45·0	265·8	88·6
Tor	32·5	298·3	99·4



Uniformity Coefficient $= \frac{\cdot 022}{\cdot 008} = 2{\cdot}75$

FIG. 146

GRADING ANALYSIS CURVES (After Johnson, 1966)

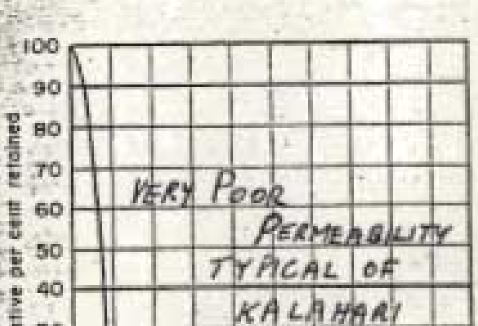


Figure 141. Class A curve, typical of fine, uniform sand that yields limited quantities of water.

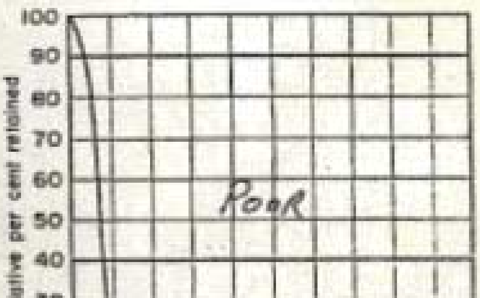


Figure 142. Class B curve shows fine sand with 10 to 20 per cent coarse particles.

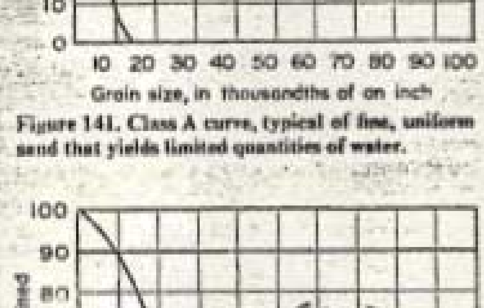


Figure 143. Class C curve, typical of medium and coarse sand mixture with good permeability.

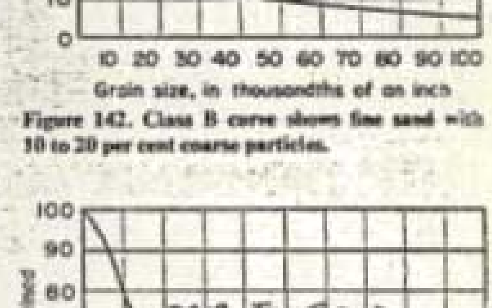


Figure 144. Class D curve, typical of sand and gravel mixture with good permeability.

Data on pump test

1.	Pump discharge	340 feet downstream
2.	Pumping rate	4396 Imperial gallons per hour (87,92 US gpm)
3.	Measuring equipment	(i) An Ott Model "X" automatic recorder placed on 6 inch diameter slotted casing. This did not operate satisfactorily during the test. (ii) Electric probes graduated in feet and inches.
4.	Well point	A three inch diameter Johnson well point sunk to a depth of 11 feet 8 inches.
5.	Observation holes	Complete penetration of aquifer with 1½ inch diameter slotted casing.
6.	Pump	Mono pump DIOD at 910 rpm, direct drive from 10 hp electric motor.
7.	Other notes	(i) Di-sodium fluorescene was placed in the pump discharge 340 feet downstream at 1400 hours on 16th September 1969 but was not detected at the well print. (ii) Water was discoloured at the start of the pump test but cleared with pumping

Observation Borehole 5N Drawdown Test See Fig 148 and Table 67

Pumping rate, $Q = 87{,}92$ gpm (US gals)

$r = 8{,}5$ ft.

$\Delta s = 0{,}2852$ ft.

$T = \frac{264.Q}{\Delta s}$ gpd per ft.

$= \frac{264.87{,}92}{0{,}2852}$ gpd per ft.

FIG 145

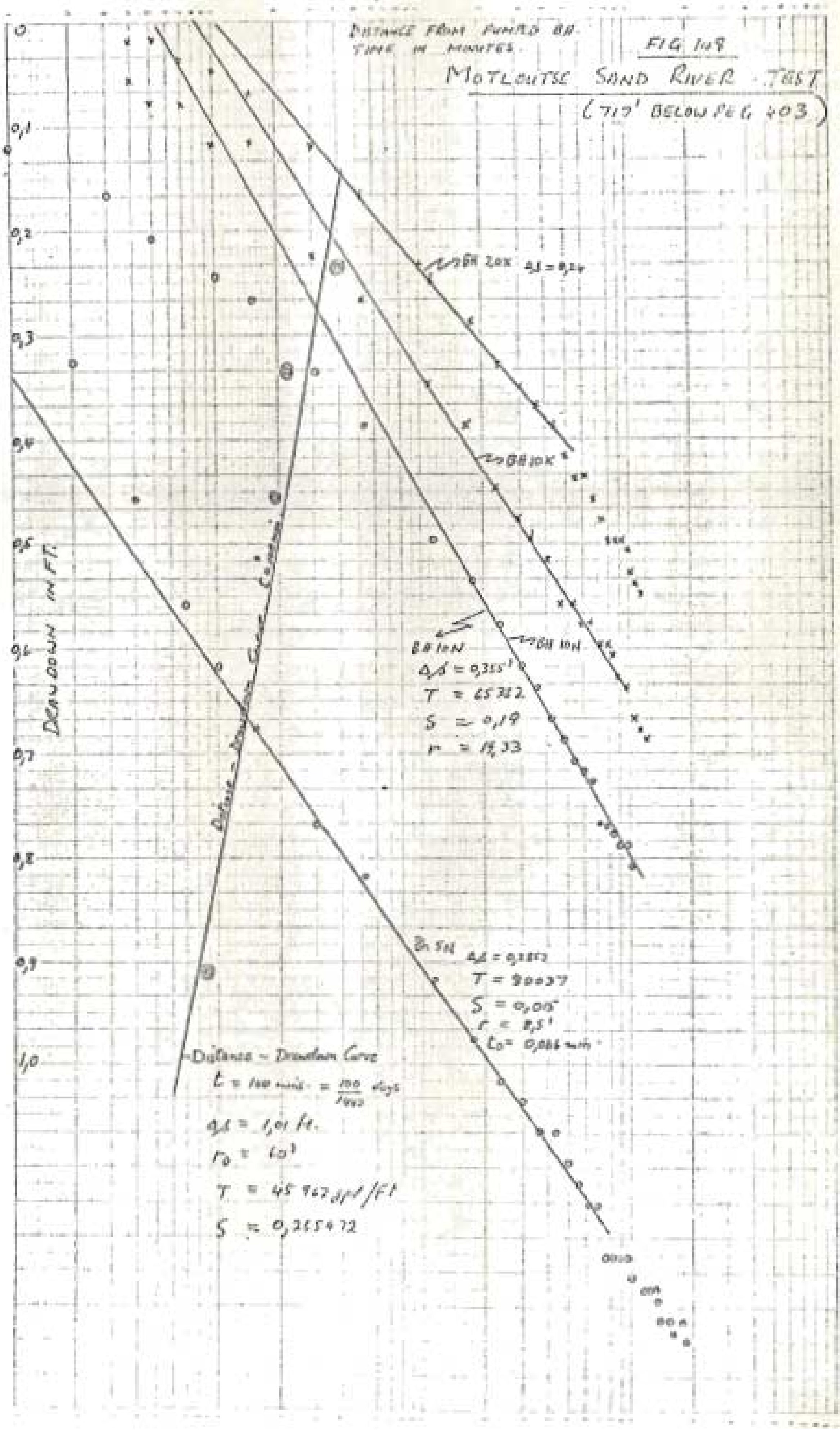

DISTANCE FROM PUMPED BH.
TIME IN MINUTES.
FIG 149
MOTLOUTSE SAND RIVER TEST
(717' BELOW PEG 403)
DRAWDOWN IN FT.
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
BH 20K
BH 10K
BH 10N
Δs = 0,355'
T = 65382
S = 0,19
BH 5N
T = 90037
S = 0,05
r = 8,5'
Distance – Drawdown Curve
Δs = 1,01 ft.
r0 = 60'
T = 45 967 gpd/ft
S = 0,265472

TABLE 67

DATA PUMP TEST 16 & 17/9/69 403' - 717'
OBVERSATION BOREHOLE NO. 5 N

Time	Feet to water from top of casing (observation well)	Drawdown (feet)	
	Ft. Ins.		
0	3 8¾	0.00	Distance to pump = 8'6"
1	3 10¼	0.12	
2	4 0¾	0.33	
4	4 2¼	0.46	
7	4 3½	0.56	
10	4 4¼	0.62	
15	4 4¾	0.67	
30	4 6	0.77	
52	4 5 5/8	0.82	
112	4 7¾	0.92	
172	4 8½	0.98	
232	4 9	1.02	
292	4 9¼	1.04	
352	4 9 5/8	1.07	
412	4 9 5/8	1.07	
472	4 10	1.10	
532	4 10¼	1.12	
592	4 10½	1.14	
652	4 10½	1.14	
712	4 11	1.19	
772	4 11	1.19	
832	4 11	1.19	
892	4 11	1.19	
952	4 11¼	1.21	
1012	4 11¼	1.21	
1072	4 11¼	1.21	
1132	4 11⅜	1.22	
1192	4 11⅜	1.22	
1252	4 11⅜	1.22	

1312	4 11½	1.23
1372	4 11¾	1.25
1432	4 11¾	1.25
1492	4 11 7/8	1.26
1552	4 11 7/8	1.26
1612	4 11 7/8	1.26
1672	4 11 7/8	1.26
1732	4 11 7/8	1.26
1792	4 11¾	1.25
1852	5 0	1.27

$= 80\ 037$ gpd per ft.

$= 994$ m2/d

Now intercept to of the straight line at zero drawdown is 0,066 minutes

$$S = \frac{0{,}3\ T\ t\ o}{r^2}$$

$$= \frac{0{,}3.80037\ (\frac{0{,}066}{1440})}{(8{,}5)^2}$$

$$= 0{,}0152$$

where S = storage coefficient

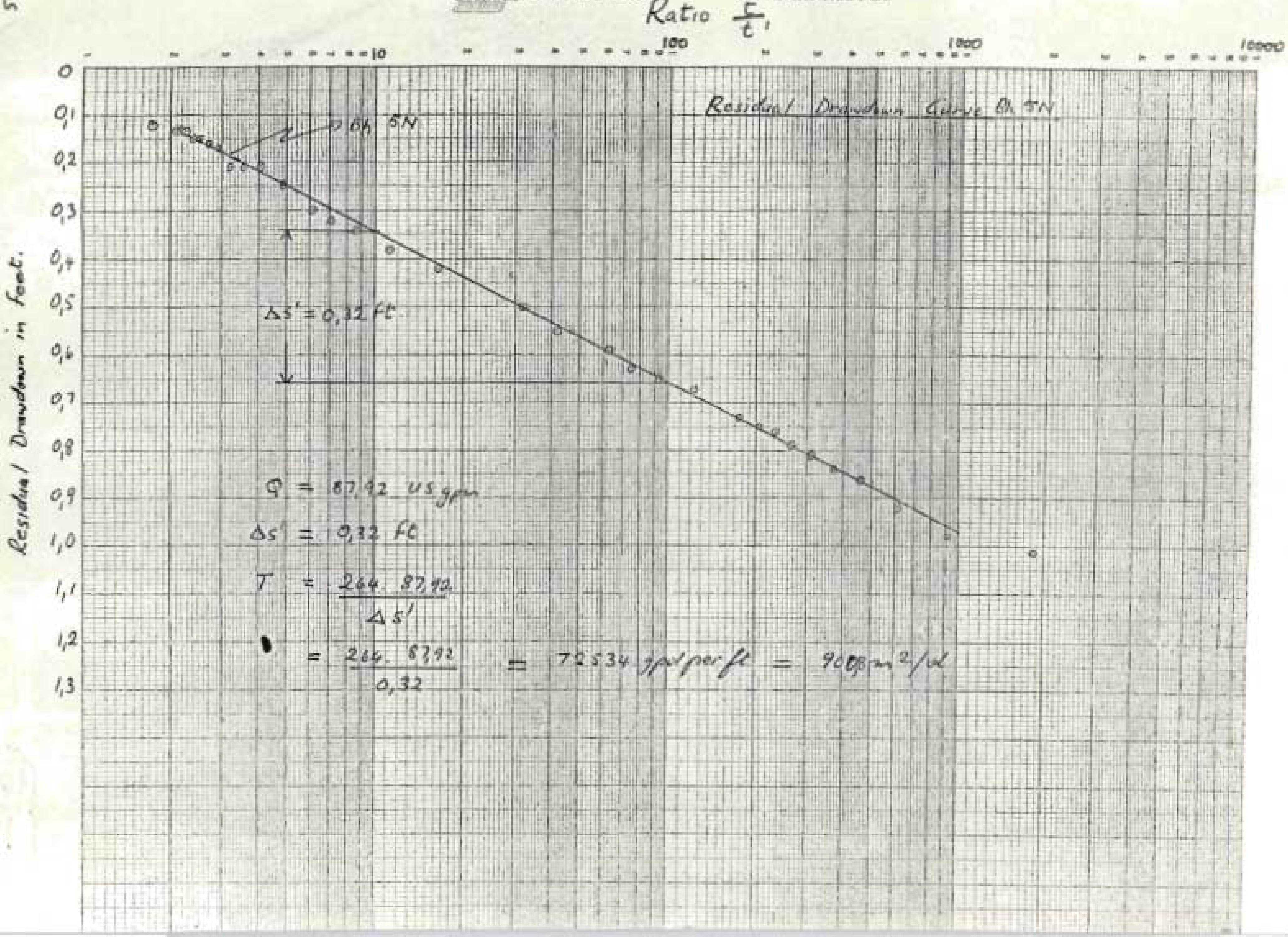
T = coefficient of transmissibility in gpd per ft.

t_o = intercept of straight line at zero drawdown, <u>in days</u>

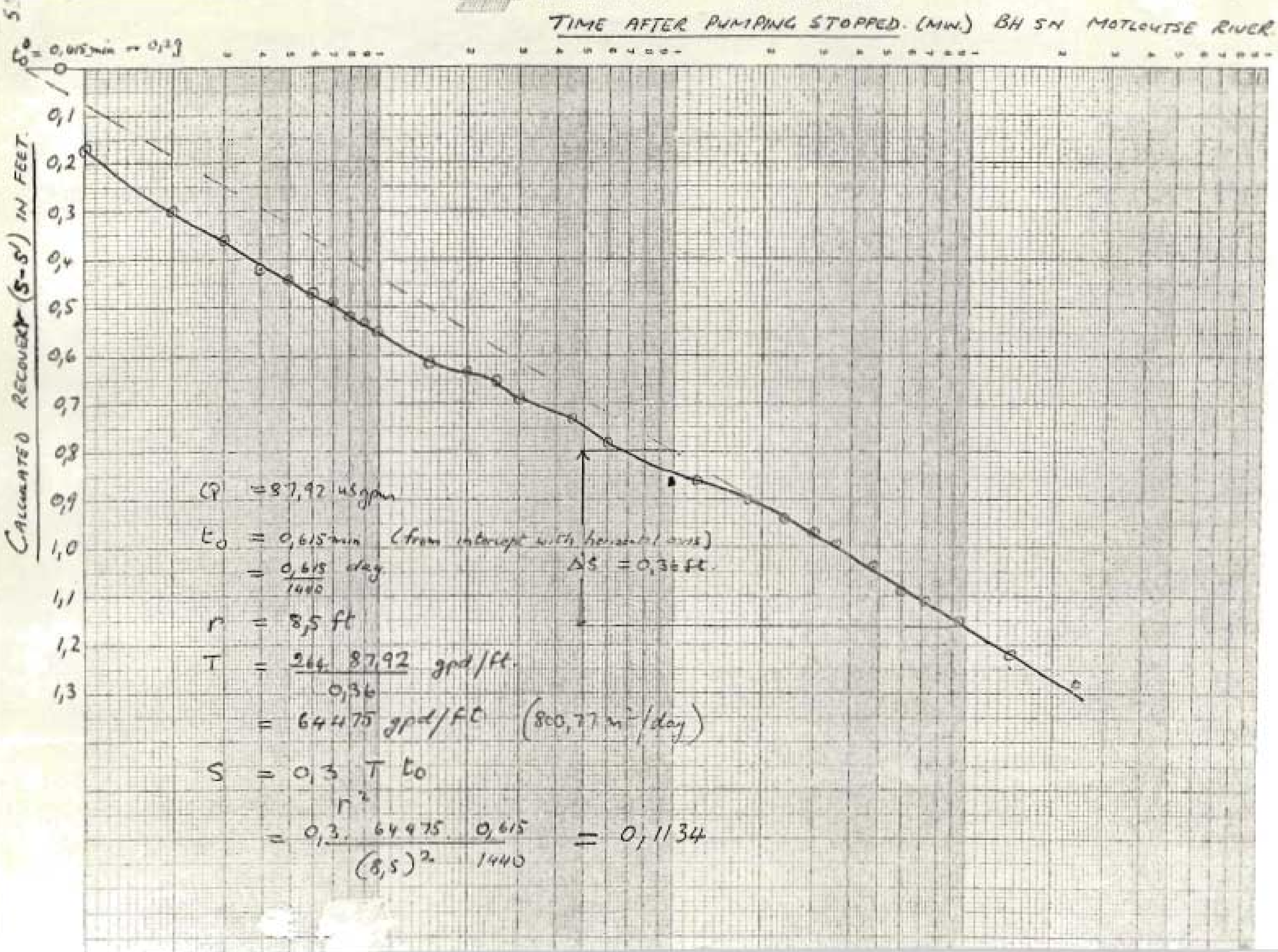
r = distance, in ft.,from pumped well to observation well.

<u>Borehole 5N Recovery Data</u>

See Fig. 149 and Table 68 for residual drawdown data. Results of the recovery data gave a value of 72534 gpd/ft (900,87m2/day) as against a value of 80 037 gpd/ft (994,06m2/day) for the drawdown data. S was obtained by first calculating the Recovery (S -s') from the residual-drawdown curve using an extended time-drawdown curve plotted on arithmetical graph paper and calculated as shown in Table 68 . A time-recovery curve was then plotted (Fig.150) and a value for T of 64 475 gpd per foot (800,77m2/day) and a value for S of 0,1134 obtained.



Ratio t/t'
Residual Drawdown Curve Bh 5N
Bh 5N
Residual Drawdown in feet.
Δs' = 0,32 ft
Q = 87,92 US gpm
Δs' = 0,32 ft
T = 264 . 87,92 / Δs'
= 264 . 87,92 / 0,32 = 72534 gpd per ft = 900 m²/d



5
TIME AFTER PUMPING STOPPED. (MIN.) BH 5N MOTLOUTSE RIVER
CALCULATED RECOVERY (S-S') IN FEET.
t_0 = 0,615 min
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
1,2
1,3
Q = 87,92 USgpm
t_0 = 0,615 min (from intercept with horizontal axis)
= 0,615/1440 day
Δs = 0,36 ft.
r = 8,5 ft
T = 264 . 87,92 / 0,36 gpd/ft.
= 64475 gpd/ft (800,77 m²/day)
S = 0,3 T t_0 / r²
= 0,3 . 64475 . 0,615/1440 / (8,5)² = 0,1134

TABLE 68

RESIDUAL DRAWDOWN - MOTLOUTSE RIVER BED TEST

DATA PUMP TEST 17/9/1969
OBSERVATION BOREHOLE NO. 5N

Static Water Level = 3,72'

Time since test started (min)	Time since pump stopped (min)	Ratio $\frac{t}{t^1}$	Feet to water from top of casing		Residual dd in ft	Drawdowns from pumping curve (Fig.)	Calculated recovery $(s-s^1)$ft
t	t^1		Ft.	Ins.	s^1		
1852	0	-	5	0	1,28	1,28	0,00
1853	1	1853	4	10	1,11	"	0,17
1854	2	927	4	8½	0,98	"	0,30
1855	3	618	4	7¾	0,92	"	0,36
1856	4	464	4	7	0,86	"	0,42
1857	5	371	4	6¾	0,84	"	0,44
1858	6	310	4	6⅜	0,81	"	0,47
1859	7	266	4	6⅛	0,79	"	0,49
1860	8	233	4	5⅞	0,76	"	0,52
1861	9	207	4	5⅝	0,75	"	0,53
1862	10	186	4	5½	0,73	"	0,55
1867	13	124	4	4¾	0,67	"	0,61
1872	20	94	4	4½	0,65	"	0,63
1877	25	75	4	4¼	0,63	"	0,65
1882	30	63	4	3¾	0,59	"	0,69
1897	45	42	4	3¼	0,55	"	0,73
1912	60	32	4	2⅝	0,50	"	0,78
1972	120	16,43	4	1¾	0,42	"	0,86
2032	180	11,28	4	1¼	0,38	"	0,90
2092	240	8,71	4	0¾	0,34	"	0,94
2152	300	7,17	4	0½	0,32	1,29	0,97
2212	360	6,14	4	0¼	0,30	1,29	0,99
2332	480	4,85	3	11⅝	0,25	1,29	1,04
2452	600	4,08	3	11⅛	0,21	1,30	1,09
2572	720	3,57	3	11⅛	0,21	1,31	1,10
2692	840	3,20	3	11⅛	0,21	1,31	1,10
2812	960	2,92	3	10¾	0,17	1,32	1,15
2932	1080	2,71	3	10⅝	0,16	1,33	1,17
3052	1200	2,54	3	10½	0,15	1,34	1,19
3172	1320	2,40	3	10½	0,15	1,34	1,19
3292	1440	2,28	3	10¼	0,13	1,35	1,22
3412	1560	2,18	3	10¼	0,13	1,35	1,22
3532	1680	2,10	3	10¼	0,13	1,36	1,23
4292	2440	1,75	3	10⅛	0,12	1,40	1,28

Observation Borehole 10N (See Fig. 148)

$Q = 87,92$ gpm

$r = 19,33$ ft.

$s = 0,355$ ft.

$t_o = 5,4$ mins.

$T = \frac{264\ 87,92}{0,355}$ gpd per ft.

$= 65382$ gpd per ft.

$= 812$ m2 per day

$S = \frac{0,3\ 65\ 382}{(19,33)2}\ \frac{5,4}{1440}$

$= 0,1968$

Observation Borehole 10X

$r = 22,0$ ft.

$s = 0,307$ ft.

$t_o = 8,4$ min.

$T = \frac{264.\ 87,92}{0,307}$

$= 75600$ gpd per ft.

$= 938,95$ m2 per day

$S = \frac{0,3.\ 75\ 600\ \ 8,4}{(22)2\ \ \ 1440}$

$= 0,2733$

Observation Borehole 20X

$r = 40,83$ ft.

$s = 0,24$ ft.

$t_o = 10,5$ min $= \frac{10,5}{1440}$ days

$$T = \frac{264.\ 87,92}{0,24} \text{ gpd/ft}$$

$$= 96,712 \text{ gpd per ft.}$$

$$= 1201,16 \text{ m2 per day}$$

$$S = \frac{0,3.\ 96712.\ 10,5}{(40,83)2\ 1440}$$

$$= 0,1269$$

Distance-drawdown curve (Fig.148)

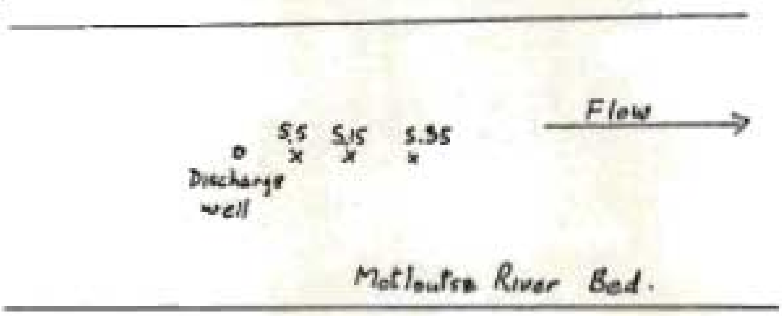
By plotting the drawdowns in the four observation wells after pumping for 100 minutes at 4396 imperial gallons per hour (87,9245 gpm) against the distance from the pumped borehole, it can be seen that the cone of depression will only extend 60 feet (18,29m) from the pumped borehole while the interference effect at 50 feet (15m) from the pumped hole will be only 0,085 feet (2,5cm). Thus optimum spacing of well points for an abstraction system can easily be calculated for different pumping rates and for different pumping periods assuming no recharge.

Pump Test 2 Motloutse River (Pump test carried out by Bamangwato Concession Ltd. Calculations and plotting by C. M. H. Jennings)

This test was carried out at Government peg 247 on the Motloutse River (See Fig.151 for positions of observation holes. The test was started at 0805 hours on the 23rd September 1969 and completed at 1005 on the 24th September 1969.

Fig 151

Borehole Locations Pump Test 2 - Motloutse R.



Data on pump test

1. Pump discharge — 240 feet downstream

2. Pumping rate — 4000 Imperial gallons per hour (80 US gpm)

3. Other data as for 1st test.

Observation borehole S.15

(See Fig. 152 for Ott automatic recorder hydrograph of pump test 2).

Observation hole S.15 (See Fig.153)

$Q = 80$ gpm

$r = 15,96$ ft.

$s = 0,51 - 0,316$ ft.

$= 0,194$ ft.

$$T = \frac{264.\ 80}{0,194}$$

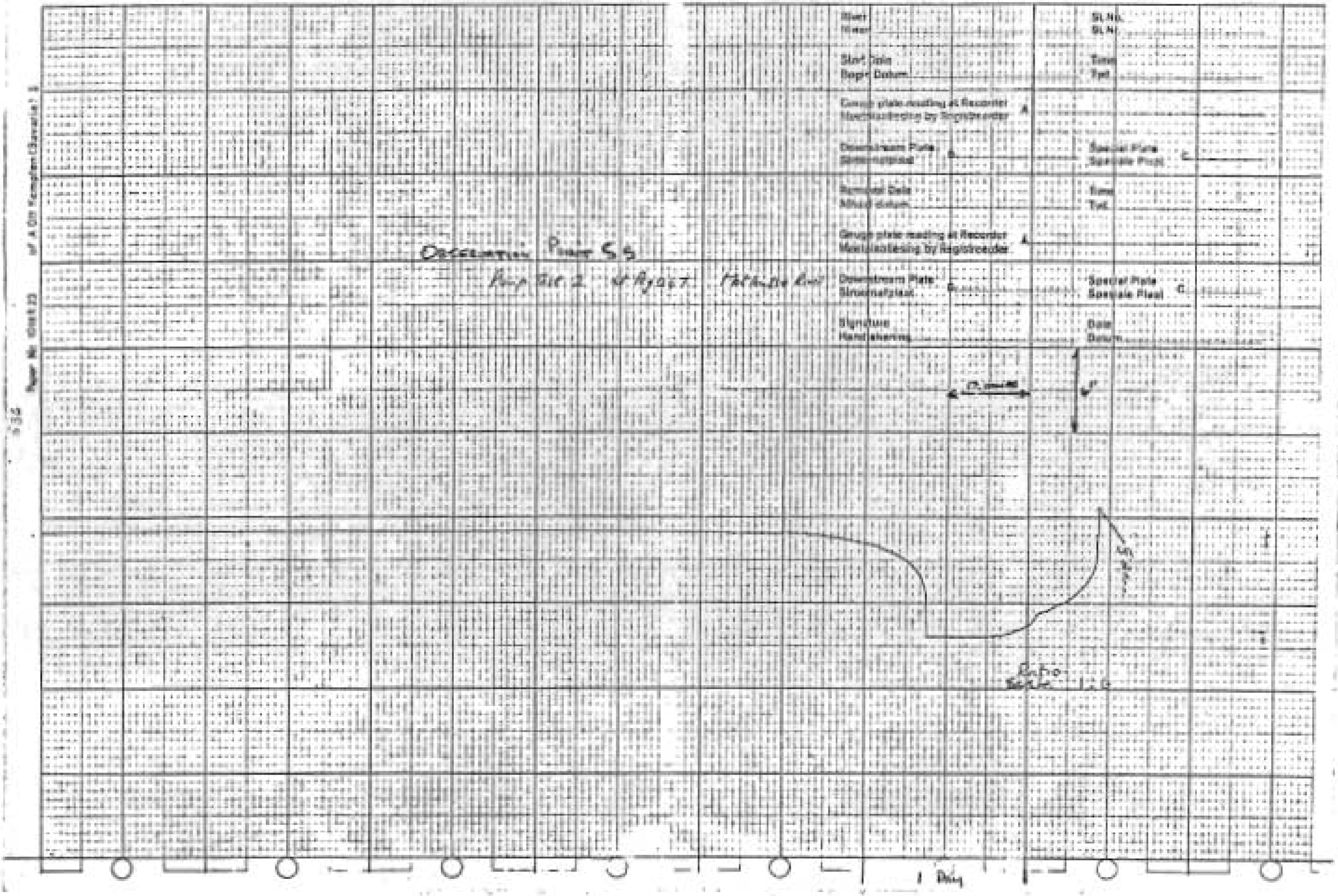
$= 108866$ gpd per ft

$= 1352,12$ m2 per day

$t_o = 2,4$ mm

$$S = \frac{0,3.\ 108866.}{(15,96)2} \cdot \frac{2,4}{1440}$$

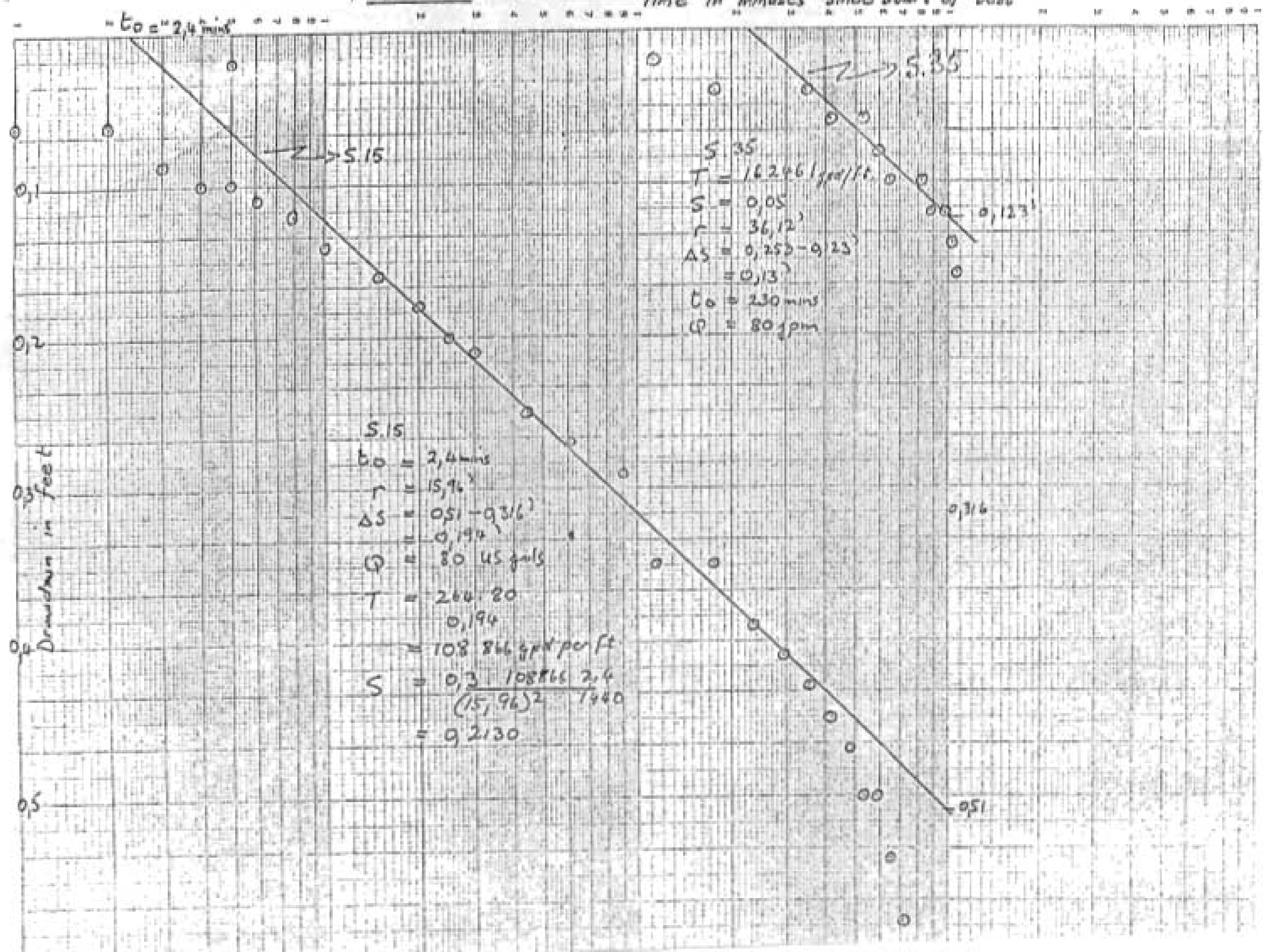
$= 0,2130$



Observation Point 5.5
Start Date
Gauge plate reading at Recorder
Downstream Plate
Special Plate
Signature
Date
1 Day

CHARTWELL GRAPH SHEET No FIG 153 LOG 4 CYCLES X MM. & CM

PUMP TEST 2 MOTLOUTSE RIVER BED AQUIFER TEST AT PEG 247



Observation hole S.35 (See figure 153)

Q = 80 gp m

r = 36,12 ft.

s = 0,253 - 0,123 ft.

= 0,13

T = 162 461 gpd per ft.

= 2017,77 m^2 per day

to = 230 mins.

S = 5,966

Conclusions

Pump tests confirm the laboratory test data that the sand in the Motloutse River bed forms a remarkably good aquifer with an average value for T of 1216m per day (98176gpd per ft) and a value for S of 0,249. As the aquifer is of water table type then this can be regarded as an aquifer with an effective porosity of very nearly 25 per cent. The extremely high values for T and S thus help offset the main limiting factor of this type of aquifer i.e. the shallow depth of sand in relation to the length and width of the aquifer. This prevents a too rapid drop of the cone of depression created by pumping beyond the limited available drawdown.

It is obvious therefore that the sand rivers of Botswana form an important and as yet largely unexploited source of additional water for agriculture, industrial and mining use and domestic

MAHALATSWE RIVER, CENTRAL DISTRICT

Houston (1972) carried out laboratory investigations on sands from the Mahalatswe River and found that permeabilities range from 20m/d (500 gallons per day per square foot to 250 m/d (6000 gals/d/ft2) and estimated that the specific yield would vary between 10 and 30 per cent. No pump tests could be carried out owing to an unseasonally early flood taking place.

Step-Drawdown Tests

The step-drawdown test is the main means of judging the performance of a borehole as a hydraulic structure. Jacob (1946) and Rohrabaugh (1953) were the first to give the theory and method for this. The total drawdown in a borehole with perforated casing or screening represents a combination of two elements of head loss. One of these is head loss in the aquifer - "formation loss". The other is the loss associated with the borehole itself and is known as the "borehole or well loss". This includes the head loss caused by the perforated casing or screening, the extra head loss in the zone of higher velocities close to the borehole where turbulent flow occurs and the loss in the borehole as the water flows upward under turbulent conditions to the pump intake. It is obvious therefore that the provision of proper well screening and proper development of a borehole will reduce the"well loss".

The formation head loss is larger than the "well loss". It is the head that pushes the water through the formation within the radius of influence of the borehole. This loss is directly proportional to the borehole discharge.

Step-drawdown test at Orapa

A step-drawdown test was carried out at Orapa in 1968 on borehole 2184. The borehole was pumped at successive rates of 29,2, 41,0 and 62,5 gallons per minute and the drawdowns carefully measured. The data was plotted on semilogarithmic paper. The vertical arithmetical scale was used to represent drawdown in feet and the horizontal (logarithmic) scale used to depict the time in minutes after the start-up of the test. (See Figure 64).

Using Jacob's (1945) equation : $SW = BX+CQ^2$

where SW is the theoretical drawdown

B is the formation constant

C is the well loss constant

Q is the discharge

the formation and well loss constants B and C may be calculated using the values of SW and SW/Q for each step of the test 1350 minutes after starting to pump at each respective rate i.e. after 1350 minutes the drawdown pumping at 29,2 gpm was 37,11. Following the increase in pumping to 41 gpm the additional drawdown was 20,3 feet after 1350 minutes and following a further increase to 62,5 gpm, the projected increase in drawdown after a further 1350 minutes was 31,7 feet. Care was taken to measure the drawdown from the projected drawdown after 1350 minutes at the previous rate and not from the last measured drawdown at the previous rate.

TABLE 69

SUMMARY OF STEP-DRAWDOWN ANALYSIS, BH 2184

Q gpm Q	SW for each step,* feet	Sum of SW Steps, feet	Specific drawdown ft per gpm	Specific capacity gpm per ft
29,2	37,11	37,11	1,27	0,78
41,0	20,3	57,41	1,40	0,71
62,5	31,7	89,11	1,42	0,70

* Each value is for 1350 minutes of pumping

Table 69 shows a summary of the results of the step-drawdown test. It can be seen that a progressive decline in efficiency takes place with increasing discharge from the borehole.

$$\text{Now} \quad SW = BQ + CQ^2 \qquad \therefore \frac{SW}{Q} = B + CQ$$

By plotting $\frac{SW}{Q}$ versus Q (Figure 64) values for B (the intercept on the vertical axis) can be used and hence C can be calculated e.g. For B = 1,18.

Boundary Effects

The presence of impermeable barriers will result in an increase in the slope of a time-drawdown curve as shown in Figs.130, 132(D.C.'s Office and Borehole 665, 2135) while more permeable zones encountered by the expanding cone of depression around a pumping borehole will result in a decrease in the slope of the curve direction (Fig.139Annandale pump test). Ferris (1948) described the use of image wells to determine the distance to a permeable or impermeable boundary.

SUMMARY AND CONCLUSIONS

Aquifer evaluation tests on a variety of aquifers have been successfully carried out in Botswana and have shown that the conventional methods of analysing the data can be successfully applied. The fact that the shape of plotted time-drawdown curves generally conform with those expected from theoretical considerations indicate that most aquifers in fissured impermeable rocks behave on a large scale in a similar fashion to ideal homogeneous aquifers. Values for S range from 0,000030 to 0,27 while values for T range from the surprisingly high values of 2 422m2/day in the coarse-grained sandy river beds to 2,23m2/day. The data accruing from such tests is far more useful than that obtained from conventional pump tests where a borehole is pumped for a certain period merely to obtain an indication of the amount of water than can be pumped from the hole. Calculations of T and S can be used for determining optimum borehole spacing; predicting drawdown for fixed pumping rates; determining the specific yield of a water table aquifer, calculating the amount of water released by a confined aquifer etc.

Results of pump tests are listed below in Table 70.

TABLE 70

SUMMARY OF AQUIFER TESTS IN VARIETY OF AQUIFERS IN BOTSWANA

Locality	Aquifer WT = water table A = artesian	T (m^2/day) Range	S Range
Motloutse River	Coarse river sand WT	974,78 - 2422,11	0,05 - 0,27
Orapa	Cave sandstone A	12,42	0,0001

Makgadikgadi Pan	Ecca Sandstone	A		
Lobatse Est. C. Basin	Magaliesberg quartzite	A	621	
Lobatse Est. S. Basin	Daspoort Shale	A	2,23 - 15,21	0,03239
Lobatse W. Basin	Dolomite	WT & A	15,75 - 2341,8	
Hildavale	Acid lava (Ventersdorp)	WT	10,66	0,0662
Pikwe, C. District*	Archaean gneiss and schist	A	77,92	0,00003074

* Average from Robins (1972)

It must be stressed that the above values are not representative of the formations shown except possibly that of the Motloutse river bed test. All the other tests were generally carried out on boreholes with above average yields for the particular formation concerned.

BOREHOLES AS AN AID TO GEOLOGICAL MAPPING

Because of the near ubiquitous cover of sands of Kalahari type (covering 84% of Botswana), and the extreme flatness of Botswana with a consequent paucity of natural sections, boreholes have assumed a special importance in unravelling the geology and geomorphology of Botswana. One has only to refer to any of the principal articles on the geology of Botswana, e.g. Green (1966) or Boocock and van Straten (1962) to realise the invaluable role played by boreholes in elucidating the geology of the country. (See Fig. 154).

Owing to the far sighted policy of the Geological Survey and the Administration of the country, the Drilling Proclamation of 1956 ensures that samples are taken from every 3m or at every change in formation from every water borehole drilled in the country, whether drilled by Government, farmers or private enterprise. Small tobacco bags are issued free of charge to anyone drilling a borehole, together with a number of forms and certificates which have to be completed.

While drilling is in progress, washed samples are generally laid out at 3m intervals and, on completion of the borehole (whether it be successful or blank), the driller bags and labels each sample and sendsit post-free to the Geological Survey, together with the various completed forms which enable the borehole to be identified. In order that the Geological Survey know where all drilling is taking place, all private drillers are also required to send a "notice of intention to sink a borehole" prior to the drilling of a borehole. This also enables the Survey to make a site inspection should they so wish during the course of the drilling.

UNDP REPUBLIC of BOTSWANA FAO

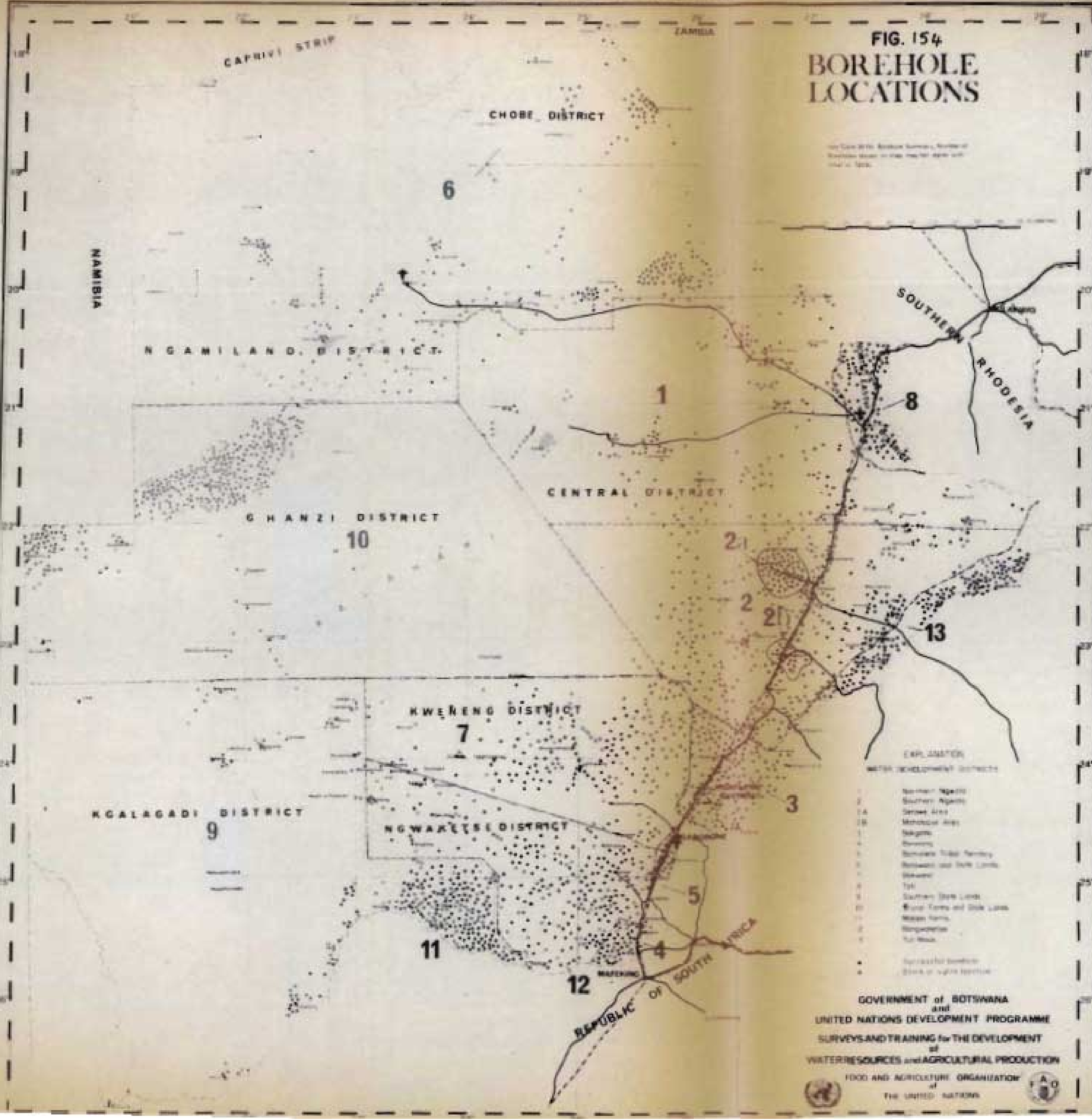


FIG. 154
BOREHOLE LOCATIONS

Once the samples arrive in Lobatse, they are removed from the bags and are stored in small glass bottles which, in turn, are stored on a wooden board which has had holes bored into it of sufficient diameter to enable the bottles to fit into the holes. By arranging the bottles in increasing depth order, it is possible to have a visual picture of the geological section and the hole can thus be easily logged. This logging is always carried out by a geologist and is recorded on a special card giving the borehole number and its locality. Private boreholes were originally given the prefix "P" before the borehole number. This was later discontinued and all privately drilled boreholes are given a "Z" prefix to distinguish them from Government drilled boreholes.

The writer has personally examined the vast majority of samples from boreholes drilled in Botswana. This has involved the examination of approximately 70 000 individual samples. The writer gratefully acknowledges the work carried out by colleagues who have also assisted in the tedious job of logging of boreholes. Among those who carried out logging of considerable numbers of boreholes are M.T. Jones, O.J. van Straten, I. Gerrard and N.S. Robins. Where difficulty is experienced in making a positive visual identification of the rock type encountered, the writer has found that several cuttings (sludge) from the percussion drilled holes can be successfully sectioned and examined under a microscope even where the rock type has been broken into very small cuttings. A typical example of a log of a percussion borehole from which sections have been made, is given below:-

Monmouth Bh. No. Z.693, Molopo Farms

Log and Depth of Samples

10' - 40'	Sand and calcrete,
50' - 60'	Calcrete and sand,
70'	Aeolian and fluviatile sand,
80' - 140'	Coarse fluviatile sand,
150' - 220'	Calcrete and sand with some larger quartz grains,
230' - 320'	Silcrete and calcrete,
330' - 400'	Chalcedonic silica and carbonate fillings and crusts with serpentinite chips (Slides 370', 2 chips serpentinite with relict olivine, 1 chip carbonate rock, 380' carbonate and chalcedony chips, 390' carbonate and chalcedony, 400' serpentinite with relict olivine and bastite pseudomorphs, locally the serpentine has concentric oval layers probably due to way in which olivine was replaced. Some of the serpentinite is replaced by carbonate).
410' - 570'	Green diabase or dolerite (Slides 410', chilled dolerite with plagioclase phenocrysts in ground mass with small laths of pyroxene. Also dolerite with hypersthene and interstitial micropegmatite 520' dolerite with micropegmatite and biotite, 570' dolerite with micropegmatite and biotite).
580'	Blue grey siltstone (hornfels) and some green dolerite (Slides 580', altered dolerite and biotite hornfels).
590' - 650'	Blue grey siltstone with rare pale silt which occurred together in one chip. Variably pyritised (Slides 590', biotite cordierite hornfels, biotite hornfels, pyroxene or epidote hornfels, 600', biotite cordierite hornfels and pyroxene or epidote hornfels, 620', biotite hornfels and tremolite biotite rock - tremolite (oblique extinction) forming large poikilitic crystals, 640' biotite hornfels, biotite-scapolite rock with a long tremolite porphyroblast. The scapolite occurs in elongated dusty areas with shear offsets. 650' biotite hornfels, biotite-scapolite rock).

Comment:

The weathered ultrabasic is probably bed-rock since diamond-drilling at Keng and Oikhe Pan indicate great depth of weathering of the ultrabasic there and which have fissures now filled by silcrete. The presence of relict olivine and bastite after enstatite indicate that this was an olivine enstatite peridotite and it thus seems to be of the same type as that at Keng Pan and Oikhe Pan. The diabase is definitely an intrusive not a lava since the chilled diabase does not resemble the basic lavas so far encountered in this area. It is doubted if a sill or sheet of diabase, 160' thick could cause hornfelsing for 60' and therefore the hornfelsing is believed to be due to the ultrabasic.

* * * * * * * * * *

In addition to the legislation governing percussion drilled boreholes, the Mines and Minerals Act ensures that core from all boreholes drilled for mineral exploration, be stored and submitted to the Geological Survey should they so wish. Numerous core boreholes have also been drilled by the Geological Survey diamond core rig for hydrogeological research purposes. All these samples are stored in a large shed at the Geological Survey. The examination of washed rock chippings (sludge samples) from percussion drilled boreholes can give surprisingly accurate results both as to the lithology and depths of lithological changes. This has been proved on a number of occasions by comparing the geological logs of a percussion drilled borehole with that of a core borehole drilled subsequently adjacent to the original borehole.

DRILLING METHODS (See Plates 66 and 68).

Two main methods are used for the drilling of water boreholes in Botswana, viz., percussion (cable-tool) and compressed air operated "downhole" hammer drills or air rigs. The first air rig was commissioned in Botswana in 1963 and the government now operates four air rigs and ten conventional percussion drills (five Mangolds and five Ruston-Bucyrus rigs) and a Ruston-Bucyrus rig with an air drill attachment. Air drilling has proved highly successful and, in the first 48 drilling days of operation in 1963, the Ingersoll-Rand Drillmaster rig drilled 973m which represented 13% of the total footage drilled by nine percussion drill rigs for the whole of 1963. Drilling is carried out by drilling units, each consisting of a staff member, a foreman, two drivers, an assistant driver and three labourers. Each unit is allocated two rigs, one of which is operational, while the other is kept in maintenance and service at the workshops.

The annual water drilling budget of the Geological Survey exceeds R 100 000 and some 100 to 130 boreholes are drilled every year. All drilling for government or local councils is carried out free of charge. Charges for boreholes drilled under the loan repayment scheme (i.e. private boreholes for individuals or syndicates) are R3.00 per foot.

Drilling Administration

The government's technical and executive water services are widely dispersed among various ministries and departments, but the general responsibility for water development lies within the Ministry of Commerce, Industry and Water Affairs, which controls both the Water Affairs and Geological Survey Departments. The former controls the design, construction, operation and

Pl. 66 Percussion Drilling in Central Kalahari.

Pl.67 Air Drilling - Lobatse.

Pl.68 Air Drilling - Letlakhane Fault Zone - Phikwe.

Pl.69 Accidental [illegible]

maintenance of all Public Water Supplies in the country as well as irrigation, engineering, hydrology and water law administration. The Geological Survey and Mines Department is responsible for hydrogeological surveys and the keeping of hydrogeological records, for the proper siting of drilling locations using appropriate geological/geophysical aids and for the actual drilling and casing of the boreholes. The drilled boreholes are then handed over to the Department of Water Affairs for the installation of the pumping systems. As most boreholes for Public Water Supply are owned and operated by local councils and were often poorly maintained with consequent frequent breakdowns, the Department of Water Affairs instigated a Borehole Preventative and Maintenance Scheme in which 22 units are responsible for the installation of pumping plant. For an annual fee of R50.00 they carry out two check ups and any other repairs, apart from spares; free of charge.

IMPROVEMENTS AND MAINTENANCE OF YIELDS

Apart from the improvement of yield by the use of geological and geophysical aids, a number of techniques are available for the improvement or restoration of yield once a borehole has been completed. Among these are: the use of properly designed well screens; the proper development of boreholes; acid treatment and the use of explosives (shot firing).

THE USE OF PROPERLY DESIGNED WELL SCREENS

A well screen is a scientifically designed perforated casing, with continuous horizontal openings having sharp outside edges, which are V-shaped, and widen towards the inside. These well screens are used particularly for unconsolidated and semi-consolidated sands and gravels, and are widely used throughout the world in the scientific development of boreholes for water supply.

Considerable scope exists for the use of this type of screen coupled with proper borehole development in Botswana, and consideration should be given to their wider use in future groundwater supply schemes.

DEVELOPMENT OF BOREHOLES

The development of a borehole is attained by removing the finer material from the aquifer, thereby cleaning out, opening up or enlarging passages in the formations so that water can enter the well more freely. This development work is essential for the proper completion of any borehole and results in the borehole yield being brought to its maximum capacity.

Three beneficial results are:

"a) Development corrects any damage to, or clogging of the water-bearing formation which occurs as a side effect from the drilling.

b) Development increases the porosity and permeability of the natural formation in the vicinity of the well.

c) Development stabilizes the sand formation around the screened well so that the well will yield water free of sand."

(Johnson, 1966)

The first two benefits can be obtained for boreholes in consolidated formations while all three benefits can be obtained in unconsolidated aquifers.

Development is carried out by a combination of surging (using a tight fitting piston or compressed air) and pumping. A jetting tool with four nozzles can be easily and cheaply constructed for use with an air compressor. During the surging any bridges of sand grains outside the screen slots are broken down and the finer material is then pumped out. Proper developing of boreholes has led to increases of yield in some cases of many hundreds of per cent.

Proper development thus gives:

1. A greater yield
2. Sand stabilization, and
3. Longer borehole life.

Development can also be carried out by "raw-hiding" as described below.

Raw-hiding

"Raw-hiding" consists of pumping a borehole until the discharge is relatively sand free. The pump is then stopped allowing the water in the column pipe (rising main) to drop back into the borehole where it backsurges the formation to break any sand bridges which were stable under the unidirectional flow of water. Pumping is then resumed until the discharge is again sand free. Raw-hiding should be carried out in steps equal to one-quarter, one-half, the design capacity and maximum discharge capacity (Ahrens, 1970).

Examples of use of well screens in Botswana

Most boreholes drilled in Botswana are lined with conventional steel casing which has been crudely perforated by cutting with a hacksaw blade or by cutting with an oxyacetylene torch. The latter perforations in particular are of variable size and are of little use when it is wished to remove a certain grain size of sand from the surrounds of the borehole in order to build up a natural gravel pack around the borehole. Despite the obvious advantages derived from the use of well screens, they have been used only in a few selected cases in Botswana such as by the Rhodesian Railways for their various sand river extraction schemes and by Makgadikgadi Soda Limited in their brine testing boreholes (for the eventual commercial production of salt/soda ash) in the Makgadikgadi Pan. One of these latter boreholes in unconsolidated sands gave an approximate three hundred per cent increase in yield following the proper development by surging with compressed air. Because of the corrosive nature of the brines, special plastic slotted casing was used.

Possible Applications in Botswana

In the past a number of boreholes drilled on the banks, or near to large sand rivers, have been abandoned as blanks because of technical difficulties in tapping the water encountered in the unconsolidated sands. Examples which come to mind are at Francistown, Maitengwe and near the Mosetse River. Considerable difficulties have also often been encountered in fine-grained fluviatile sands found in Ngamiland and the Northern State Lands. Proper development and screening of boreholes could thus possibly help solve the water supply problems of Mahalapye and Francistown as well as parts of the Northern State Lands and the Ngamiland District. The Cave Standstone aquifer may also give increased yields on proper development.

Correct Casing and Drilling Techniques

In Botswana little heed has been paid in the past to the fact that the driving of casing in unconsolidated sands using the percussion drilling method vibrates the sand around the casing and can result in the compaction and consequent reduction in porosity of the granular material. This can be overcome by working the casing down by bailing and following up with proper development.

The Use of Explosives (shot firing)

Because of the physical nature of the majority of Botswana's aquifers, i.e. secondary type aquifers in consolidated formations, it should be theoretically possible to obtain increased yields in brittle, jointed and fractured rocks by the judicious use of explosives to give increased permeability and to assist the speeding up of the borehole development. Unfortunately few scientific attempts to increase borehole yields have been made in Botswana. Of the two known attempts to improve the yield, one ended in spectacular failure and the other resulted in a 16 per cent increase in borehole performance.
The first test was carried out in a borehole (number 2000) drilled on Pumula Farm near Lobatse, which penetrated a thin succession of quartzites (Black Reef, Transvaal Supergroup) and a thick succession of dark grey shales (Ventersdorp Supergroup). A small supply of water had been obtained at about 30m and it was decided to detonate a case of ammon-gelignite in the borehole in order to increase the permeability of the Ventersdorp Supergroup shales. The gelignite was placed in a short length of five inch diamter steel casing, which was lowered into the borehole and detonated electrically. Unfortunately because of the steel casing used as a container for the gelignite, the main force of the explosion was directed upwards and resulted in the base of a continuous 30m length of 6 inch diameter casing present in the borehole being forcibly ejected to a height of

more than 30m above ground level (see Plate 69). This length of casing fortunately only caused minor damage to the rig and the explosion caused no increase in yield probably largely due to the plastic nature of the Ventersdorp shales. The second test was conducted at Orapa (Borehole 2183) when a 20 pound explosive charge was detonated at the basalt/sandstone contact (Stormberg Group, Karoo Supergroup). The effect of shot firing was assessed by comparing the theoretical and actual specific capacities after 700 minutes of pumping. The "well-efficiency" was calculated for each test i.e. before and after shot firing. The effect of shot firing was to improve the well performance by at least 16 per cent. The total improvement was probably greater than this, but the high rate of pumping in the second test will have tended to reduce the specific capacity value for this period.

The results of the tests are give in Table 71 below:

TABLE 71

	Specific capacity after 700 minutes (gpm/ft)	Theoretical specific capacity after 700 minutes	"Well-efficiency" %
First test	0,212	0,178	83,9
Second test (after shot firing)	0,178	0,178	100,0

Martin (1961) noted that blasting of secondary aquifers with 400 - 500 pounds of explosives at the right spot after filling up the borehole with wet sand resulted in borehole yields increasing from 100 to 600 or even 2000 gph - (from 7,6 to 45,6 or even 152 litres per minute).

BOREHOLE STATISTICS

These are given in Tables 72 and 73.

TABLE 72

STATISTICS ON BOREHOLES DRILLED BY DRILLING DEPARTMENT 1929-1971

YEAR	NUMBER OF BOREHOLES DRILLED	NUMBER SUCCESSFUL	NUMBER OF BLANKS	NUMBER ABANDONED	TOTAL METERAGE DRILLED	SUCCESSFUL METERAGE	BLANK METERAGE	ABANDONED METERAGE	TOTAL YIELD: LITRES PER MINUTE	%SUCCESS	REMARKS
1929	2	1	1	-	88	25	63	-	60,6	50	
1930	9	6	3	-	597	465	132	-	266,0	66.67	
1931	19	4	15	-	970	265	713	-	148,5	21.05	
1932	2	-	2	-	137	-	137	-	-	0	
1934	5	3	2	-	273	135	138	-	152,0	60	
1935	3	3	-	-	186	186	-	-	359,9	100	
1936	16	9	7	-	1369	811	558	-	344,2	56.25	
1937	24	16	8	-	1642	1123	518	-	1204,3	66.67	
1938	37	25	12	-	2513	1699	813	-	1328,9	67.57	
1939	35	26	9	-	2970	2456	514	-	2385,7	74.29	
1940	30	20	10	-	2127	1506	620	-	1599,0	66.67	
SECOND WORLD WAR											
1947-48	30	15	15	-	2313	1045	1268	-	610,6	50	
1949	50	30	18	-	2878	1980	898	-	2844,3	64	
1950	51	26	25	-	3004	1757	1248	-	1661,4	51	
1951	65	40	25	-	4865	3017	1847	-	4051,9	61.5	
1952	63	29	33	1	4702	2317	2384	-	1620,3	46.7	
1953	68	26	38	4	4641	1649	2992	-	7001,7	40.7	
1954	83	41	35	7	4892	2756	1799	338	2617,8	49.5	
1955	75	42	29	4	4117	2395	1502	211	4313,5	56	
1956	83	42	39	2	6156	3237	2877	42	4635,7	50.5	
1957))	146	83	62	1	11128	6574	4543	12	5501,7	57	)Commencement of siting of boreholes by)Geological Survey on fairly large scale
1958	150	96	51	3	11982	7682	4243	56	5307,3	64	
1959))	120	85	32	3	10233	7351	2722	159	6412,9	70.9	)Geological Survey took control of)Drilling Dept. from 1st April, 1959.
1960	114	90	24	-	7532	5369	2163	-	8590,5	79	
1961	95	64	14	17	6167	4288	1879	-	6396,9	67.3	
1962	71	47	8	16	6224	3421	2256	548	5411,9	66.2	
1963	89	66	16	7	7735	5293	1644	798	7020,9	74.1	
1964	98	68	20	10	8350	4524	2859	996	6475,2	69.2	
1965	153	114	37	12	12148	8355	3072	722	10685,6	74.5	
1966	130	80	45	5	9667	5873	3509	296	8278,9	61.54	
1967	106	83	19	4	9515	7792	1249	474	6837,0	78.30	
1968	82	66	12	4	6349	5808	1182	360	9303,9	80.49	
1969	68	53	14	1	5803	4410	1299	95	9917,6	77.94	
1970	69	51	11	7	5937	4288	1387	263	3375,9	73.91	
1971	60	38	17	5	5678	3806	1523	349	3996,6	63.33	

TOTAL YIELD = 8154,6 m^3 per hour (1794 014 g.p.h.)

∴ Average yield of successful boreholes = 91,78 litres per minute (207,7 g.p.h.)

T A B L E 73

ANALYSIS OF BOREHOLE YIELDS 1929 - 1968

Boreholes with yields between	50 and	100 g.p.h.	(3,8-7,6ℓ/min)	7,23%
" " " "	100 and	500 g.p.h.	(7,6- 19ℓ/min)	27,81%
" " " "	500 and	1000 g.p.h.	(19- 76ℓ/min)	23,65%
" " " "	1000 and	2000 g.p.h.	(76-152ℓ/min	23,87%
" " " over	2000 g.p.h.			17,44%

MAINTAINING BOREHOLE YIELDS

A reduction in the yield of a borehole can be caused by any one, or a combination of a number of causes. These can be pump wear; a general drop in water table; interference from new boreholes or clogging of the aquifer or well screen by encrustation.

Chemical encrustation is caused by the deposition of insoluable calcium and magnesium carbonates following the loss of carbon dioxide caused by pressure reduction when water is drawn down in a borehole during pumping. Iron and manganese compounds are also sometimes deposited. This type of encrustation is best removed by treating with a strong acid. Acid treatment can also cause increased yields in carbonate rocks by increasing the number of openings. Serious consideration has been given to acid treatment (using sulfamic or hydrochloric acid) of the sandstone on the basalt/sandstone contact (Stormberg Group, Karoo Supergroup) in order to give larger yields. This sandstone is calcite cemented and laboratory experiments carried out by the writer, in which diamond drill core was immersed in hydrochloric acid, showed that completed disintegration of the core took place within a short period of time and hence greater yields might be expected if acid treatment in the field were to be carried out. Chemical encrustation of consolidated aquifers is often best treated by blasting with explosives (Johnson, 1966). Mechanical encrustation can occur when silt and clay block the aquifer.

ARE BOTSWANA'S GROUND-WATER RESOURCES DRYING UP?

Since the commencement of drilling by government in Botswana in 1929, 124 boreholes, for which reliable records are available, have been worked on subsequent to their being drilled. Reasons for this are generally because of a reported drying up or reduction in yield; because the hole has collapsed due to insufficient lining; because it was considered on geological or geophysical grounds that deepening the borehole would result in further water supplies being encountered; or because local "basimane" (young boys) have filled the unequipped borehole with rocks and other objects.

In the writer's experience most reported cases of a borehole drying up are due to mechanical failure of one sort or other - generally worn pump cylinder leather washers or rod failures. Careful examination of the records of government boreholes which have been subsequently worked on by a drilling rig (see Table 74) has shown that only 21 out of the 2000 odd succesful holes drilled in Botswana have in fact dried up or shown reduced yields. Of the 21 boreholes, only two dried up completely while of the two, one was subsequently found to have a yield of 7,6 litres per minute. The total initial tested yield of these 21 boreholes was 1715,3 litres per minute while their final tested yield was 448,8 litre per minute - 73% less than the original yield.

It is concluded that less than one per cent of boreholes drilled in Botswana have shown reduced yields with the passage of time. It would appear therefore that no marked drying up of boreholes is taking place in Botswana.

TABLE 74

BOREHOLES SHOWING REDUCED YIELDS WITH TIME

(Yields in litres/minute)

Bh. No.	Date drilled	Date of cleaning	Original yield	Final yield
93	11.3.38	10.5.40,	53,2	13,7
		24.3.48,		13,7
		11.6.59		9,1
169	4.9.40	24.11.54	57,0	17,5
271	4.2.51	1.10.52,	38,0	9,1
		18.4.56		30,4
286	31.3.50	20.10.64	82,1	Dry
299	20.8.50	18.7.53	57,0	27,3
348	19.7.51	19.10.52	228,0	95,8
401	29.3.52	26.3.65	54,7	7,6
416	8.8.52	20.1.54	45,6	7,6
422	10.10.52	18.1.54	53,2	6,8
513	20.3.54	16.1.69	121,6	53,2
626	6.7.55	3.12.64	30,4	4,6
670	16.3.56	24.11.58,	228,0	38,0
		24.6.66,		63,8
		23.6.70		91,2
679	11.6.56	19.9.59	197,6	11,4
854	10.7.57	22.12.64,	12,2	Dry
		12.2.65		7,6
891	19.2.58	26.9.63	68,4	19,0
893	31.10.58	16.3.65,	68,4	11,4
		16.6.72		13,7
936	.58	11.6.71	57,0	5,7
989	23.9.58	5.1.60	76,0	9,1
1000	15.10.58	18.8.70	4,6	0,8
1344	21.6.61	16.4.68	114,0	64,6

GEOLOGY AND PHOTOGEOLOGY AS AN AID TO LOCATING GROUND WATER

In the section on statistics relating to the various water bearing formations (Table 12) it can be seen that there are marked differences between the success ratios obtained in boreholes in differing geological formations. Geology thus plays a major role in determining the likelihood of success in the siting of boreholes. This is partially true in the siting of boreholes, say, to intersect the Stormberg basalt/ Cave sandstone contact; Middle Ecca sandstone (Karoo Supergroup); Transvaal Supergroup shale and quartzitic sandstone, or in areas of Kalahari Beds with a shallow ground water table (Nata, Gweta, Odiakwe, areas north of Makgadikgadi Pan). However, in many instances, because of the secondary nature of the aquifer, careful geological/photogeological interpretation must be made, preferably backed up by geophysical work, prior to the siting of water boreholes. In the southwestern part of Ngamiland, for example, the highly folded Ghanzi Group succession of interbedded shale and quartzite forms a remarkably poor aquifer. Consequently successful boreholes are only likely to be obtained if sited on joints near the nose of fold structures. These are selected from photogeological studies and then located on the ground using aerial photographs and possibly self-potential or electromagnetic techniques. The use of geology and photogeology to select favourable geological formations, and structures such as faults, major joints in Waterberg sandstone, dyke contacts, permeable fault planes and other secondary features in normally poor water-bearing formations is thus essential for the planning of any ground-water development programme. In Botswana geological and geophysical aids have thus resulted in an increase in the success ratio of boreholes by 25 per cent (Table 75).

TABLE 75

GENERAL BOREHOLE STATISTICS - BOTSWANA

GOVERNMENT BOREHOLES DRILLED WITHOUT GEOLOGICAL/GEOPHYSICAL AIDS 1929 - 1958:

TOTAL NUMBER	674
TOTAL SUCCESSFUL	214
% "	46,7 %

GOVERNMENT BOREHOLES DRILLED USING GEOLOGICAL/GEOPHYSICAL AIDS 1953 - 1971:

TOTAL NUMBER	1641
TOTAL SUCCESSFUL	1168
% "	71,2 %

i.e. Geological/Geophysical aids have resulted in an increase of 24,5% in the success ratio. Furthermore yields of properly sited boreholes increased by 26,6 L/min over unsited boreholes.

GEOPHYSICS AS AN AID TO THE LOCATION OF GROUND WATER

Prior to the siting of any borehole a detailed study is made at the Geological Survey office of available geological maps, aerial photographs and existing data on all boreholes in the area. In this manner some indications of the expected depths to water, water quality and geological formation can be obtained prior to actual geophysical surveys being carried out. In addition, all existing geophysical data for the area is studied. To date a library in excess of 15 000 depth probes has been built up. These depth soundings vary from less than 15 m to over 300 m.

The spectacular rise of approximately 25 per cent in the percentage of successful boreholes sited following the takeover of siting by the Geological Survey is undoubtedly due in large measure to the use of geophysical aids in the siting of boreholes.

THE ELECTRICAL RESISTIVITY METHOD

Introduction

The pioneer of electrical prospecting was Conrad Schlumberger, who in 1912 prefected the technique which to this day remains the basis of electrical resistivity prospecting. Details of the early history of the method have been given by van Nostrand and Cook (1966) and Kunetz (1966).

In Botswana widespread use of the resistivity method as an aid to the siting of boreholes was commenced in 1956 to cope with an expanded drilling programme to develop the underground water resources of the Protectorate funded by a grant from the Colonial Development and Welfare Fund.

The use of this method was followed in 1956 and 1957 by a marked increase in the success rate of boreholes drilled in Kalahari sandveld areas from 32 to 73 per cent. The electrical resistivity method now constitutes the most widely used and most successful geophysical technique used for the siting of boreholes in Botswana. The method is furthermore characterised by it's flexibility and it's ease of operation.

Resistivity

Resistivity is defined as the ohmic resistance of a cylinder of unit cross-sectional area and of unit length. Resistivities are normally quoted in ohm-metres ^{2}/metre or ohm-metres. Ohm-centimetre may also be used and equals 0,01 ohm-metre. The conductivity is the reciprocal of the resistivity. Where a non-homogeneous medium is present, a different value of the resistivity (ρ), designated ρ_a, the apparent resistivity, is obtained.

Conductivity

The conductivity of rocks may be affected by metallic conduction caused by large amounts of metallic sulphides such as pyrite, pyrrhotite, chalcopyrite, galena etc; by magnetite or by graphite. More generally however, the conductivity of rocks is affected by electrolytic conduction because of mineralised water present in pores and fissures. The electrolytic conductivity depends on the conductivity of the water present in the host rock; the amount of water present; and the manner in which it is distributed within the rock (Kunetz 1966). At first it would appear that useful interpretation of resistivity data would be well nigh impossible because of the large number of variables. However, in practice there is a distinct relation between resistivity and rock facies and useful data can be deduced on the nature and number of rock types present; the quality of water likely to be encountered within the rock; and the degree and depth of weathering or fissuring (i.e. porosity) present in a rock type. All this data is extremely useful in groundwater surveys.

Electrode Configurations

Some experimentation using different electrode configurations was carried out initially in Botswana, but far and away the greatest number of depth soundings was carried out before 1969 using the Wenner (1915) equidistant electrode spacing configuration. This quadripole configuration consists of two outer metal stakes through which current is made to flow through the ground while the potential difference is measured between the two inner non-polarizing electrodes consisting of porous pots with a copper electrode in a copper sulphate solution. By expanding the electrode system about a fixed central point,but still keeping them equidistant from each other, a vertical profile or depth sounding (probe) can be carried out because of the progressively deeper current penetration as the electrodes are moved further apart. Should information be required for a constant depth penetration,a constant separation traverse (horizontal profiling) can be carried out. In this method and the whole configuration is moved along a traverse. Readings are taken at regular intervals and results are plotted at a "station" taken as the point midway between the two potential electrodes.

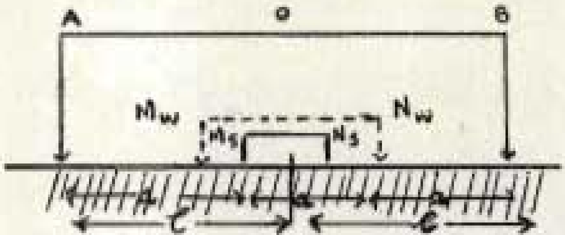
The Schlumberger configuration is shown diagrammatically in Fig.155. With this configuration, vertical profiling is carried out by initially expanding only the outer current electrodes, and expanding the inner potential electrodes M_s N_s, only once every 5 changes of the outer electrodes. The major advantage of the Schlumberger configuration is that it is less sensitive to unknown lateral inhomogeneities. On the other hand far more sensitive equipment is required to measure the extremely small potential differences.

Instrumentation

A standard wiring diagram for a direct current potentiometer electrical resistivity instrument was finally evolved following the design and building of series of prototype instruments at the Geological Survey. This type of instrument was found to operate satisfactorily in the arid regions of the country where high contact resistances were encountered. A direct current instrument was favoured because it was not limited in regard to the amount of high tension current which could be used to overcome high contact resistances. A battery box consisting of 25 x 45 volt dry cell batteries was generally used but on occasions 2 battery boxes each of 1500 volts were coupled together for use in areas of thick dry Kalahari sand.

FIG. 155.

FIGURE SHOWING SCHLUMBERGER AND WENNER QUADRIPOLE CONFIGURATIONS



$AM_w = M_wN_w = N_wB$: WENNER CONFIGURATION

$M_sN_s \leq \frac{AB}{5}$: SCHLUMBERGER CONFIGURATION

(AFTER KUNETZ, 1966)

For the Wenner configuration ρ_a (apparent resistivity) $= 2\pi a \frac{V}{I}$

" " Schlumberger $\rho_a = K \frac{\Delta V}{E}$

Where V is potential difference between the potential electrodes and

$$K = \frac{2\pi}{\left(\frac{1}{AM_s} - \frac{1}{AN_s}\right)\left(\frac{1}{BM_s} - \frac{1}{BN_s}\right)}$$

$$\text{or } K = \frac{\pi \ell^2}{M_sN_s}$$

$$\therefore \rho_a = \frac{\pi \ell^2}{M_sN_s} \frac{\Delta V}{I}$$

$$\text{or } = \pi \ell^2 \frac{E}{I}$$

In 1964 the normal galvonometers in the resistivity sets were replaced by transistorised electronic null detectors designed in the Department. A wiring diagram for this improved instrument is given in Fig.166. This type of instrument was used with very little trouble until 1970 when the instruments were again modified to cope with the more accurate measurement required for the Schlumberger configuration.

In 1969 following a visit by Dr. J.S. van Zijl of the Acoustics Division of the National Physics Research Laboratory for the Council for Scientific and Industrial Research, who had pioneered the use of the Schlumberger configuration in Southern Africa, it was realised that more sophisticated techniques enabling a more quantitative assessment of resistivity data were becoming necessary in Botswana. This was offered by the Schlumberger configuration accompanied by curve matching techniques to give reliable depth estimates in multi-layered formations. This configuration is furthermore far less susceptible to errors due to lateral surface inhomogeneities than the Wenner method.

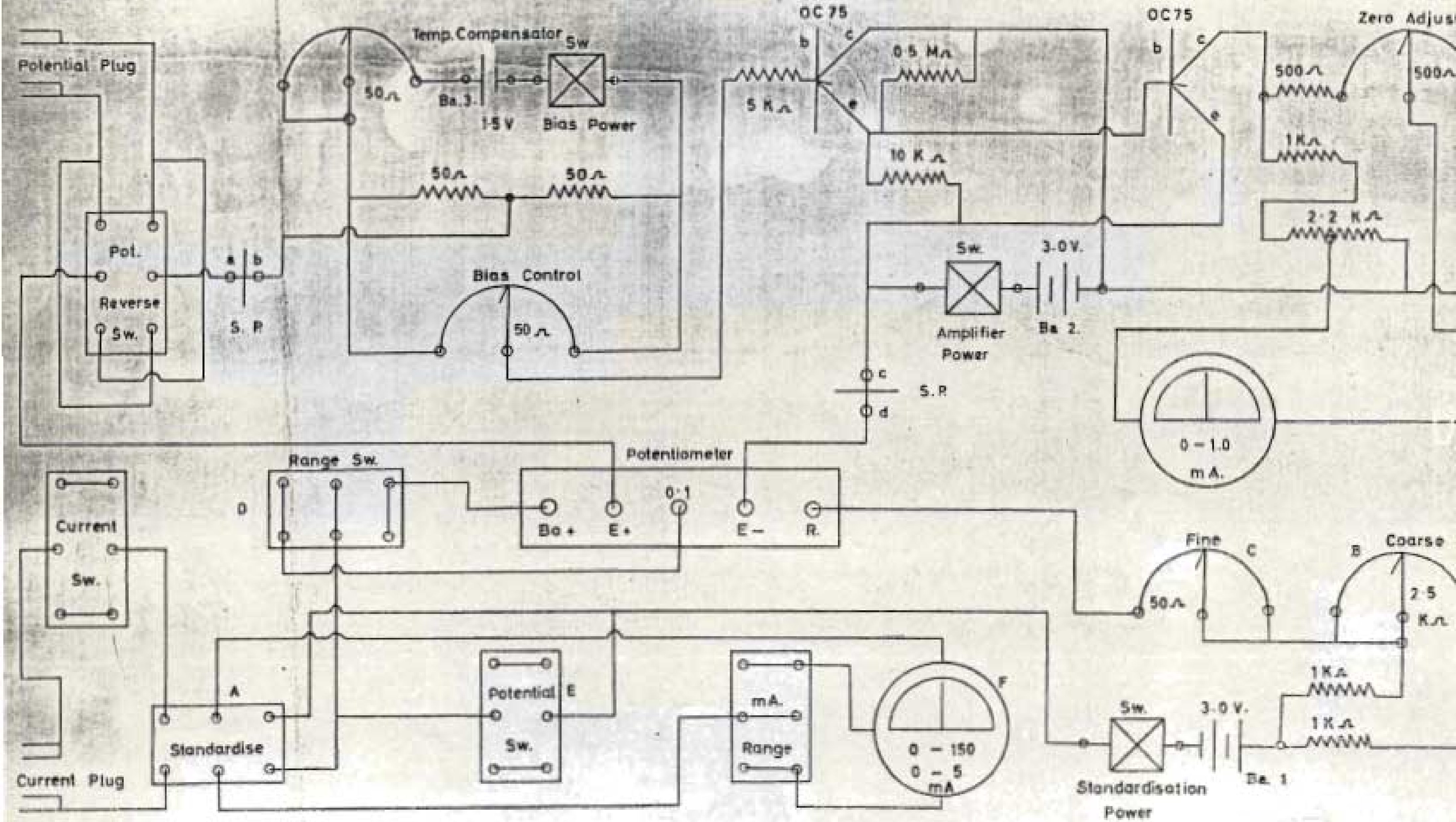
Interpretation

Interpretation of all electrical resistivity depth probes was initially carried out using a simple empirical interpretational method described by Enslin (1969).

In this method an asymptote is drawn to the curve in which the resistivity is plotted against the electrode spacing

Fig 156

RESISTIVITY APPARATUS



NOTE:

(one third the distance between the outer current electrodes using the Wenner configuration). The depth to the asymptote point is then taken as the depth of decomposition of the formation being probed electrically. Examples of this type of interpretation are given in Figs. 157, 158.

In practice this method of interpretation has proved to give rapid and reasonably reliable results for the interpretation of depths of decomposition, and hence in delineating basins of decomposition both of igneous and carbonate rocks.

In certain cases excellent results were obtained in determining depths to the Cave sandstone contact beneath a resistant cover of Stormberg basalts (Fig. 101). Where the Stormberg basalts are overlain by a thick cover of low resistivity soil, the depth to the basalt/Cave sandstone contact may prove impossible to determine.

In 1970, following the switch to the Schlumberger configuration, the empirical interpretation was abandoned, and more accurate quantitative interpretations made by curve matching techniques, using master tables and curves described by Orellana and Mooney (1966). This technique, however, has the disadvantage of needing adjustments to the field data before analysis and the actual curve matching is far more tedious than the empirical interpretation which could always be carried out on the spot.

Practical Examples of the Use of the Resistivity Method in the Siting of Water Boreholes

Determining Depth and Extent of Basins of Decomposition

Without doubt the most valuable use of the electrical

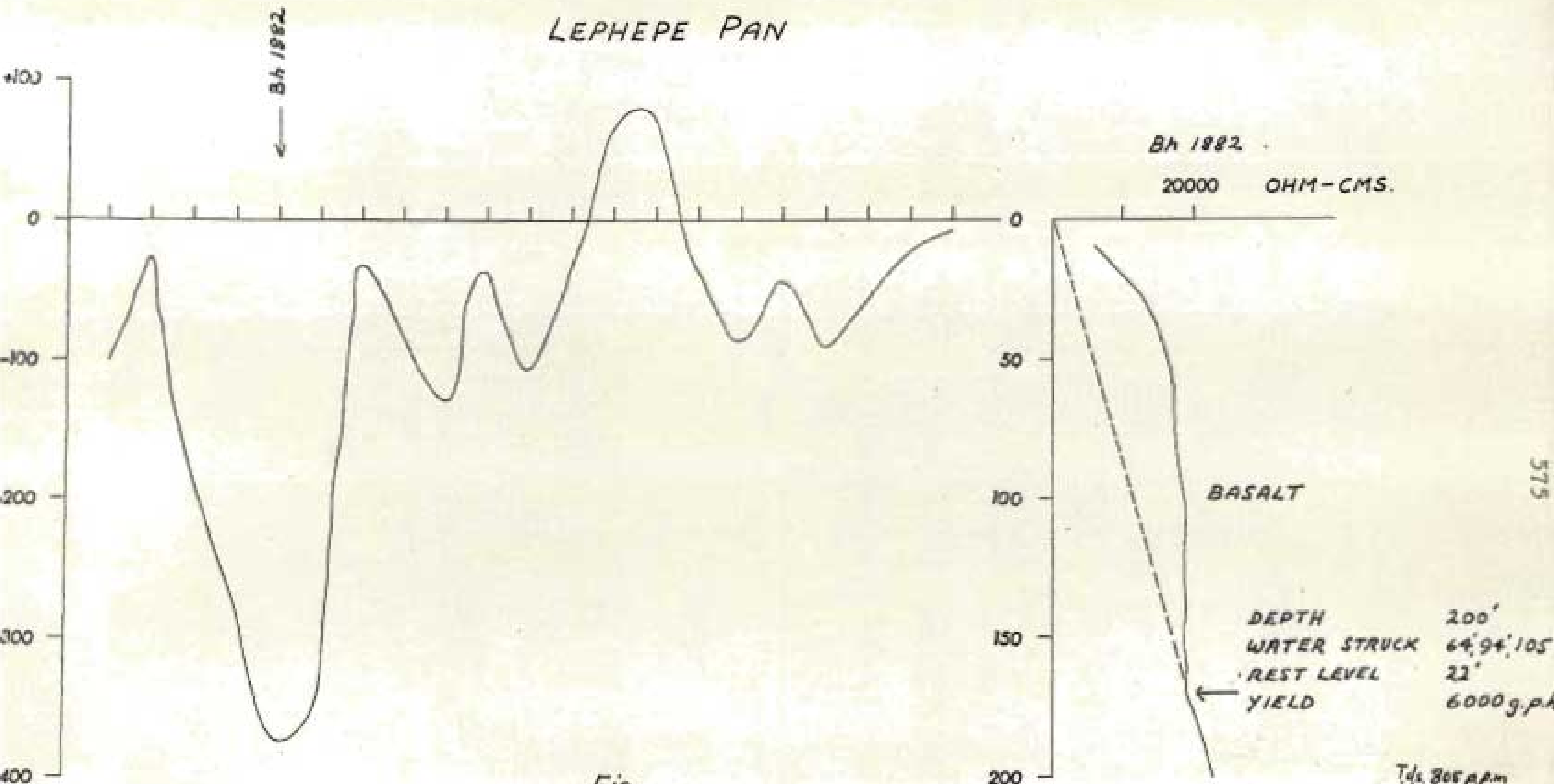
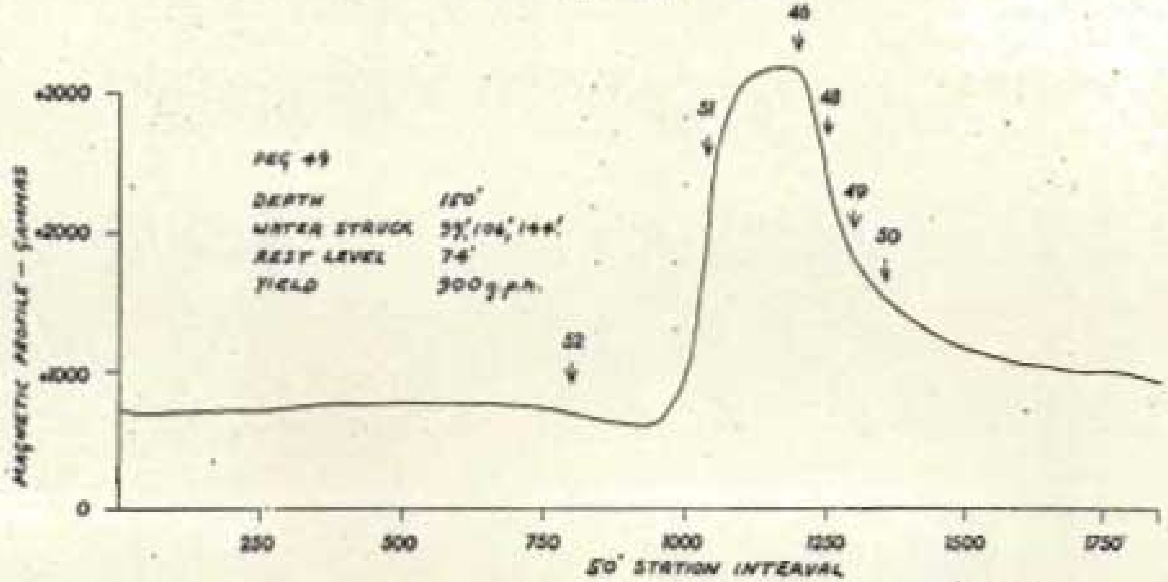

LEPHEPE PAN
Bh 1882
+100
0
-100
-200
-300
-400
Bh 1882
20000 OHM-CMS.
0
50
100
150
200
BASALT
DEPTH 200'
WATER STRUCK 64',94',105'
REST LEVEL 22'
YIELD 6000 g.p.h
Tds. 805 ppm

Fig 157

Fig 158

MASINGWANENG – Bh 2114



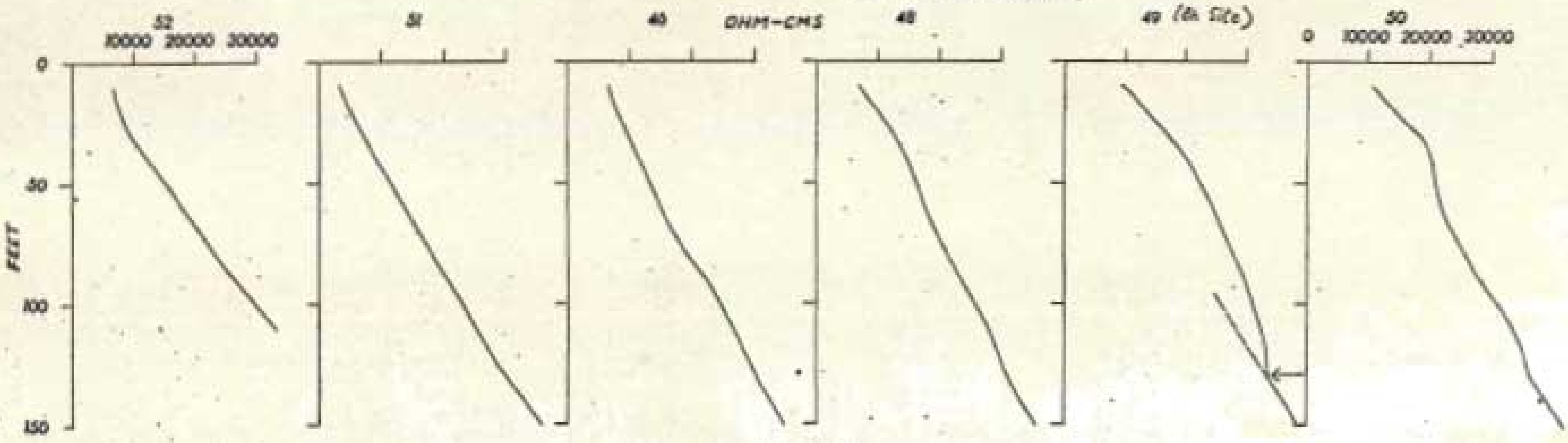


Fig. 158

resistivity method in the siting of boreholes, is in the delineation of basins of decomposition in Basement Complex terrain, as these basins cannot as a rule be detected by surface geological work. As a result of the use of this method, a success ratio of over 70 per cent has been achieved because of the greater permeability of the rock on the contact between partly decomposed rock and the unweathered rock below. Wildcat drilling in similar areas usually gives a success ratio of about 35 per cent. The siting of successful boreholes is thus dependent on determining areas where the fractured contact zone at the base of the decomposed zone is likely to occur at a depth greater than the expected water table depth for that area. An example of a survey in a Basement Complex area is given in Figure 159. The resistivity method has also proved extremely successful in determining depths of decomposition in dolomitic rocks (Transvaal Supergroup) and of acid and intermediate lavas (Ventersdorp Supergroup). Apart from it's use in delineating basins of decomposition (with concomitant softer drilling and hence greater drilling rates), this method is widely used in Botswana in sedimentary formations, and optimum apparent resistivity ranges for a number of formations are becoming apparent especially for the Waterberg Supergroup (20 000 ohm-cm), for the Transvaal Supergroup (15 000 ohm-cm) and the Ecca Supergroup (Karoo Supergroup, 5 000-15 000 ohm-cm).

Determining Depths to Horizontal Contacts

Because of a marked resistivity contrast between the Stormberg lavas and the underlying Cave sandstone, considerable success has been attained in determining the depth of this contact.

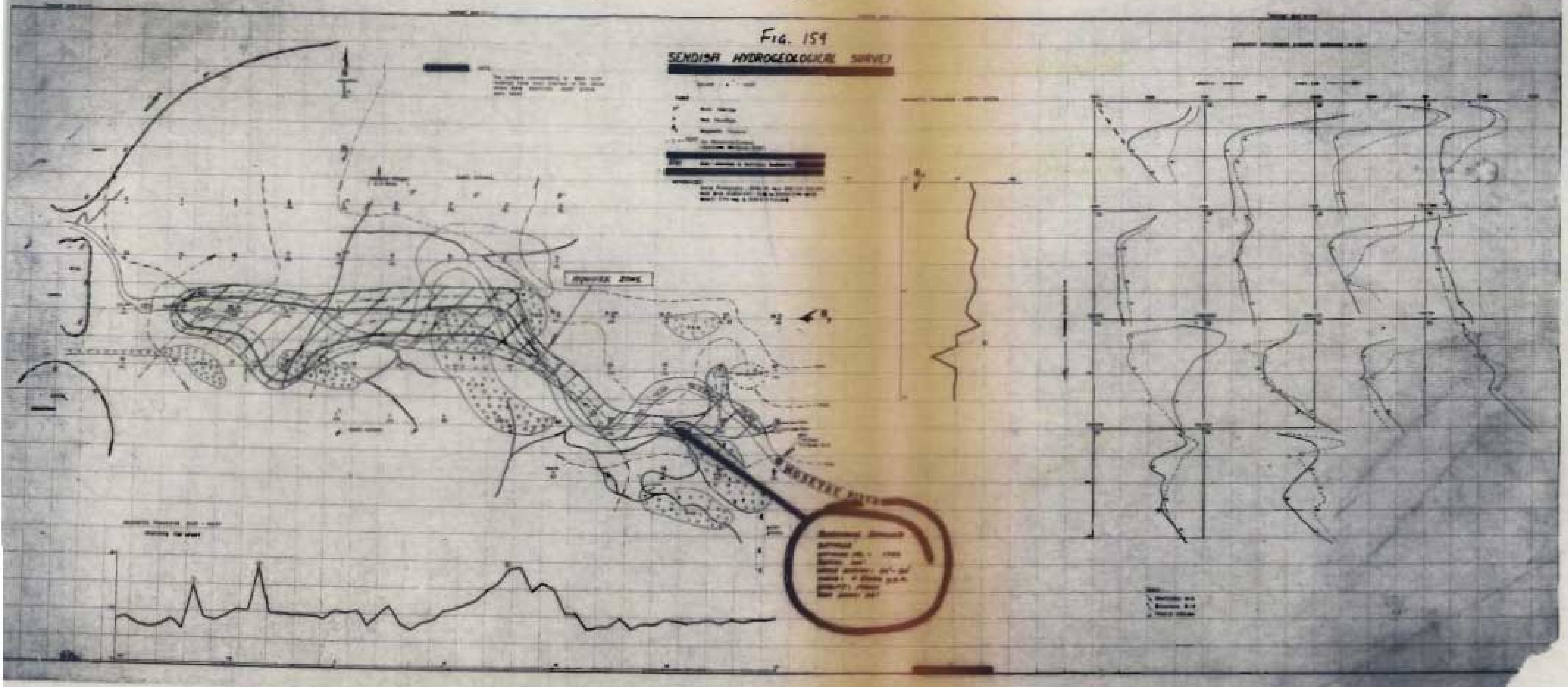


Fig. 159
SENDISA HYDROGEOLOGICAL SURVEY

This fissured and indurated contact forms Botswana's most important and consistant aquifer. (See Fig.101).

Determining Fresh Water Lenses in a Saline Environment

In the Northern State Lands, and parts of the Ngamiland District, where large tracts of land are being opened up for cattle ranching, the resistivity method is particularly useful for the determination of fresh water horizons overlying the general saline water-table. A comparison of resistivity curves with chemical quality data from boreholes drilled in Kalahari Beds sediments has shown that all boreholes with apparent resistivity values in excess of 3 000 to 5 000 ohm-cm, at expected water-table depth, invariably give potable water supplies, whereas those with values less than this yield saline supplies. Examples of two curves are given in Fig.160, while in Fig.161 the apparent resistivity at 15 m depth, measured by depth probing, is plotted versus the conductivity of water from boreholes drilled at the depth probe sites. A very clear relationship between apparent resistivity and water quality can be seen. The reason for the distribution of the fresh water horizons within the general salt water area is not yet clear but preliminary indications are that the fresh water boreholes are related to areas of greater surface permeability such as nodular calcretes.

Combined Resistivity and Magnetic Surveys

In the area north of the Molopo River a considerable amount of success has been obtained in the siting of boreholes using a combination of data from resistivity data and airborne and ground magnetic surveys. In this area the best

NYIE PAN AREA

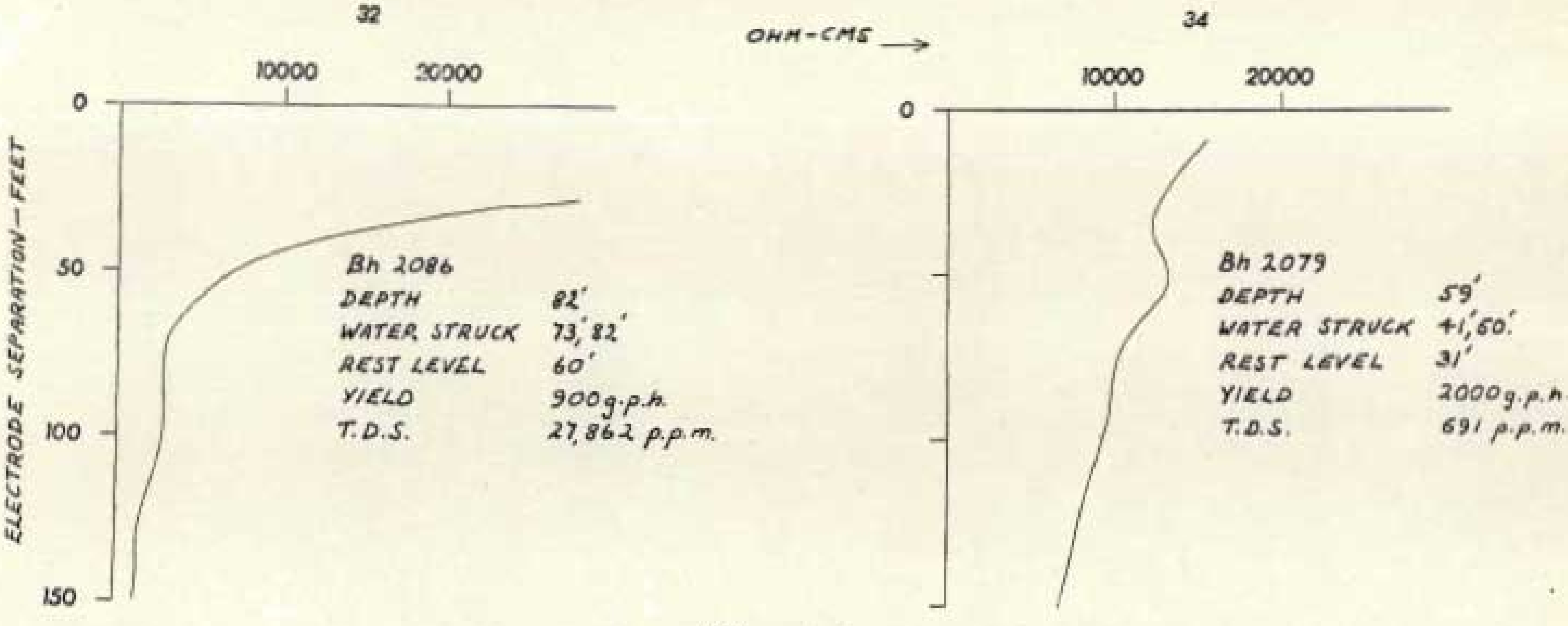


Fig. 160

Typical Resistivity depth probes on fresh (34) and saline water (32)

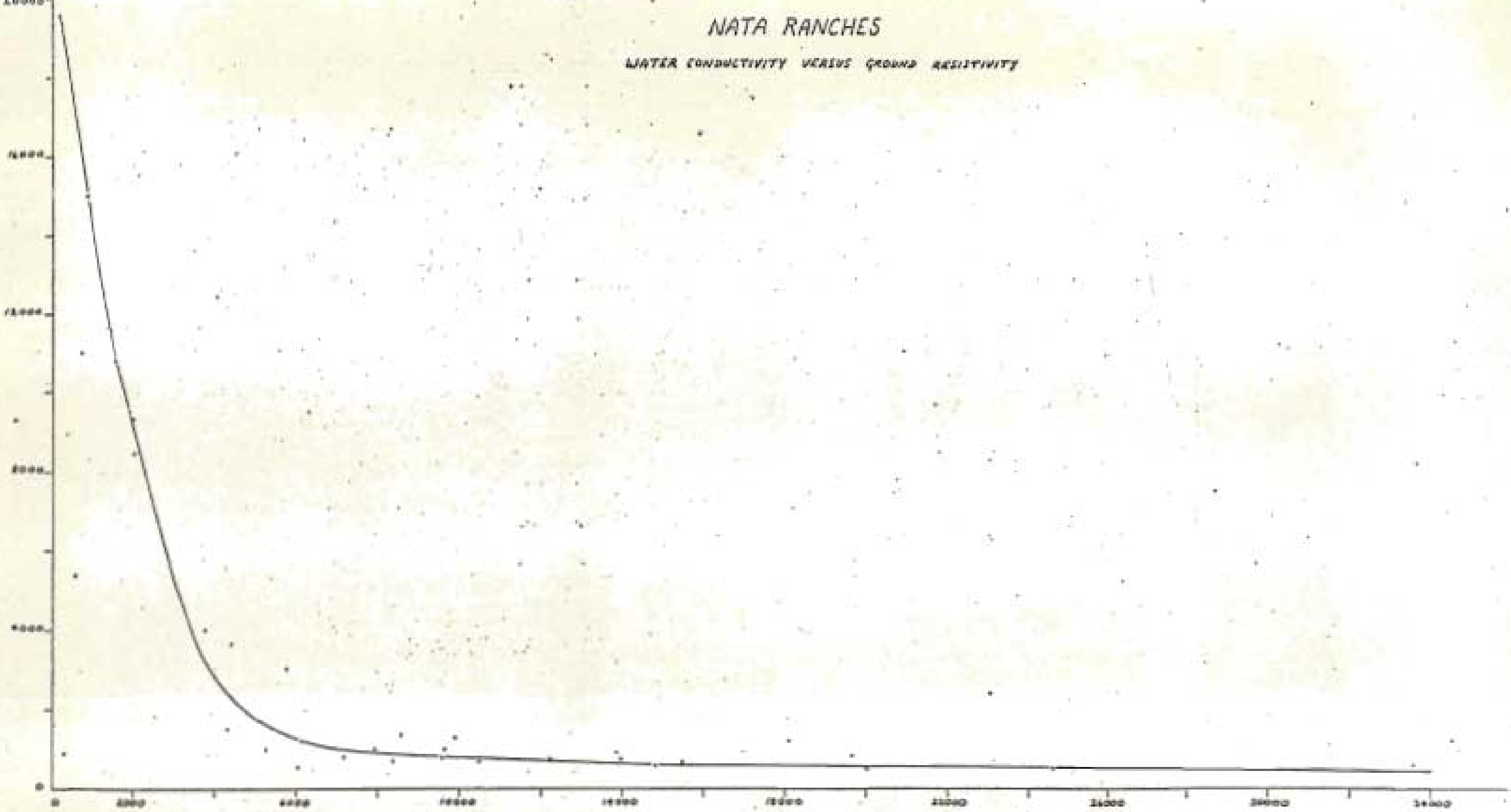

NATA RANCHES
WATER CONDUCTIVITY VERSUS GROUND RESISTIVITY
CONDUCTIVITY MICRO-MHOS
OHM-CMS
RESISTIVITY AT 50'

Fig. 161

formations for yielding water are dolomite (Dolomite Subgroup) and quartzite of the Pretoria Subgroup (Transvaal Supergroup) together with partly calcreted gravel and sandstone forming part of the Kalahari Group. Deep depth probes to depths of up to 300 m are of considerable use in determining the thickness of the Kalahari Beds and also in distinguishing between mafic and ultramafic intrusives and sedimentary types.

Plate 70 shows a typical resistivity survey in progress.

Pl.70 A resistivity survey in progress - Mokoro hill

Pl.71 A seismic refraction survey using explosives to determine the depth to bedrock - Motloutse River.

SELF - POTENTIAL

The self-potential method (spontaneous polarization) has been relatively little used as an aid to the siting of boreholes and only Cooper (1951) mentions this method as a possible aid for ground water detection. Some experimentation was carried out in Botswana to determine the applicability of the method and some noticeable successes were obtained using the method. This method is based on the "streaming potential" set up when water moves through a porous or semi-porous medium. It follows therefore that the method is likely to be most successful under dynamic conditions of water movement particularly along shears and fissures and in areas of shallow water table. Conditions under which rapid movement of ground water or movement of water to the ground-water table are likely to occur, are immediately after heavy or prolonged rainfall, or when recharge has occurred following the flooding of an ephemeral river course.

Method used and instrumentation

Most of the tests carried out were done using a modification to the standard resistivity unit designed by Mr. O. J. van Straten. The modification involves the introduction of an extra switch in the earth balance circuit which enables the transistorized amplifier of the resistivity earth balance circuit to be switched out of the circuit and which brings a sensitive galvanometer into the circuit. In practice, the earth currents are measured directly by balancing the galvanometer back to an arbitrary zero using the instrument's potentiometer. The potentiometer then gives a relative value for the potential difference.Positive and negative readings with respect to the arbitrary zero can be made with the instrument's potential reverse switch in the appropriate position.

Surveys were generally carried out using the "fixed pot" method, i.e. a fixed reference porous pot (Cu - CU SO_4) was placed in a well-watered hole at an "infinite" (several hundred metres) distance while the other pot was used as a "travelling" pot and was moved at 3m intervals over the area to be traversed. Holes for the travelling pot should be well watered, preferably some time before actual readings are taken. The travelling pot is then placed in each hole in turn and readings of the potential difference at each station read off. Once an anomaly is recorded a short traverse is run at right angles to the original traverse to record the extent of the anomaly and to determine where the largest anomaly is situated.

Examples of the use of S.P. in the siting of boreholes

A successful application of this method is shown in Fig. 157. This traverse was carried out over a large pan with a thin veneer of sand and clay overlying Stormberg basalt known to be over 300m thick and a notoriously poor aquifer in the area; Many completely blank boreholes and a few low yielding boreholes had been drilled in the vicinity. The traverse was carried out on the day following exceptionally heavy rains. Some run-off had accumulated on the pan surface in one locality but drained away rapidly prior to the S.P. traverse. It can be seen in Fig. 157 that a marked S.P. "low" was detected along a traverse across the pan. Electrical resistivity depth probes were carried out at various points along the traverse, but that at peg 53 showed the lowest apparent resistivity values and the greatest depth of decomposition of the basalt. A borehole (No. 1882) with a yield in excess of 454 litres per minute (6 000 g.p.h.) was subsequently drilled at this spot.

Fig. 162 shows a similar traverse carried out at Mathale near Pikwe, over Archaean gneiss and schist and, once again, a borehole sited on a combination of "low" S.P. values and a favourable resistivity depth probe obtained a yield of 181 litres per minute (2 400 g.p.h.) in an area where less than 50 per cent of all boreholes yielded any water at all, and where the average yield of successful boreholes was about 23 litres per minute (300 g.p.h.).

Further examples of the successful use of self-potential for the location of borehole sites are given in Fig. 163. These surveys, using the Afmag, self-potential, magnetic, reconnaissance electromagnetic inductive techniques (McPhar, R.E.M. Unit), and electrical resistivity techniques as a follow-

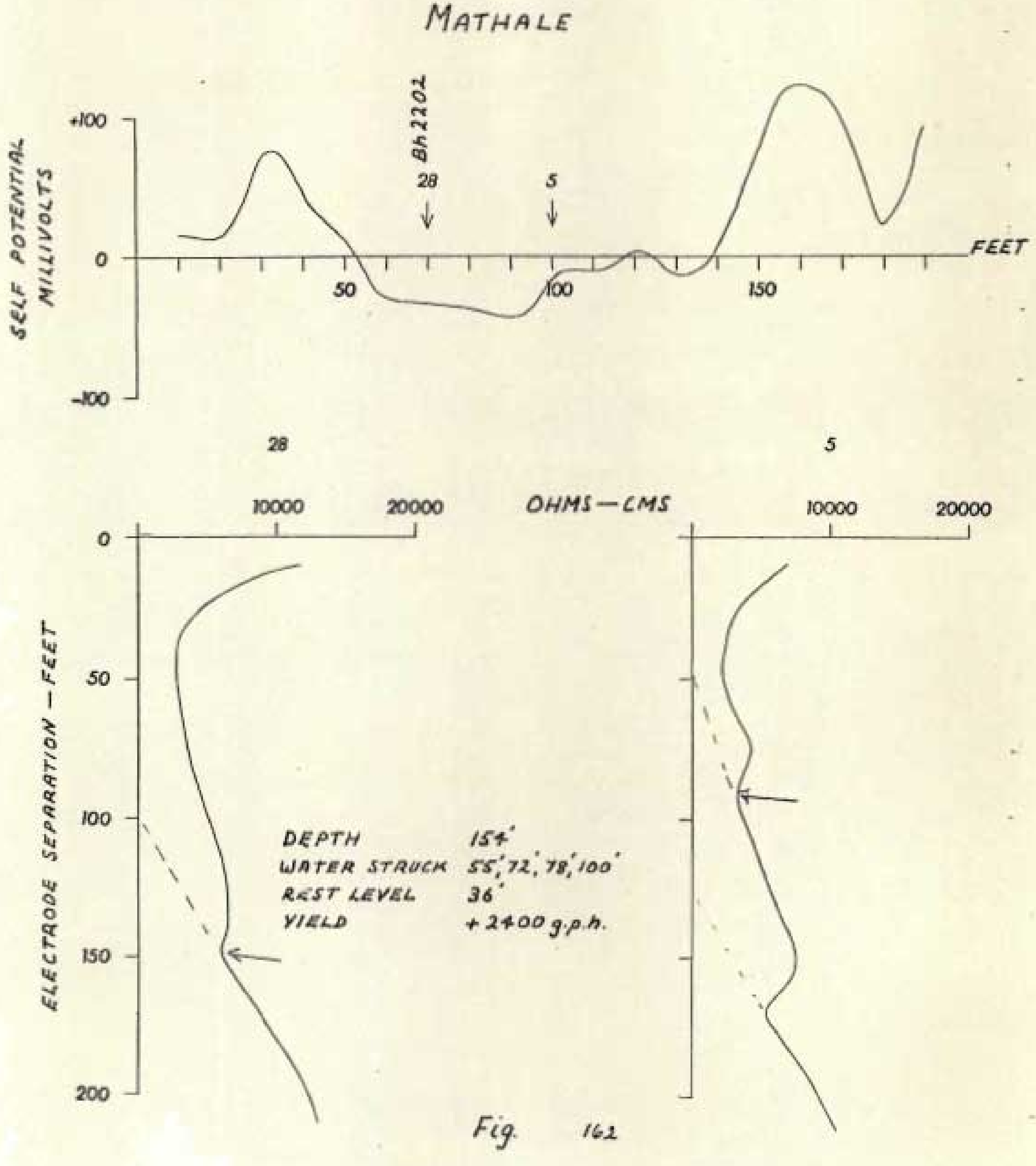
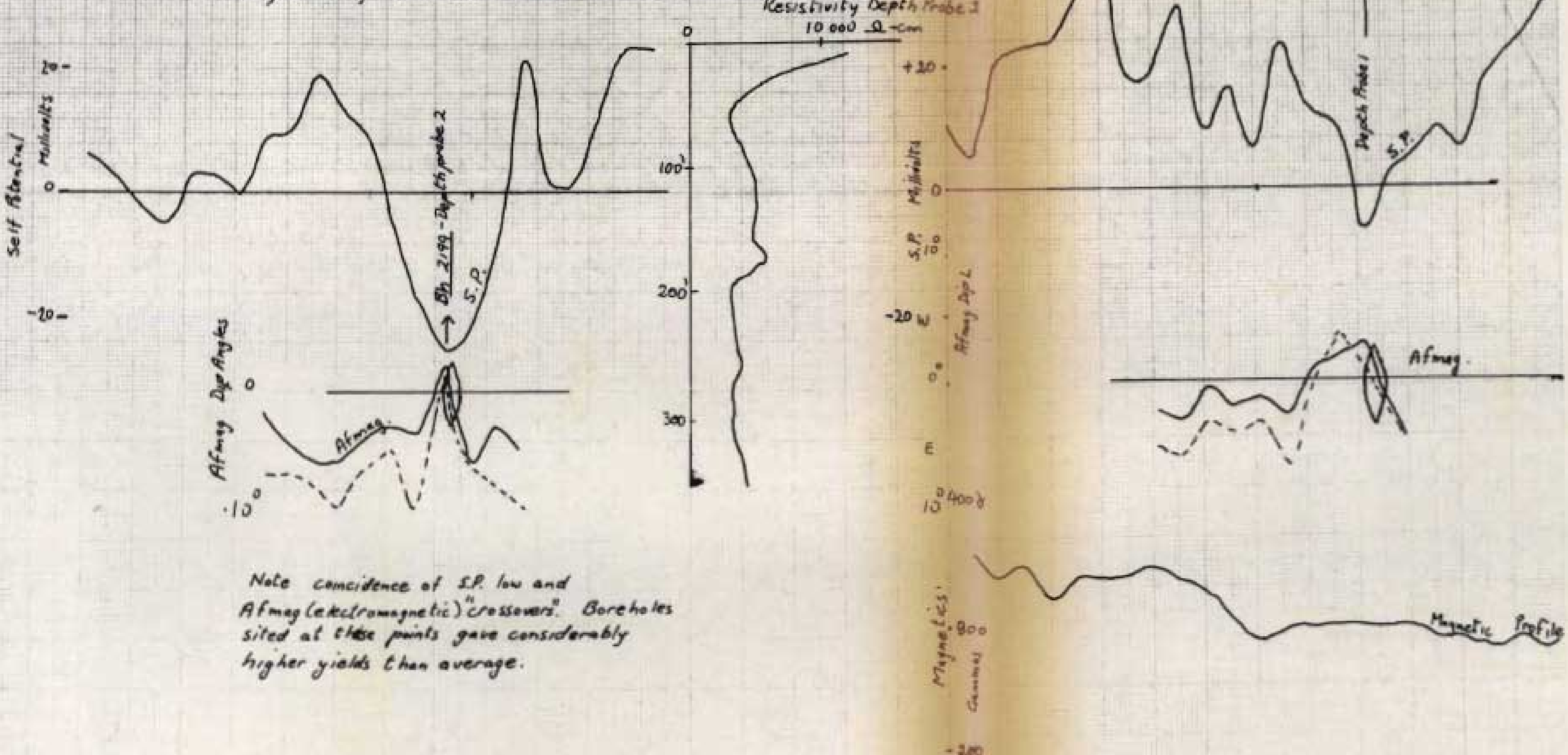


Fig. 162

Self potential and resistivity profiles.

Fig. 163

INTEGRATED S.P., AFMAG, MAGNETIC SURVEYS - 12 MILE WELLFIELD - ORAPA.



Note coincidence of S.P. low and Afmag (electromagnetic) "crossovers". Boreholes sited at these points gave considerably higher yields than average.

up to a Barringer INPUT airborne electromagnetic survey, resulted in the siting and drilling of two highly successful boreholes which penetrated the underlying Stormberg lava/Cave Sandstone formations (Karoo Supergroup) and gave yields (Boreholes 2199 and 2206) of 378 and 529 litres per minute. These are more than 300 and 400 per cent higher than the average for the area.

Self-potential logging of boreholes

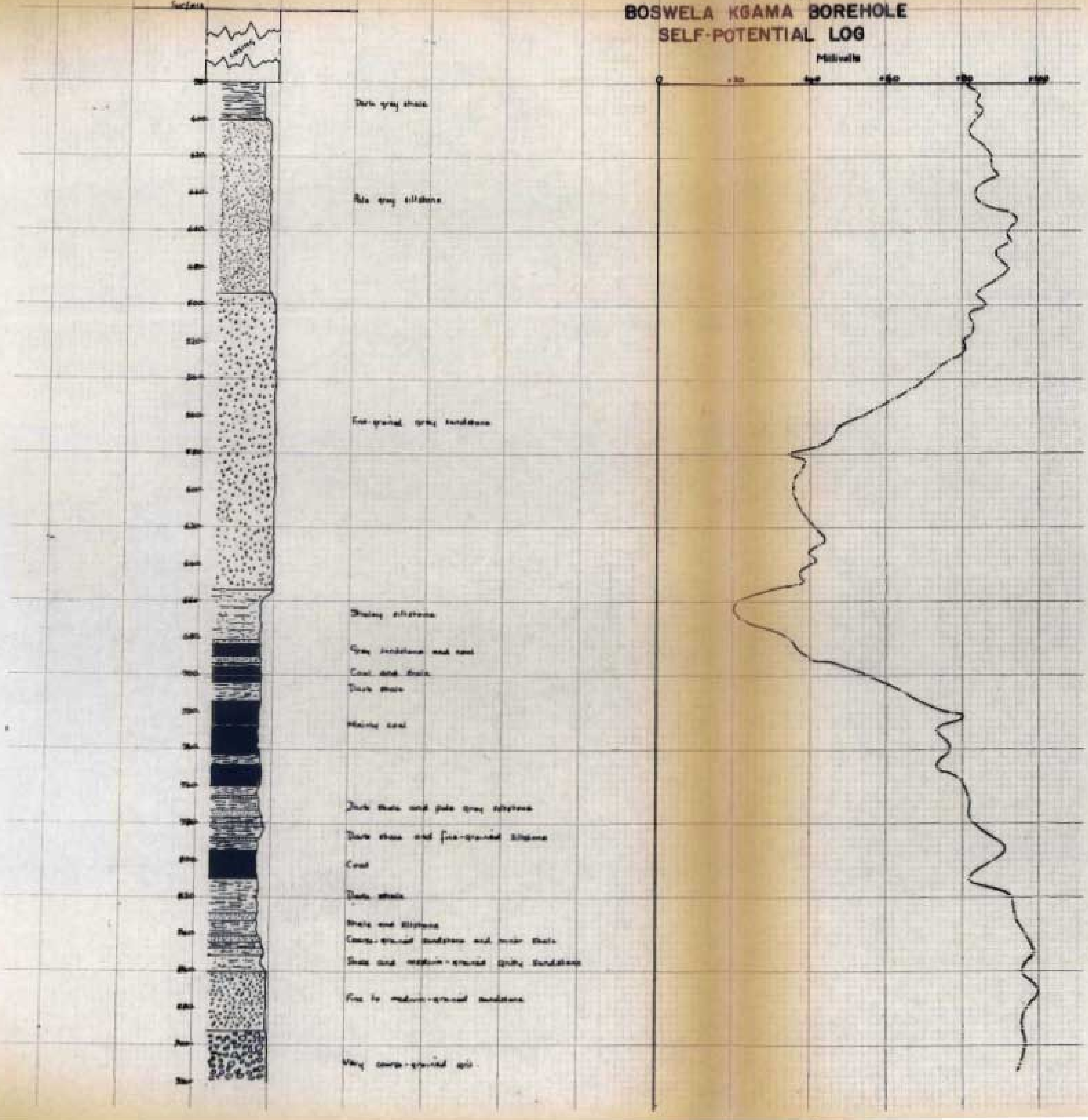
Only two logs of boreholes were carried out. These were carried out using the same instrumentation described above using a porous pot with copper electrodes and copper sulphate solution and using a lead plumb-bob. Self-potential readings were taken at selected intervals and the curve plotted as shown in Fig. 164 The prominent S.P. "low" from 580 to 650 feet below the borehole collar is probably due to a more porous zone in the lower part of the fine-grained grey sandstone unit shown in the log of the borehole in Fig. 164.

An S.P. log of borehole 2153 was given (Fig. 88) in the chapter on Orapa.

Use of S.P. to determine locality of leaks in a dam wall

Crockett (1966) described the successful use of the S.P. method to determine the location of leaks in dam walls in Botswana.

FIG. 164
BOSWELA KGAMA BOREHOLE
SELF-POTENTIAL LOG



Conclusions

The self-potential method has been used in Botswana with varying success, but has been shown to be capable of giving excellent results for detecting permeable zones in areas of shallow water table especially when surveys are conducted after prolonged or very heavy rains. The method should also yield good results along major river courses situated in Basement Complex terrain after flooding down the river has taken place.

MAGNETICS

A number of magnetic variometers are used by the Geological Survey. These include the Hilger & Watts vertical force variometer, Minimag, Askania torsion magnetometer, Jalander fluxgate magnetometers and a proton magnetometer. The value of tracing dyke contacts for the siting of boreholes in Southern Africa has long been appreciated and Maree (1943) van Eeden & Enslin (1948), and Enslin (1950) and others have described their value. An example of a magnetic and resistivity survey in Botswana resulting in the successful siting of a borehole is given in Fig. 158. This was sited following the drilling of three blank boreholes prior to the geophysical survey. However, experience has shown that the siting of boreholes along dyke contacts both in sedimentary and metamorphic formations seldom gives rise to high yielding boreholes and in fact magnetics are often used to delineate dykes rather for their avoidance than for siting on their contacts. In the Francistown area, for example, which is situated on greenstones of the Tati schist belt, a number of high yielding boreholes was sited away from the numerous dykes cutting the schists, after they had been traced by a series of magnetic traverses. Earlier siting of boreholes in proximity to dykes had given rise only to poor yielding boreholes.

In addition to the direct siting of boreholes using magnetics, this method has also been used indirectly to locate structures or changes in lithology, which in turn have been used successfully for the siting of boreholes. An example of this was the successful use of magnetics to indicate the faulted boundary, beneath Kalahari cover, between Karoo basalts and Upper Ecca shales (non-water bearing) in the northeastern

Kweneng District. Following the delineation of the fault using the magnetic method, a successful borehole (No. 1883, yield 304 l/min., F6), was sited in the basalt. This followed the drilling, by private individuals, of three blank boreholes in the thick impermeable shale south of the fault.

A similar survey was carried out in a sand covered area in the Kgatleng District where a fault separates Waterberg Supergroup sediments, forming a very poor aquifer, from Stormberg lavas. After the basalt boundary had been outlined by magnetics a successful borehole was sited in the lavas.

Use of Regional Airborne Magnetics

The regional airborne magnetic intensity map of the area north of the Molopo River, was used on a number of occasions to help elucidate the structure of the Transvaal Supergroup lying beneath a thick cover of Kalahari Beds.

A number of magnetic markers, such as the banded ironstone at the top of the Dolomite Formation and the Ongeluk lavas, were used, together with data from existing holes drilled in the area, to help site further boreholes in the more favourable water bearers of the Transvaal Supergroup. By doing this the poorer aquifers, which are concealed by up to 130 metres of Kalahari Beds, can be avoided.

ELECTROMAGNETIC METHODS

Electromagnetic methods are based on the principle that a signal from a transmitter, which is picked up by a receiver, is considered in phase with the transmitter. When a conducting body is present, a shift in phase of frequency may be detected at the receiving station. Common frequencies used are from 150 - 5 000 Herzian. The depth of penetration of an electromagnetic instrument depends on the frequency used and the conductivity of the overburden. Electromagnetic methods have been fairly widely used in Botswana in the search for ground water and have met with mixed success. The method is particularly useful for detecting secondary aquifers such as faults, shear zones, joint planes etc, which are filled with slightly mineralised ground water and hence form good conductors.

Two main methods have been used. These are a conductive (grounded) technique and a variety of inductive techniques in which a signal is induced into the ground through portable loops.

Conductive (Galvanic) Electromagnetic Technique

Prior to the use of the inductive electromagnetic technique in Botswana considerable use was made of the grounded conductive technique devised by Enslin (1954) using equipment described by Bellairs (1955) and manufactured by F.G. Slack & Company. This method consists of the injection into the earth of a stable alternating current of fixed audio frequency between two widely separated earth electrodes, and the subsequent detection of narrow conducting zones, resulting in clearly defined anomalies, (in the form of current concentrations), by measuring the tangential component of the resultant horizontal electromagnetic field. Measurements are made on two concentric circles round a point centred at one electrode. Results are plotted as Ht curves with the amplitude given in decibels. Measurements were also made on straight line traverses following a method

Examples of two case histories using the conductive electromagnetic technique:

1. <u>The Successful Use of the Conductive EM Technique - Lobatse Abattoir</u>:

   Figure 165 shows a plan of four electromagnetic set-ups (1 to 4) used to trace the major fault in the vicinity of the Abattoir. The conductor axis is shown as a solid line running in a north-south direction past the centre points of set-ups 1 and 2 and towards set-up 3. A second conductor runs from set-up 1 to set-up 4. Figure 166 shows the field data. Boreholes drilled subsequently on sites 1, 2 and 3 (Boreholes A.12, A.8 and A.7 respectively) all gave yields in excess of 38 litres per minute.

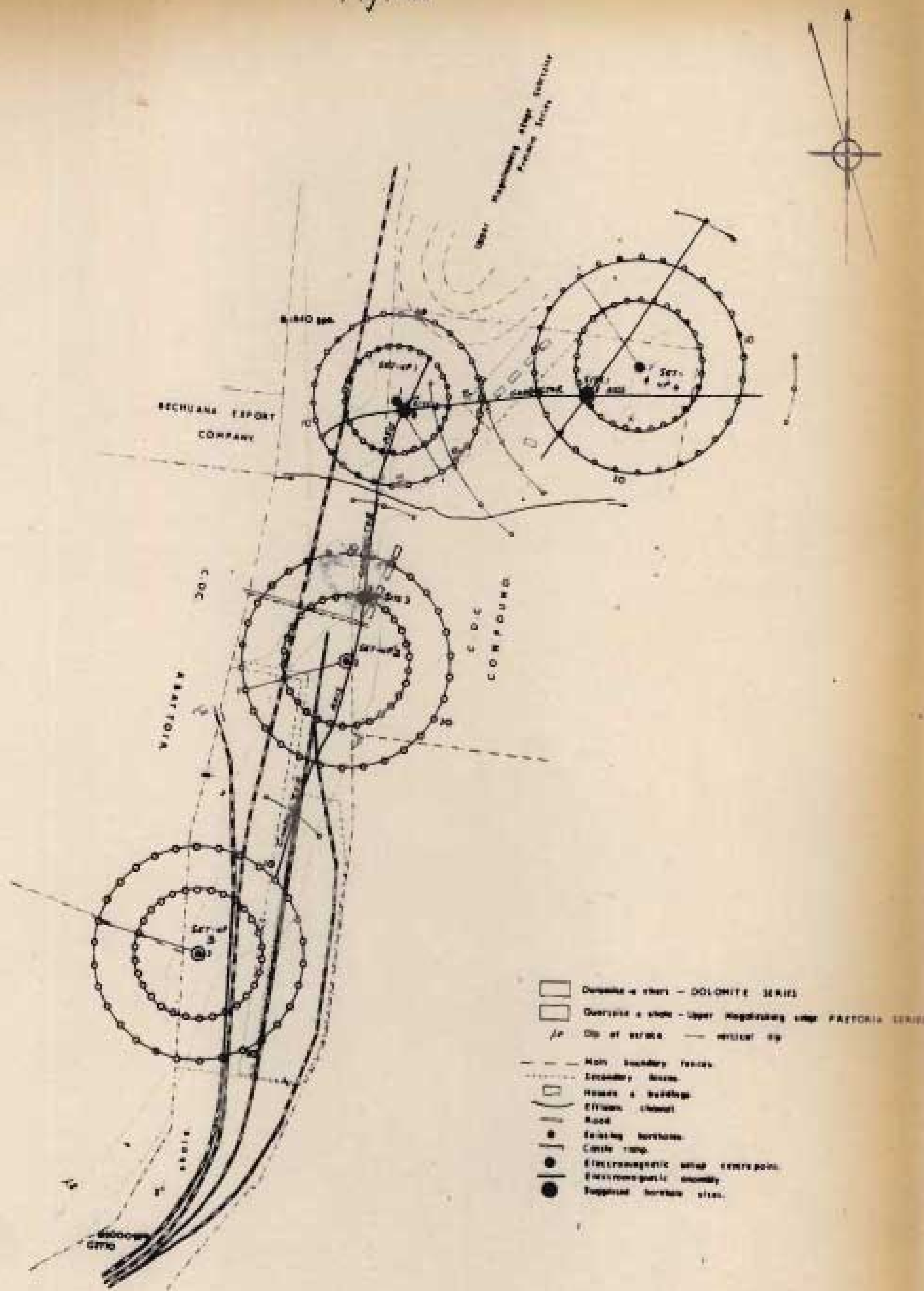
2. <u>An Unsuccessful Survey using the Conductive EM Technique</u>:

   The Lobatse Estates Western Reserve farm immediately southeast of Lobatse is largely underlain by unweathered and unjointed black, purple and grey quartz-feldspar porphyries (Ventersdorp Supergroup) in which numerous blank water boreholes have been drilled. A study of aerial photographs indicated a prominent linear feature several kilometres in length characterised by numerous shrubs and trees in an otherwise treeless area. An electromagnetic survey over the "tree line" (aar) gave a pronounced anomaly centred on the middle of the "tree line". Drilling on this anomaly encountered approximately 6 metres of soil and highly weathered diabase underlain by unweathered diabase which yielded no water whatsoever. A

Fig.
ELECTROMAGNETIC SURVEY
C.D.C. Abattoir, Lobatsi

P. 596

Fig. 165



p. 597

Fig. 166

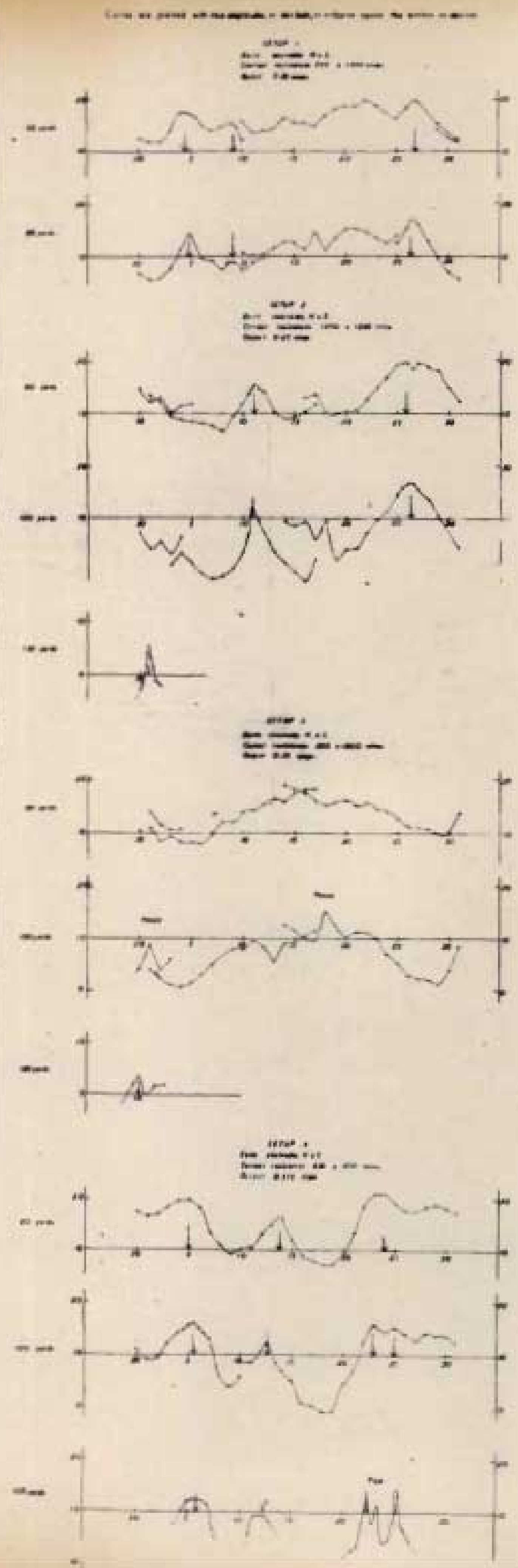
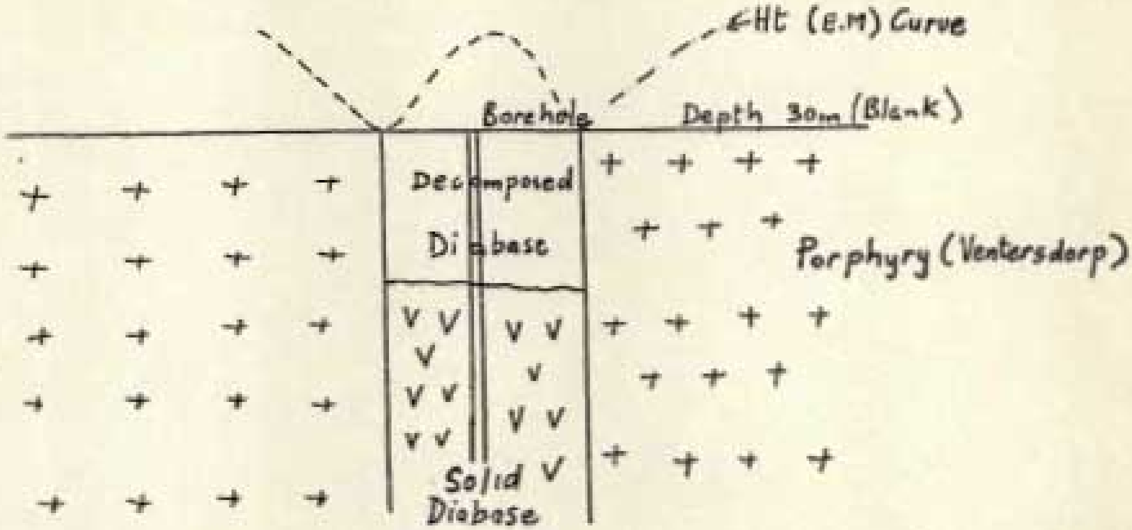


Fig. 167.

Schematic Section and E.M. Profile



In the above case, the damp soil and conductive decomposed diabase dyke proved far more conductive than the adjoining massive porphyries which have practically no overlying soil. As a result the excellent electromagnetic anomaly was caused not by ground water, but by a conductive soil/decomposed diabase zone within the highly resistive surrounding porphyries.

In retrospect a borehole sited on the margins of the dyke on the sheared and jointed wall rocks might have proved more successful than the borehole drilled in the centre of the dyke.

An Unusual Use of the Electromagnetic Method to Determine the Lateral Extent of Fresh Ground Water in a Saline Environment

An unusual application of a possible valuable method for outlining areas of fresh ground water in a saline environment, was discovered accidentally. It was found that the horizontal loop electromagnetic method (being used for a mineral survey), clearly showed that the immediate neighbourhood of the ephomeral Lake (Nghabe) River (forming the high flood overflow of the Thamalakane-Boteti River System (C.4)), was underlain by fresh ground water in a saline environment.

Geology of Area

Test drilling has revealed that the area is underlain by Kalahari Beds consisting of sand, marl and calcareous sandstone which is 43 m thick. This is underlain by 26 m of pink basalt (Karoo Supergroup) underlain by 1 m of agglomerate and this in turn is underlain by more than 168 m of highly epidotised mafic to intermediate lavas (Nosib Formation).

Method used

A variety of methods, including gravity, magnetics, horizontal loop (Huntematic) and vertical loop electromagnetic methods (McPhar REM), were used during a mineral survey in an attempt to outline some copper mineralisation discovered when a borehole was put down to test a gravity anomaly.

The results of both electromagnetic surveys, and in particular that of the horizontal loop, showed that in the vicinity of the Lake River, there was a marked decrease in ground conductivity due to the presence of fresh water when compared with the surrounding highly conductive area which contained saline ground water. This showed up as a marked positive intensity response both for the "in-phase" and "in quadrature" components (Figs.168,169).This area of high positive response thus corresponds to a zone of fresh water, which is regularly recharged by the annual flow

FIG. 168

KGANTSHANG - ELECTROMAGNETIC SURVEY

HORIZONTAL LOOPS: "IN-QUADRATURE" RESPONSE INTENSITY

Frequency: 1000 Hz. Coil separation: 500ft. Station interval 200ft.

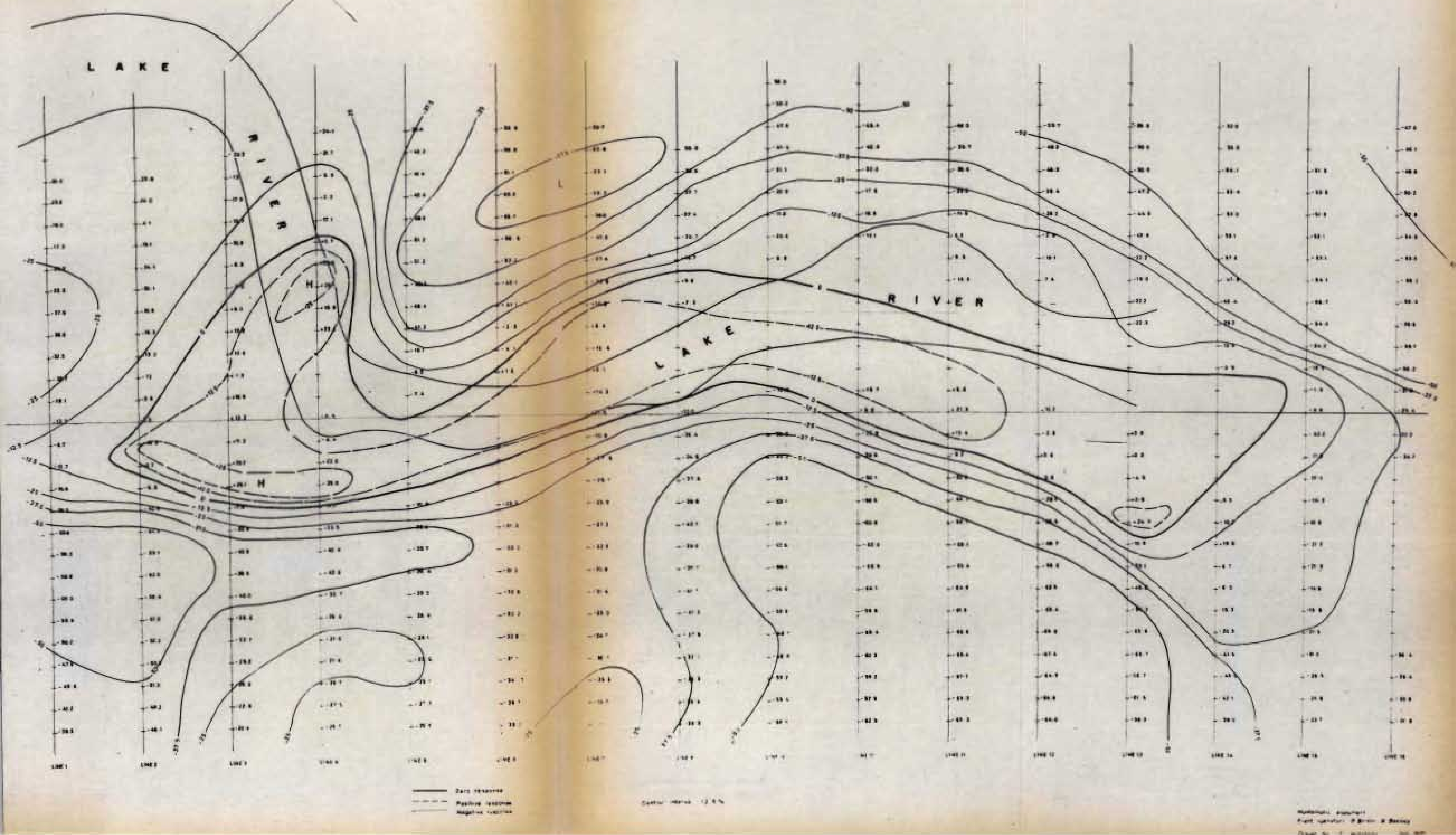
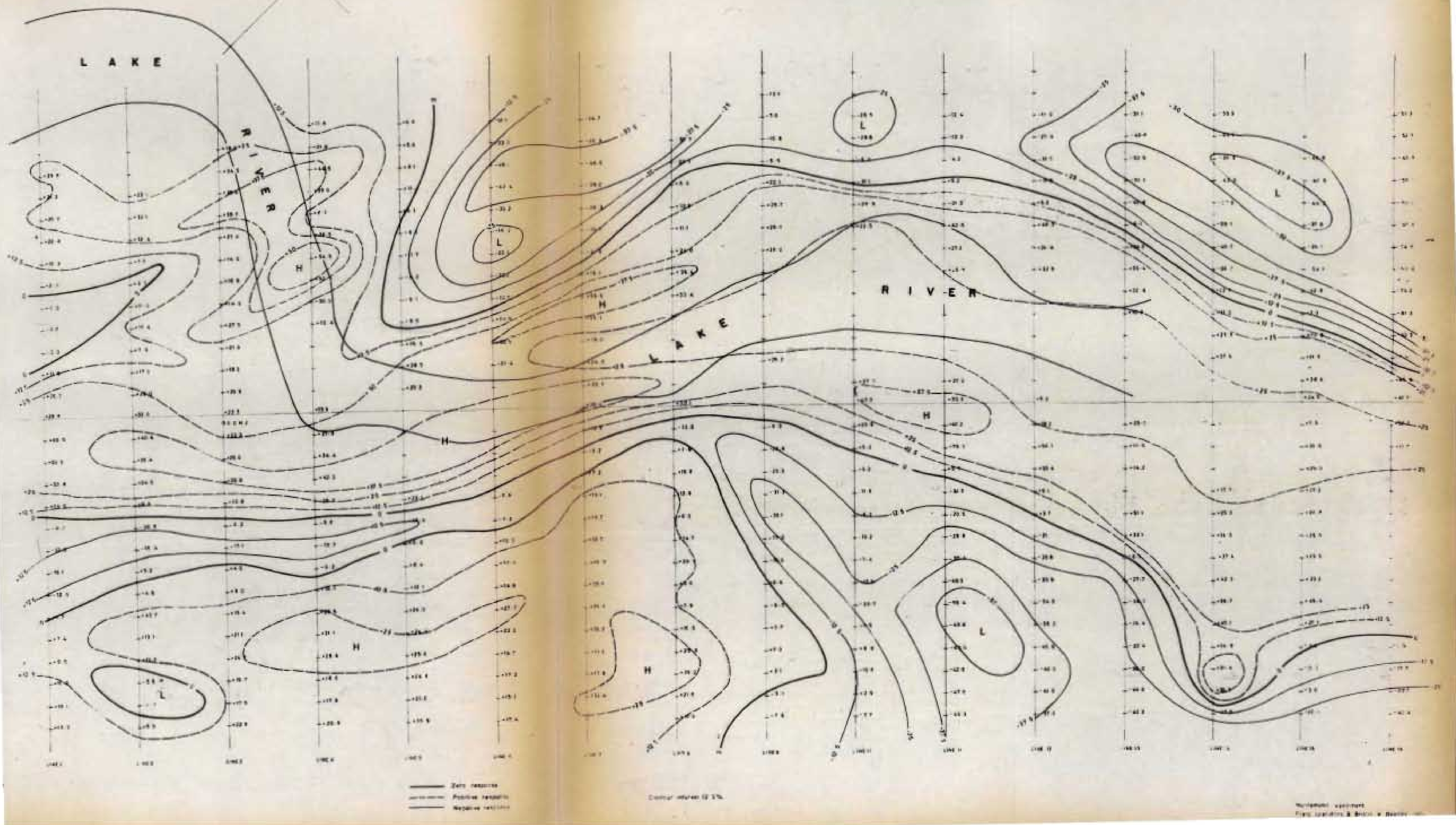


FIG. 169

KGANTSHANG - ELECTROMAGNETIC SURVEY

HORIZONTAL LOOPS: "IN- PHASE" RESPOSE INTENSITY

Frequency 1000 Hz. Coil separation: 500' Station interval 200'



down the Lake River. The fact that this zone does not extend more than 365 m on either side of the present river course (which was in full flood at the time of the survey), indicates that fresh waters have very little lateral extent, and hence, permeabilities of the Kalahari Beds aquifer are likely to be low. Saline supplies can be expected further away from the river.

The use of Airborne Electromagnetic Surveys for Ground Water Detection

Airborne electromagnetic surveys have long been known to detect innumerable anomalies, a large number of which are caused by conductive water-filled shears, faults or jointed zones. Very little use has been made of this valuable aid to the location of secondary aquifers in Southern Africa, largely because of the confidential nature of the airborne surveys, which are invariably carried out by mining companies as part of their mineral exploration programme. In Botswana however, all this information is passed on to the Geological Survey and this data has been used by the writer on two occasions as an aid to the location of ground water with excellent results - once near Orapa and once near Pikwe on the Letlhakane fault (D.8).

Letlhakane Fault

During the course of an airborne electromagnetic mineral survey, using the Barringer INPUT system, a number of prominent six channel anomalies, with first to fifth channel ratios exceeding 60 : 12, were detected over a zone several kilometres long, and coinciding with a major fault along which the ephemeral Letlhakane has aligned itself.

Integrated ground geophysical follow-up surveys were undertaken and seven boreholes were drilled in the areas outlined by the airborne survey with the following results:

Bh	2210	Yield	274 l/min
	2213		228 l/min
	2216		137 l/min
	2230		342 l/min
	2397		304 l/min
	2401		380 l/min
	2403		760 l/min

Prior to this only blank or low yielding (less than 46 l/min) boreholes had been drilled in the area. (See Fig. 170).

Detailed pump tests on borehole 2403 gave a transmissivity of 27 780 gal/day/metre (126 m^2/day) and a coefficient of storage of 0,00003074 (Robins, 1971).

Orapa

A similar airborne electromagnetic mineral survey, also using the INPUT system, detected a number of major electromagnetic anomalies of considerable strike length running along the dry Letlhakane River valley, southeast of Orapa (D.6). Ground follow-up work using an Afmag electromagnetic unit and self-potential resulted in two boreholes being drilled through the Stormberg lavas and Cave Sandstone (Karoo Supergroup) which yielded 380 and 532 litres per minute. These yields are 200-400 per cent higher than the average for this area. (Fig. 163).

AFMAG

The Afmag instrument is an ingenious instrument which utilises naturally-occurring electromagnetic fields caused mainly by distant thunderstorm activity. In the instrument used

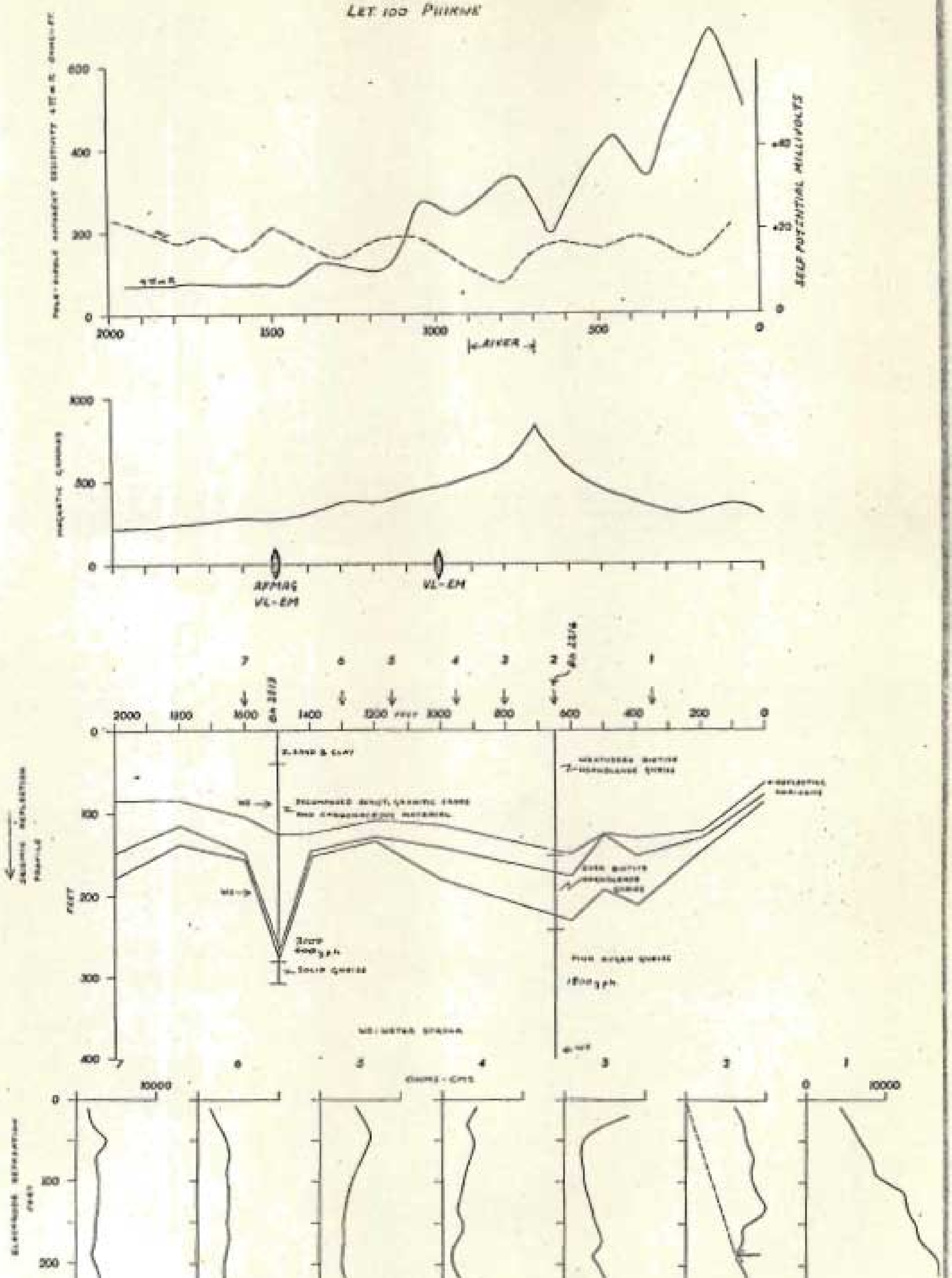


Fig. 176

in Botswana (McPhar), a frequency (510 Hz) was used during the surveys and was selected so that minimum interference from man-made electrical noise would occur. In addition the azimuth of the earth's horizontal field can also be read and plotted on a vector diagram. This method appears to be particularly useful in detecting linear, secondary conductive aquifers and it is rather surprising that more use has not been made of this method in the search for ground water in Southern Africa. The VLF (very low frequency) electromagnetic system should theoretically also prove useful in ground water surveys. The writer has not had personal experience of the VLF system for ground water surveys, but mineral surveys carried out by the writer using the system have shown that two transmitting stations-Cutler (Maine), and North West Cape, give sufficiently strong signals in Southern Africa to obtain useful results.

Examples of the Use of Afmag

Afmag was successfully used to pick up a conductive fault zone running along the Letlhakane valley east of the Orapa diamond field in the Central District. Dip angles (high frequency) of up to 13 degrees were obtained when a reconnaissance Afmag traverse was carried out at 200 foot station intervals. The fault zone was later pinpointed more accurately by a traverse at 25 foot intervals and a self-potential traverse (See Fig.163).

A similar traverse, a few kilometres further south, gave a small Afmag crossover and a clearly defined self-potential anomaly on which another high yielding borehole was drilled.

These two boreholes (2199 and 2206) constitute the Orapa wellfield number three, which is at present one of the mainstays of the mine water supply.

SEISMIC METHODS

Introduction

In the seismic method an elastic pulse is generated at or near the ground surface and the resultant motion of the ground at nearby points on the surface is detected by geophones. Measurement of the time intervals between the generation of the pulse and its reception at various distances gives the velocity of propogation of the pulse in the ground. The ground is generally not homogeneous in it's elastic properties and velocities may vary both with depth and laterally. Thus,in areas with a relatively simple structure,the values of elastic wave velocity and the positions of boundaries between regions of differing velocity can be calculated from the measured time intervals. These velocity boundaries usually coincide with geological boundaries and a cross-section,on which velocity interfaces are plotted,may resemble the geological cross-section. Two main seismic methods are used in ground-water surveys: the refraction and reflection methods.

A. Refraction Method

In the seismic refraction method, the travel time of shock waves, generated by a hammer blow or an explosion, to a number of detectors (geophones) is recorded and the first-arrival time T is plotted against the shot-detector distance X for different separations of source distance graphs to calculate the thickness of the various horizons through which refraction has taken place. In addition to simple depth determinations to different refracting horizons, continuous profiles may also be drawn up and are often extremely useful for ground-water surveys. The methods for calculating profiles have been described by Pakiser and Black (1957), Hagedoorn (1959), Hawkins (1961), and the Hunting F.S.3 Manual. In certain areas with water table aquifers, the depth to water can be determined as the saturated layer is characterised by a slightly greater velocity than the unsaturated overlying formation. Under favourable conditions, an estimate of the porosity of the aquifer may be found from the relation between seismic velocity, depth of burial and porosity as discussed by Levshin (1961). Consequently, knowing the extent and thickness of the aquifer, it's storage capacity can be calculated.

B. Reflection Method

In field operation the main difference between the refraction and reflection methods is in the lay-out of the detectors with respect to the shot point. In reflection work, the distances between shot points and detectors are normally a fraction of the depth of the reflecting horizons and, unlike the refraction method, later events than the "first arrivals" on the records are used.

..../Instrumentation

Instrumentation

Originally a commercially manufactured seismic instrument the F.S.-2 (made by Huntec Limited of Toronto, Canada) was used for shallow refraction work. This is a shallow, single channel, facsimile percussion seismic instrument which is a refinement of the instrument first described by Gough (1952). This instrument was subsequently modified (the Huntec F.S.-3) for use in shallow reflection surveys. The reflected events are separated from refractions, surface waves, and other superimposed wave types at short record times, by means of a correlator which discriminates against waves which are phase shifted at two geophones by more than an arbitrarily set amount. This has been described in detail by Meidav (1968).

Practical Applications of the Seismic Method

Depth of Penetration of Refraction Surveys

Under favourable conditions, refracting horizons up to a depth of 30 m can easily be detected, using a steel plate and a 12 to 14 pound hammer as energy source. For greater depth penetrations the use of detonators or explosives was successfully used to detect refracting horizons at depths of 50 to 60 m. An example of a deep refraction sounding is given in Fig. 171. An example of a seismic reflection profile is given in Fig.170. (See also Plate 71).

Advantages and Disadvantages of the Seismic Method

The operation and interpretation of a seismic instrument is more complex and hence more expensive than the electrical resistivity method. It can nevertheless be extremely useful in interpreting data where resistivities of different

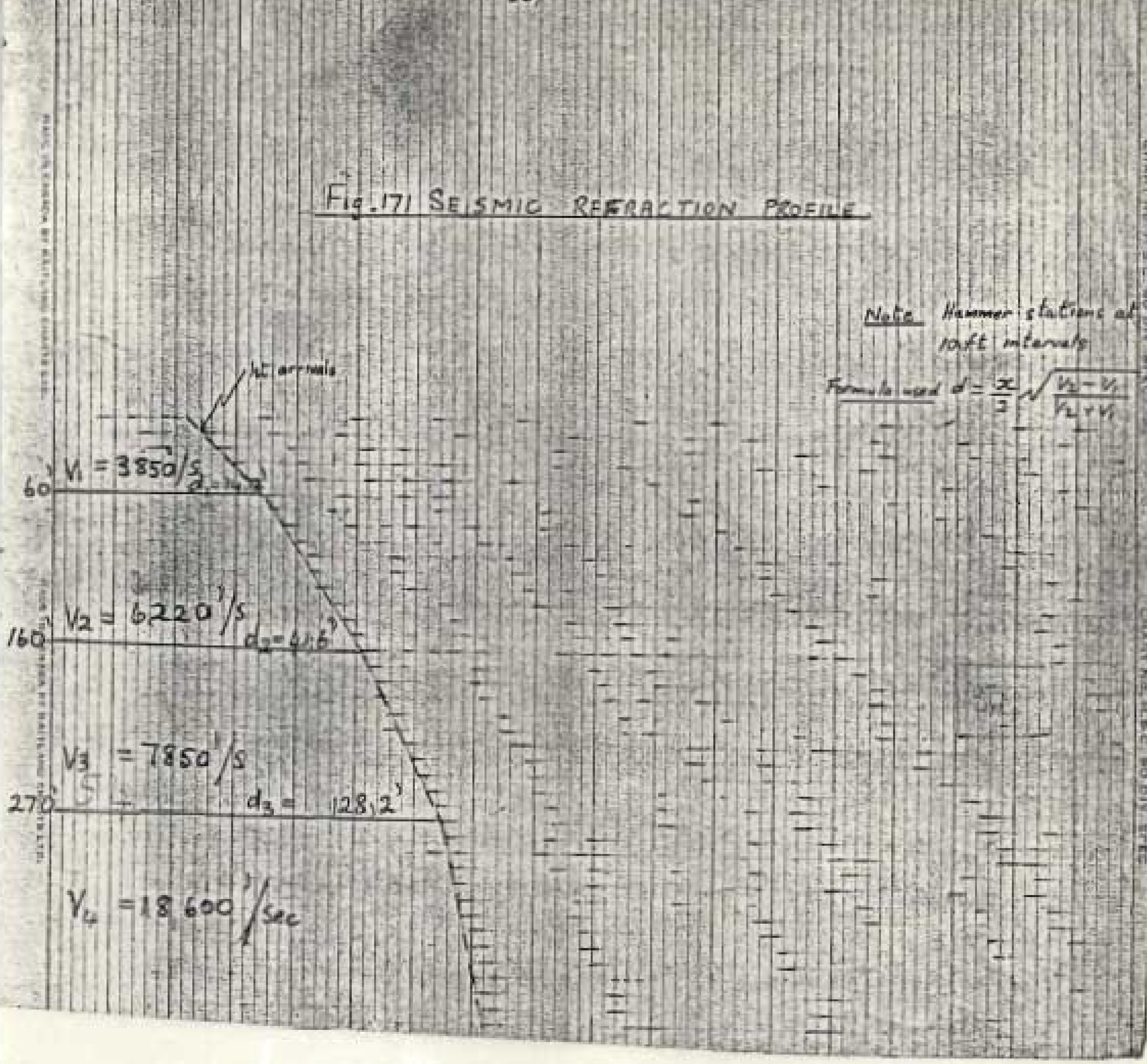


Fig. 171 SEISMIC REFRACTION PROFILE

lithological types are close to each other or where a highly conductive overburden tends to mask the depth to bedrock in the resistivity method. This often occurs when conductive soils overlie solid basalt yet electrical resistivity soundings show apparent low resistivity material as being present to considerable depths. This results in misinterpretation of the resistivity depth probe.

INTEGRATED GEOPHYSICAL SURVEYS

A variety of geophysical techniques may often be used to give complementary data required for the siting of water boreholes. An example of such an integrated survey is given in Fig.170. Detailed resistivity constant separation traverse profiles using a pole-dipole array with an induced polarisation instrument, electrical resistivity depth probes, self-potential, reconnaissance and vertical loop electromagnetic techniques, Afmag and seismic reflection profiles were carried out over a known fault zone where a large airborne electromagnetic (INPUT) anomaly had been detected. The two boreholes drilled subsequently, (2213 and 2216), gave yields of 228 and 137 litres per minute which is at least 300 per cent higher than the average for the area.

Another example of an integrated geophysical survey was described earlier in the section on Afmag (See Fig.163).

SUBSURFACE GEOPHYSICAL METHODS

The main subsurface method used in Botswana is the electrical resistivity method (formation resistivity). This enables the depths to different lithological horizons to be accurately determined (See Fig. 87), and is particularly useful for delineating zones for the insertion of well screens or perforated casing, and for making correlations from borehole to borehole. Other methods used occasionally are self-potential (Fig.83), fluid resistivity and temperature logging (Fig.89). The use of fluid resistivity logs has proved extremely useful in indicating the depths of entry of water into boreholes.

THE USE OF ENVIRONMENTAL ISOTOPES IN BOTSWANA

Introduction

The provision of adequate water supplies for the rapidly growing population in Botswana, which by the turn of the century will probably require three or four times the amount of water used at present, forms one of Botswana's most pressing problems. In common with most other developing countries, Botswana has been faced with a serious lack of adequate hydrological and hydrogeological records ,caused mainly by a lack of funds to enable these records to be built up. In addition, as available surface water resources become fully utilised, a growing need has arisen for refined quantitative answers concerning the country's ground-water resources. During the past fifteen years, a considerable amount of research has taken place elsewhere in the world using a variety of novel methods involving the use of isotopes in the hydrogeological field. These have proved conclusively, despite Carlston's (1964) cautiously pessimistic warnings, that the use of isotopes can considerably aid in the solution of hydrogeological problems which could often otherwise only be solved by extremely long and costly research programmes using conventional methods.

In Botswana, where the majority of the country's human and cattle populations are dependent on ground water, it is essential to know whether the ground-water resources are being replenished or whether the waters are "fossil". If they are fossil, it then becomes vitally important to know the size of the underground reservoir (i.e. its storage capacity) and hence, knowing the rate of abstraction, predictions can be made as to how long the supply will last whilst it is being "mined" as a non-replenishable natural resource. In addition, important data can be obtained on storage capacity of the reservoir, flow rate (under ideal circumstances),the transit time within the reservoir and the storage capacity of the ground water reservoir.

RADIOACTIVITY

Isotopes

Isotopes of an element are atoms or nuclides having the same number of protons in the nucleus (and thus the same atomic number), but differing in the number of neutrons and hence in their atomic mass, from other atoms of the same element. Whenever a nucleus of an isotopic species is unstable, it undergoes a nuclear transformation leading to a stable state in the form of a different element or isotope. This change is accompanied by emission or radiation of nuclear particles and/or protons of energy known as radioactivity. The three principal kinds of radiation are alpha, beta or gamma whose energy is measured in electron volts (eV; 1 keV = 10^3eV). The above are often referred to as radioisotopes in contrast to stable nuclides or stable isotopes which give off no radioactive emissions.

Law of radioactive decay

The process of radioactive decay is normally spontaneous and cannot be altered by external influences. This decay obeys an exponential law and is unique for each radioisotope and is described by the half-life ($T_{\frac{1}{2}}$) which is the time required for one half of the radioactive atoms to decay.

The "decay law" is expressed as follows:-
$N = No^{e^{-\lambda t}}$ (1) where N is the number of radioactive atoms present at time t, No the number of radioactive atoms present at the beginning, and λ the decay constant.

It follows from (1) above that the time required for one half of the original activity to decay is independent of the number of atoms at the beginning. As this time was defined as the half-life ($T\frac{1}{2}$) we obtain, by inserting in equation (1) the following:-

$$1\ No = No\ e^{-\lambda T\frac{1}{2}} \quad (2)$$

$$\lambda T\tfrac{1}{2} = \ell n2$$

$$\therefore \qquad = 0{,}693 \quad (3)$$

The decay law is the basic relationship on which radioactive dating is based.

Environmental Isotopes

Environmental isotopes are those whose natural abundance variations may be used for hydrological studies. The four main environmental isotopes used in ground-water studies are the two heavy stable isotopes of hydrogen and oxygen in water molecules (deuterium = ^{2}H = D and oxygen - 18 (^{18}O) and the cosmic-ray produced radioactive isotopes tritium (^{3}H or T) and carbon - 14 (^{14}C). Included in this group are also man-made radioisotopes, T and ^{14}C, which are produced by thermonuclear testing in the atmosphere and become distributed by natural processes in the environment and are transported with water through the complete hydrological cycle. Although these latter isotopes can be artificially produced, the research scientist has little or no control over their production and mode of release to the environment. These environmental isotopes because of their widespread regional distribution, often have marked advantages over locally injected artificial radioactive tracers or sealed radioactive sources.

The low energy tritium beta-radiation is detected at the Nuclear Physics Research Unit laboratory of the Witwatersrand University in low level gas proportional counting systems which can detect concentrations as low as 3TU. By enriching the tritium content of water twelvefold in a bank of electrolysis cells, the overall sensitivity of detection can be raised to about 0,2 TU.

History of use of isotopes in Botswana

Following a letter by the writer to the Nuclear Physics Research Unit of the Witwatersrand University on 14th July 1965, it was agreed by the Director of the Unit (Professor J. P. F. Sellschop) to carry out a joint research programme in Botswana. Research work of a purely exploratory kind was commenced with the first collection of samples in June 1966. On 15th December 1968, a research contract for the continuation of this work on a more comprehensive scale was granted by the International Atomic Energy Agency. This research project is entitled "A study of the effectiveness and application of environmental tritium as a ground-water tracer in a semi-arid region in Botswana". Chief scientific investigators in the project are J. P. F. Sellschop, B. Th. Verhagen and the writer. The writer gratefully acknowledges the help given by both Prof. J. P. F. Sellschop and Dr. B. Th. Verhagen of Witwatersrand University in this particular project.

This project forms a pioneering project on research using environmental isotopes in ground-water studies in Southern Africa and probably represents one of the most detailed studies of its kind undertaken. Its principal aim is to evaluate, as accurately as possible, the limits of applicability of this technique in Southern Africa. It was, furthermore, hoped that the techniques involved would be able to be applied elsewhere in areas where little long-term geohydrological data had been accumulated. This could be vitally important in other semi-arid and developing countries where funds are seldom available to conduct long-term ground-water research.

At the same time as making an approach to the Nuclear Physics Research Unit at Witwatersrand University to carry out tritium measurements, the writer contacted Professor J. C. Vogel, head of the Natuurkundig Laboratorium of the Rijks-Universiteit in Groningen (Netherlands), with a view to carrying out a research programme in Botswana using ^{14}C. As a result, it was agreed by Dr. Vogel in a letter dated 3rd April 1965, to carry out a joint project in which approximately 15 samples per year would be analysed. Dr. Vogel remains as head of the Natuurkundig Laboratorium, but in addition is now head of the Natural Isotopes Division at the Council for Scientific and Industrial Research in Pretoria.

History of Use of Tritium in Geohydrological Studies

Following the discovery of the existence of tritium by Grosse et al (1951), it was soon realised that it could be used as an extremely useful tool in surface and ground water hydrological studies and even in meteorology. Pioneering investigations were carried out by Libby (1946, 1953), Kaufmann and Libby (1954), Brown and Grummit (1956), Begemann and Libby (1957), Eriksson (1958), von Buttlar and Wendt (1958) and Giletti et al (1959). These early studies were followed by a spate of investigations by Carlston et al (1960), Libby (1961), Brown (1961), Kaufmann and Todd (1962), Payne and Dincer (1965), Gat (1965), Thatcher and Payne (1965), Stewart (1965), Verhagen and Sellschop (1965), Davis et al (1966), Haskell et al (1966), and many others.

In Southern Africa pioneering work was carried out by Verhagen and Sellschop (1966), Verhagen, Sellschop and Jennings (1970, 1970a, 1974), Verhagen (1971), Jennings et al (1974), Mazor et al (1974, 1974a), while Wurzel and Ward (1969) carried out pioneering work in Rhodesia in the Sabi Valley.

Properties and Occurrence of Tritium

Tritium (H^3) is the only known naturally occurring radioactive isotope of hydrogen and has an atomic mass number of three. It disintegrates into helium -3 giving off an extremely low energy beta particle, which possesses an average energy of 5,9 KeV and a maximum energy of 18 KeV. The half-life of tritium is 12,262 $\pm$ 0,004 years and its mean life is 18 years.

Tritium occurs in relatively large amounts due to the comparatively high cross-section for its production by the nuclear interaction of cosmic ray produced neutrons with atmospheric nitrogen. $_7N^{14} + {}_0n^1 \longrightarrow {}_1H^3 + {}_6C^{12}$ at the rate of 0,14 atoms/cm^2 /sec. Tritium is also produced by thermonuclear explosions, where the rise in tritium level is proportional to the total energy release. Tritium is also produced during the operation of atomic piles.

The average production from natural sources (i.e. thermonuclear tests - 1952), is uncertain because of the lack of measurements. Libby (1954) obtained a figure of about 3,3TU for average natural world-wide content of land rainfall. Craig and Lal (1961) calculated the figure to be double that of Libby (i.e. 7TU). This latter higher figure is probably for inland areas where "scavenging" of extra tritium from atmospheric moisture takes place.

Tritium decays at such a rate that within 30-50 years rainwater containing 5-10 TU initially would be effectively dead. Where the time scale involved is longer than 50 years other isotopes - ^{14}C ($T\frac{1}{2}$ = 5 700 years) and ^{32}Si ($T\frac{1}{2}$ = 600 years) have to be used. These are present in dissolved bicarbonates and silicates present in ground water respectively.

The measurement of tritium in nature requires the determination of very low concentrations which are measured in tritium units (TU), where $1TU = \frac{T}{H} \times 10^{-18}$ (i.e. ITU = 1 tritium atom per 10^{18} hydrogen atoms).

Since the commencement of the thermonuclear era in 1952, tritium levels have increased by several orders of magnitude with the highest recorded level of 10 000 TU being recorded in Yukon in April 1963. Latitude trends in the distribution of tritium have been noted for both hemispheres with the quantity increasing towards the poles. Tritium concentrations are much higher in the northern hemisphere because of the majority of weapons tests have been conducted north of the equator. A seasonal variation with maxima in late spring and summer also occurs. At present the tritium content of rainfall in the southern hemisphere is 10 - 100 Tu with ground water having considerably lesser amounts.

Because it forms an integral part of the water molecule, tritium holds a number of advantages over organic and inorganic chemicals as a tracer in water. These include the fact that it moves with the same velocity and in the same direction as the water body it labels; it is unaffected by ion exchange of tritium or by precipitation, and it suffers no absorptive losses. Furthermore, its weakly radioactive nature does not result in any health hazard. In addition, the higher periodic concentrations resulting from thermonuclear tests should theoretically result in periodic pulses being injected into ground-water bodies, and hence, should form a valuable tool to determine the rates of ground-water storage and even the storage capacity. Major drawbacks of tritium as a tracer are its relatively short time range (after 50 years only about 7% of tritium remains) and the fact that it is non-detectable in the field because of its weak beta radiation. Even the high levels of activity found in northern hemisphere rains are too low to be measured directly and the heavy isotopes can only be measured in a gas proportional chamber after enrichment by electrolysis. Where samples contain relatively high specific activities, they can be measured directly by liquid scintillation counting.

Tritium Measurement

All tritium measurements were carried out by the Nuclear Physics Research Unit (N.P.R.U.) of the University of the Witwatersrand on either a semi-commercial basis or as part of a joint research project between the

N.P.R.U. and the Geological Survey of Botswana and partly supported financially by the International Atomic Energy Agency in Vienna (I.A.E.A.).

The tritium laboratory at the Nuclear Physics Research Unit has been in operation for a number of years. During this period, techniques for the sensitive and accurate detection of tritium have been developed.

Facilities at the N.P.R.U. include shielded low background counting rooms in the basement of the building. These rooms have three foot thick concrete walls and are fully enclosed in a copper mesh Faraday cage. Special provision was made during the construction of the building for the 10 metre high enrichment column.

Thermal Diffusion Isotope Enrichment System

For low activity waters such as are commonly encountered in Botswana, a thermal diffusion system for the enrichment of tritium was originally used. This system has been described by Verhagen and Sellschop (1964). Enrichments of 6 times can be carried out in 4,5 hours with a yield of 10 litres S.T.P. hydrogen or of 68 times in 8 hours with a final yield of 1 litre S.T.P. hydrogen.

At 6 times enrichment, the minimum measurable and minimum detectable concentrations are reduced to 1,5 and 0,3 T.U. respectively. Two samples per day can be handled in this mode.

The enrichment plant consists of a concentric tube column 7,2 metres in length, a hot wire column 2,75 metres long, two self-regulating magnesium reduction vessels, a furnace with regulator for reduction vessels, and has a handling console, with metal vacuum line, pump and sampling vessels and an electrical control console for the columns. This whole system was developed and constructed at the N.P.R.U. (Verhagen and Sellschop, (1963, 1964, 1965, 1965a); Verhagen, (1964, 1967).

Electrolytic Enrichment

To cope with the increasing volume of samples that justify enrichment, it was decided to supplement the thermal diffusion system by the instalment of an electrolytic enrichment plant. All samples are now routinely enriched electrolytically and direct counting only resorted to when sample volume adequate for enrichment is not available.

Method of Measurement in the N.P.R.U. Laboratory

All samples are first quantitatively distilled under vacuum. They are then enriched by electrolysis by a factor of 11 - 12 times with an accuracy of 7%. The resulting electrolyte is then again vacuum distilled and the enriched water sample is reduced to hydrogen by reaction with magnesium turnings at 600°C. The hydrogen is quantitatively reacted to ethane by the catalytic saturation of ethylene. The ethane is purified by vacuum distillation and counted in one of a number of proportional counters with a nominal background of 2 counts/min and sensitivity of 35 TU per counts/min. The overall sensitivity of the enrichment-detection system is $0,2 \pm 0,2$ TU and the maximum overall contamination level is estimated at 0,2 TU. (See Plate 72).

Two samples per day are counted in each counter. Samples are stored after counting and were usually re-counted. After processing many hundreds of samples, it was found that the reproducibility of the results was sufficiently good to dispense with the second count. Present practice is to retain the gas sample until the tritium concentration has been calculated. Only when some doubt exists as to the validity of the results is the sample re-counted. Working backgrounds are run twice per week. New background ethane is produced from time to time from water with a tritium concentration less than 0,5 TU.

Method of Sampling

All borehole water samples for tritium analysis were taken either by a specially designed water sampler manufactured in the workshop of the Nuclear Physics

Pl.72 Tritium Laboratory - Nuclear Physics Research Unit. Photo - Dr. B. Th. Verhagen.

Pl.73 Small diameter sampler for point sampling in boreholes. Photo - Prof. J.P.F.Sellschop.

Research Unit of the Witwatersrand University (See Plate 73) or by pumping directly from the borehole into watertight polythene containers.

The "Spot" samplers are a design improvement of a commercially made sampler manufactured by Hydro Products of California. The sampler is so designed that it can be lowered by cable, in a cocked position with the valves (rubber balls) in an open position to allow flow of water through the sampler to the desired sampling depth. The trigger pin can be released at any depth by sending a weighted "messenger" down the braided nylon cable to depress the pin and seal the tube mechanism. Two different diameter samplers have been designed - one for normal six inch boreholes and the other for narrow diameter diamond core boreholes (less than 2½ inches) drilled for research purposes. These samplers thus cause a minimum disturbance of water in the borehole column. Proof of this is afforded by good repeatability of results following repeated sampling of boreholes which have known chemical and age (tritium) stratification.

The large sampler has a half gallon capacity (2,3ℓ) which was found to be sufficient for low activity tritium measurement and also for reasons of storage and transport. Originally, 1 gallon samples were collected.

Pl.74 H. Ramoshu about to send "messenger" down cable to release trigger pin. Photo - Prof. J.P.F. Sellschop.

Pl.75 Pump Test on Bh. 1463 - Lobatse Estates N. Basin.

The sampler has been successfully used down to depths of 150m. It is lowered by a portable winch with a drum, calibrated in feet, measured by revolution counters.

Rain samples are collected in standard rain gauges. In Lobatse,rainfall is collected in two gauges to give a larger sample volume.

All bottles are carefully "topped up" to over-flowing point, and then screwed tightly shut to prevent leakage or the ingress of moisture laden air which could possibly cause isotopic exchange with the lower activity ground water. Research was also conducted using a variety of light and heavy quality polythene and glass containers to determine whether exchange took place through the walls of the containers. Water used for the experiment was from the very low activity water in borehole 1379 from Lobtase Estates. This research was carried out as it had been found that appreciable exchange took place through the walls of polythene containers in the northern hemisphere where atmospheric tritium levels were of the order of ten times higher than in southern Africa. Results of measurements taken some months after collection of the samples are given in Table 76.

TABLE 76

Lab.No.	Locality	TU
B.35	Bh 1379 Lobatse Estates Unbaked glass	0,6+0,31+0,5+0,3
B.37	Bh 1379 Lobatse Estates L.D. Polythene	0,4±0,3 0,5±0,3
B.38	Bh 1379 Lobatse Estates H.D. Polythene	0,5±0,3 0,2±0,2

As can be seen from the above, no exchange of tritium from the higher levels of tritium in the air moisture (30-70 TU) appears to have taken place through the walls of any of the containers and it was therefore concluded that unbreakable polythene containers could be used without giving erroneous results.

Programme of Sampling

Following the award of the research grant by I.A.E.A., systematic sampling was commenced in December 1968 in the two areas, viz. Lobatse and Serowe, selected for the detailed studies. Sampling in the Lobatse area was carried out at selected depths in individual boreholes not equipped with pumping plant or pumping from equipped boreholes initially at monthly intervals. More recently sampling was reduced to bi-monthly intervals. Systematic sampling at Serowe was also carried out at bi-monthly intervals.

In the Orapa area occasional samples were collected as early as 1968, but following the award of a research grant in February 1970 by de Beers Industrial Diamond Division (Diamond Research Laboratory), sampling on a bi-monthly basis was extended to the Orapa area. In addition, sampling of selected boreholes and wells as well as surface waters, was extended along a line of boreholes from Serowe through to Orapa and onwards as far as the Okavango Swamp - Lake Ngami area. Selected samples for stable isotope analysis were collected from this same area.

Boreholes sampled in the Lobatse area are:- (Figs.172,173).

<u>Lobatse Western Basin</u>

61(65), 467, 629, 665, 917, (2136), 952, 2268, 2278, 2283, 2285.

A.2, A.3, A.4, A.5, A.6, A.7, A.10, P.212.

<u>Lobatse Eastern Basin</u>

X.1, X.4, 2261.

<u>Railway Basin</u>

D.C. No. 1 (1368), D.C. No. 3.

Figure 172 : Lobatse township borehole numbers

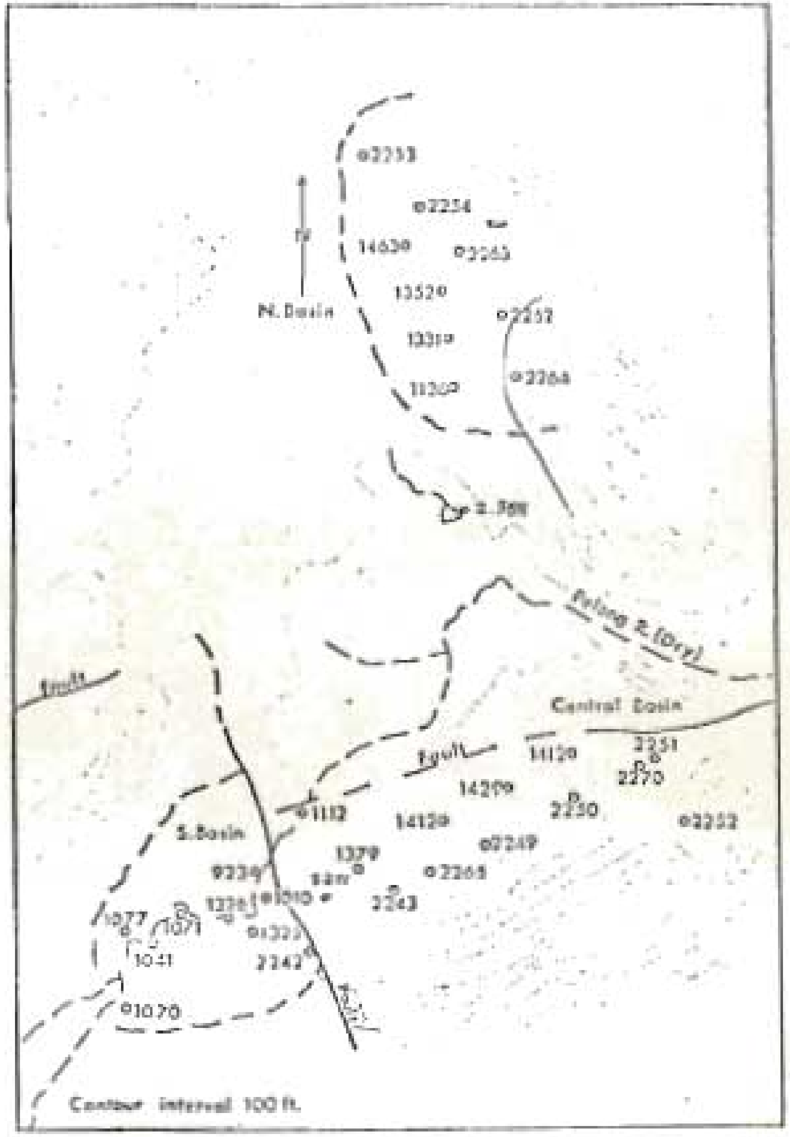


Figure 173 : Lobatse Estates borehole numbers

Lobatse Estates South Basin

923, 1010, 1041, 1071, 1077, 1325, 1326, 2242.

Lobatse Estates Central Basin

1112, 1379, 1412, 1414, 1429, 2243, 2249, 2250, 2252, 2265, 2270, 2271.

Lobatse Estates North Basin

1131, 1352, 1463, 2253, 2254, 2262, 2263, 2264.

Miscellaneous - Lobatse Estates

1400, Z.388.

Serowe (Fig. 94).

No. 1, 2(1054), 3, 489, 670, 1056, 1062 (Mokwene), 1065, 1510, 1539, 1643, 1929, 1930, Blackbeards, Botalaote S. Khama's, Newtown, Palmer's Palamaokuwe, Ratshosa, Swaneng Hill School, J. Wright's, Woodford's.

To date about 2100 samples have been delivered to the Nuclear Physics Research Unit,of which ± 1000 have been measured. The main sampling results are summarised in Tables 77-86.

TABLE 77

LOBATSE ESTATES SOUTH BASIN

Bh. No.		6/66	2/67	3/68	4/68	12/68	1/69	2/69	3/69	4/69	5/69	6/69	7/69	8/69
9231	D= 15								2.3±0.5*	3.9±0.7*	2.0±0.4*	1.6±0.3*	1.8±0.4*	2.8±0.5*
	D= 30										2.5±0.4*			
	D= 60								1.8±0.4*	1.5±0.4*	*	*	1.6±0.4*	*
	D= 90								1.9±0.4*	2.2±0.4*	2.3±0.5*	*	3.9±0.4*	1.3±0.4*
	D=120								0.8±0.3*	2.3±0.4*	2.0±0.6*		4.0±0.4*	1.8±0.3*
1010		3.5±0.5*	3.5±0.6*			2.5±0.6*	6.5±0.7*							
1041	D= 15			5.2±0.8*	6.0±0.7*			3.8±0.6*	4.1±0.7*	3.2±0.5*	5.0±0.6*	*	*	3.2±0.5*
	D= 30			5.2±0.8*	5.7±0.7*						5.9±0.6*		*	
	D= 60							3.3±0.4*	2.9±0.6*	3.9±0.5*	4.1±0.7*	*	*	*
	D=90			3.3±0.7*	4.1±0.7*			4.4±0.6*	2.3±0.4*	3.5±0.1*	3.7±0.7*	*	*	
	D=120						*		2.1±0.5*	3.0±0.5*	3.3±0.6*	*	*	3.6±0.5*
	D=140								2.9±0.5*	3.5±0.6*	*	*	*	
1071														
1077		4.8±0.6*	5.4±0.7*			8.5±1.5*	6.5±0.8*							
1325														
1326	D= 30													
	D= 90													

LOBATSE ESTATES CENTRAL BASIN

		6/66	2/67	3/68	4/68	10/68	1/69	2/69	3/69	4/69	5/69	6/69	8/69	9/69
1112								19.9±1.7*						29.6±0.6*
1412									2.0±0.4*					(100m) 1.0±0.9*
1414		1.3±0.3*	1.8±0.4*											
1429		2.1±0.4*	0.8±0.3*			*								
1379		1.6±0.3*	0.8±0.4*	0.5±0.2*		0.1±0.3*								0.7±0.3*
1400	D= 25								*	*	*			
	D= 35								0.5±0.4*	1.3±0.4*	*			

TABLE 78

LOBATSE ESTATES SOUTH BASIN

Bh. No.	9/69	10/69	12/69	1/70	4/70	5/70	6/70	7/70	9/70	11/70	1/71	2/71	3/71
973: D= 15	2.0±0.4*	7.8±0.4*	*										
D= 30		*		2.6±0.3*		*	*	5.3±0.4*					
D= 60		*	*	*		*	*	5.8±0.4*		*	2.2±0.3*		4.0±0.4*
D= 90	0.8±0.3*	2.4±0.4*	*			*	*	5.7±0.4*					
D=120		2.1±0.4*	*	*		*	*	*					
1010	*	5.3±0.4*		6.8±0.4*	7.3±0.5*	7.7±0.3*		7.6±0.4*	8.0±0.5*	6.6±0.5*	4.3±0.4*	5.3±0.3*	5.1±0.4*
1041 D= 15			1.1±0.2*	*	3.0±0.4*	*							
D= 30				*	3.0±0.4	2.9±0.3*		3.0±0.3*	2.2±0.4*	3.7±0.3*	1.8±0.3*		3.4±0.2*
D= 60			1.7±0.3*	*	*	3.2±0.4*		3.0±0.3*	2.0±0.4*	1.7±0.3*	1.1±0.4*		1.2±0.2*
D= 90			2.4±0.3*	*	3.9±0.4*	2.7±0.4*		2.7±0.4*	2.2±0.4*	1.7±0.2*	1.3±0.3*		3.3±0.2*
D=120			2.2±0.3*		*	1.7±0.3*		1.7±0.2*		*	*		*
D=140													
1071													8.0±0.4*
1077	6.3±0.7*	8.7±0.4*	*	P.T. *	*	*		*	8.8±0.6*	7.5±0.4*	4.9±0.4*	6.5±0.3*	*
1325			*	P.T. *	*	*		*			1.9±0.3*	0.8±0.3*	2.7±0.3*
1326 D= 30									*	*	2.2±0.3*		*
D= 90									-- *	*	*		2.9±0.3*

LOBATSE ESTATES CENTRAL BASIN

	10/69	12/69	1/70	2/70	4/70	5/70	6/70	7/70	9/70	11/70	1/71	2/71	3/71
1112	20.7±2.0*	*	P.T. *	*	*	*		*	19.7±1.1*	*	32.1±0.9*	17.3±0.3*	19.8±0.8*
1412													
1414		-	0.2±0.3*	0.6±0.3*	*	*		*		*	1.3±0.3*	0.7±0.2*	
1429	0.7±0.3*	*	0.7±0.3* 1.4±0.3	P.T. 0.7±0.2*	*	*		*	0.7±0.7*	1.1±0.2*	0.6±0.3*	0.7±0.2*	0.6±0.2*
1379	0.2±0.3*		0.2±0.2*	0.3±0.2* 0.4±0.3		0.2±0.3*		0.4±0.2*	0.4±0.4*	*	*		0.2±0.2*
1400 D= 25													
D= 35													

TABLE 79

LOBATSE ESTATES SOUTH BASIN

Bh No.	5/71	6/71	7/71	10/71	2/72	7/72	3/73	5/73
973		2.1±0.3*			3.5±0.5	4.0±0.3	2.0±0.3	1.6±0.3
1010	5.2±0.3*	5.1±0.3*	3.7±0.5*		3.1±1.2	4.8±0.5		
1041 D = 15								
D = 30		1.9±0.3*			3.5±0.5	3.0±0.5	2.5±0.4	2.1±0.4
D = 60		2.1±0.3*			2.4±0.3	2.7±0.4	2.4±0.4	2.8±0.4
D = 90		1.4±0.2*			4.3±0.4	3.7±0.4	3.3±0.4	2.7±0.4
D = 120		1.7±0.2*				4.4±0.8	3.4±0.4	-
D = 140								
1071								
1077		4.9±0.3*						
1371 D = 45		2.8±0.4*						
D = 90		3.1±0.3*						
1326	2.5±0.3*	1.0±0.2*						

LOBATSE ESTATES CENTRAL BASIN

	5/71	6/71	7/71	10/71	2/72	7/72	3/73	5/73
1112	32.0±0.5*	16.8±0.7*	16.5±0.5*	9.9±1.3				
1378	0.6±0.2*	1.2±0.5*				0.4±0.3		0.1±0.2
1400								
1412								
1414	0.2±0.2*	0.7±0.3*			3.3±0.5			0.5±2.6
1429	0.0±0.2*	0.5±0.3*						

TABLE 80

LOBATSE GOVERNMENT SUB-BASIN (WESTERN BASIN)

Dh No.	12/68	1/69	2/69	3/69	4/69	5/69	6/69	7/69	8/69	9/69	10/69	12/69	1/70
61(65) D = 25			1.8±0.3										
D = 30			0.5±0.2										
467 D = 25			0.7±0.3										
D = 30			0.4±0.3		0.4±0.3	0.2±0.3							
629 D = 30					1.4±0.3	1.3±0.3			0.6±0.2	1.0±0.4	0.9±0.2		P.
D = 55					1.7±0.3								P.
D = 60					0.7±0.3	0.3±0.2				0.6±0.3			
665 D = 40	1.1±0.4		0.9±0.4	0.0±0.3	0.7±0.4								
2136 D = 52				0.0±0.3	0.7±0.3		0.6±0.3				D.P.		D.P.
917 D = 55					1.9±0.4		3.8±0.5						
D = 85					1.7±0.4		0.6±0.3						
D = 95					0.9±0.4		0.7±0.2						
952 D = 30		0.3±0.9			1.0±0.4	0.5±0.3	0.0±0.2	0.1±0.2		0.0±0.3			
D = 60		0.4±0.3		0.2±0.2		0.3±0.2	0.6±0.1		0.7±0.3				
D = 90		0.3±0.3		0.2±0.3	1.0±0.4		0.3±0.2	0.4±0.3				0.7±0.3	
D = 120		0.6±0.3											
D = 140		0.0±0.3		0.4±0.2	0.7±0.4	0.8±0.3		0.5±0.2					
P212											3.4±0.4		P.T. 0.0±0.2

TABLE 81

LOBATSE GOVERNMENT SUB-BASIN (WESTERN BASIN)

Bh No.	2/70	4/70	5/70	7/70	9/70	10/70	11/70	1/71	2/71	3/71	6/71	5/72	5/73
61(65)D = 25			P. *	P. *	P. *		P. 0.9±0.3 *	1.6±0.3 *					0.3±0.2
D = 30													
467 D = 25			*	*	*		*	*		0.5±0.2 *	0.7±0.2 *		0.5±0.2
D = 30										*			
529 D = 30	*	*	*	*	2.5±0.4 *		*	*		1.5±0.2 *	2.7±0.3 *	2.2±0.3	1.6±0.3
D = 55	*	*	*	*	0.6±0.6 *		*	*		1.3±0.2 *	0.5±0.2 *	0.4±0.2	2.1±0.4
D = 60													
665 D = 40									*				1.2±0.3
2136 D = 52		D.P. *	**	**	*		*	1.1±0.4 *		*			
917 D = 55		*	*	*	*		2.6±0.3 *			*	2.2±0.3 *		3.9±0.5
D = 85		*	*	*		*							
D = 95		*	*	*	*		3.1±0.3 *	1.7±0.3 *		*	1.4±0.3 *		3.6±0.3
552 D = 30		*	*	1.3±0.4 *									
D = 60		*	*	0.5±0.3 *									
D = 90		*	*	0.4±0.3 *	*		1.4±0.2 *	2.4±0.2 *			0.4±0.2 *	0.6±0.2	0.0±1.1
D =120		*	*	*						0.0±0.2 *			
D =140		*	*									7/72	
*P212		2.9±0.3	3.3±0.7 *	*				0.7±0.2	0.7±0.3		1.0±0.2	0.2±0.7	0.6±3.3

TABLE 82

LOBATSE B.M.C. BOREHOLES • EASTERN BASIN

Bh	3/69	4/69	5/69	6/69	7/69	8/69	9/69	10/69	11/69	12/69	1/70	2/70	4/70
A2		P.T. 4.9±0.9	P.T. 3.3±0.5 *								P.T. *		
A3								1.6±0.3 *		*	P.T. *		*
A4											*		*
A5											P.T. *		
A6 D = 25	15.7±1.4 *	16.1±1.5 *	15.9±1.8 *	13.6±1.1 *	*	13.8±1.5 *	*	14.8±1.0 *		*	*		*
D = 40	*	13.3±1.4 *	*	*	*	*	3.6±0.4 *	3.1±0.4 *		2.7±0.3 *			*
D = 45	3.6±0.5 *	4.5±0.6 *	3.7±0.7 *	3.1±0.4 *		*	*	*			*		*
A7 D = 20	*			*	4.0±0.5 *	2.0±0.4 *	*						
D = 35		2.9±0.4 *		*	3.1±0.5 *	2.7±0.7 *	*						
A10											*	*	6.2±0.5 *
X1;X4 D = 15			14.6±1.5 *	12.8±1.2 *	13.3±1.0 *	12.8±1.7 *	14.3±1.1						
D = 30			*	*	*	*	13.6±0.8				*		
D = 45			*				12.8±0.8				*		
D = 50			9.9±1.0 *	8.9±0.9 *	8.5±0.8 *	9.0±1.0 *							
D.C. No.1								6.1±0.8 *			3.0±0.4 *		5.6±0.4

LOBATSE ESTATE NORTH BASIN

Bh	3/69	4/69	5/69	6/69	7/69	8/69	9/69	10/69	11/69	12/69	1/70	2/70	4/70
1463							0.5±0.3 *	*		*		*	*
1331 D = 45						2.4±0.4 *		*		2.6±0.3 *			
D = 70						*		*		0.1±0.2 *			
D = 100						0.5±0.2 *		0.2±0.2 *		1.3±0.3 *			
1352 D = 50	2.2±0.4 *	1.5±0.4 *	1.8±0.4 *	4.2±0.4 *		*	0.7±0.2 *	*	2.4±0.4 *		*		4.3±0.4
D = 60		1.3±0.4 *		3.4±0.4 *		0.4±0.2 *	*	*	2.5±0.4 *	3.4±0.4 *	*		
D = 80	0.6±0.3 *	0.4±0.3 *	1.6±0.4 *	0.7±0.3 *		*	*	*	3.8±0.5 *				
D = 90	*	0.8±0.3 *	1.3±0.4 *	0.5±0.3 *		0.3±0.2 *	0.7±0.2 *	*		3.3±0.3 *			

TABLE 83

LOBATSE B.M.C. BOREHOLES + EASTERN BASIN

Bh No.	5/70	7/70	9/70	11/70	1/71	2/71	3/71	4/71	5/71	6/71	8/72	7/72	5/73
A2					3.7±0.3	5.9±0.4							
A3				2.1±0.4	4.0±0.3	3.0±0.2							
A4					1.7±0.2	1.6±0.2	0.6±0.2			0.8±0.7			
A5						3.3±0.3							
A6 D = 25			14.8±1.0	14.9±9.7	12.0±0.4				14.8±0.7	14.2±0.7		17.4±4.8	13.6±1.1
D = 40				10.0±0.6			7.8±0.5		11.4±0.5	9.7±0.6		11.9±0.9	11.3±3.4
D = 45													
A7 D = 20					4.7±0.3	4.5±0.3							
D = 35													
A10												11.6±0.9	24.4±1.9
X1;X4 D = 15			14.3±1.4		16.6±0.5					22.4±0.8		13.6±1.2	13.5±0.4
D = 30			13.6±0.8		12.4±0.6		12.6±0.5			10.8±0.4	26.3±2.1	13.0±1.5	16.0±1.2
D = 45			12.8±0.8							12.3±0.4			
D = 50											13.7±2.4	13.6±1.3	
D.C. No.1		3.1±0.3		3.4±0.3									

LOBATSE ESTATE NORTH BASIN

	5/70	7/70	9/70	11/70	1/71	2/71	3/71	4/71	5/71	6/71	7/71	7/72	5/71
1463		2.5±0.3				0.5±0.2	0.8±0.2		0.8±0.3				
1331 D = 45	P.	P. 2.7±0.5	P. 1.3±0.1	P.	P. 0.5±0.2	P. 0.4±0.2	P. 0.2±0.2		0.1±0.2	0.4±0.2		0.1±0.2	0.6±0.3
D = 70										10/71			
∑ 388		-					22.3±0.8			16.4±1.2	29.2±1.5	24.1±[illegible]	
1352 D = 50				1.7±0.2			0.8±0.2			0.8±0.3			
D = 60				3.7±0.2									
D = 80							0.7±0.2						
D = 90													

TABLE 84

LOBATSE NEW CONTRACT HOLES

Bh No.	7/69	10/69	11/69	12/69	1/70	7/70	9/70	11/70	1/71	2/71	3/71	5/71	6/71
2243		P.T. 0.5±0.3 *		D.P. 0.6±0.2 *			1.7±0.3 *						
				1.3±0.3									
2249	D.P. 1.8±0.4 *	D.P. 1.8±0.3 *		D.P. 1.1±0.2 *			D.P. *	D.P. 0.7±0.2 *	D.P. 0.5±0.2 *		D.P. *		2.8±0.2 *
		0.4±0.2 3.1±0.3		0.3±0.2				0.7±0.2	0.3±0.2				
2250		D.P. 1.3±0.4 *	D.P. *	D.P. *									
		2.0±0.4	1.7±0.3										
2252	D.P. 1.0±0.3 *		1.2±0.3 *	2.7±0.4 *									
2265		D.P. 0.0±0.4 *	D.P. *	P.T:D.P. *		2.8±0.2 *		*	0.8±0.2 *		1.4±0.2 *		
		0.5±0.3 1.0±0.3	0.3±0.2										
2270		D.P. 0.5±0.3 *											
		0.3±0.2											
2278				D.P. 3.1±0.4 *	P.T. 1.9±0.4 *		*						
2279				P.T. *									
2261		D.P. 4.4±0.6 *		*		P.T. 5.1±0.3 *	4.3±0.5 *						
2253		0.2±0.3 *		D.P. 0.5±0.2 *			D.P. 0.9±0.3 *	*	D.P. 0.4±0.2 *		D.P. 0.1±0.2 *		
							1.7±0.4		0.2±0.2 0.6±0.2				
2254						1.6±0.3 *	P.T. 0.7±0.2 *	*	1.0±0.2 *	0.9±0.2 *	2.0±0.2 *	1.7±0.2 *	*
2262		P.T. 0.3±0.2 *							2.0±0.3 *		*	*	*
2263				3.4±0.5 *						1.2±0.4 *	2.7±0.4 *		D.P. *
2264				*		*	0.7±0.3 *	*	0.7±0.2 *	0.4±0.2 *	P.T. 0.0±0.2 *		
2242	0.8±0.3 *	D.P. 0.5±0.2 *											
2268		P.T. 0.7±0.3 *											
2283					D.P. 3.4±0.4 *								
2285					P.T. *								

TABLE 85

SEROWE PUMPED SAMPLES

Bh No.	2/67	3/69	5/69	11/69	3/70	6/70	9/70	10/70	3/71	4/71	6/71	6/72	6/73
No. 1			2.4±0.4*	*	*	*	*	2.8±0.2*	2.6±0.3*	1.8±0.2*	2.1±0.3*		
No. 2(1054)	4.3±0.7*	0.5±0.3*	0.4±0.2*	*	*	*	*	2.3±0.2*	0.4±0.2*	0.5±0.2*	0.5±0.2*	2.8±0.3	
No. 3		1.0±0.5*	0.9±0.2*	*	*	*	*	*	0.1±0.2*	1.7±0.2*	*		
1677		0.7±0.3*	0.2±0.2*	*	*	0.2±0.3	*	1.2±0.2*	0.4±0.2*	0.4±0.2*	0.5±0.3*		
Blackbeard's		0.8±0.3*	5.9±0.6*	*	*	1.0±0.3*	*	0.9±0.3*	2.6±0.4*	0.9±0.2*	*	7.0±0.7	
Botalaote		0.0±0.2*	0.0±0.2*	*	*	0.6±0.2*	*	*	0.7±0.2*		*	0.1±0.2	
S.Khama		*	0.9±0.5* 0.7±0.3		*	0.5±0.2*	*		0.3±0.2*	0.4±0.2*	*	1.1±0.2	
(1062) Mokwena			5.3±0.6*	*	*		*	4.2±0.3*	7.5±0.4*	*			
Newtown		0.5±0.3*	0.6±0.3*	*	*	0.7±0.2*	*	2.5±0.2*	0.8±0.2*	*		0.6±0.3	
Palmer's		4.8±0.7*	1.7±0.4*	*	*	1.7±0.3*	*	*	3.7±0.3*	2.3±0.3*			
Palamaokwe				*	*	0.3±0.2*	*	0.8±0.2*	1.9±0.2*	0.7±0.2*	*		
Ratshosa		1.8±0.4*	1.6±0.3*		*	1.8±0.3*	*	2.5±0.2*	2.0±0.2*	1.2±0.2*	*		
S.Hill School		0.1±0.2*	0.3±0.3*	*	*	0.5±0.2*	*	2.7±0.2*	0.8±0.2*	0.6±0.2*	*		
J.Wright's		2.5±0.5*	0.2±0.3*	*		0.6±0.2*	*	0.9±0.2*	0.8±0.3*	*	*	2.7±1.3	
Woodford's		*	*	*	*	0.5±0.3*	*	0.7±0.2*	0.0±0.2*	*	*	1.7±0.2	
					SEROWE DEPTH PROFILES								
405 D = 12		0.5±0.4*	0.2±0.3*		*	*		1.5±0.3*	0.1±0.3*	*	*	0.0±0.2	0.4±0.2
D = 30		0.2±0.2*	0.4±0.2*					0.2±0.3*	0.0±0.2*	*	*	0.5±0.4	0.5±0.2
D = 60								0.3±0.3*					(0.4±0.2) P
670H D = 15			8.7±1.0*						*				
D = 30		12.1±1.0*								5.7±0.3*		P 7.8±0.7	
D = 60		12.0±1.6*	8.8±0.9*		*		7.1±0.7*	5.9±0.6*	13.0±0.6*	7.3±0.5*	8.4±0.4*		
D = 90		12.3±1.7*	8.1±0.7*		*		8.1±0.7* 8.4±0.7	7.2±0.5*	7.7±0.6*	7.0±0.4*	8.4±0.4*		
D = 100											10.2±0.5		

TABLE 86

SEROWE DEPTH PROFILES

Bh No.		2/67	3/69	5/69	11/69	3/70	6/70	9/70	10/70	2/71	4/71	6/72	2/73	6/73
1056	D = 40		*	2.7±0.5*		*	*	*	*	*	4.3±0.3*	5.2±0.7*		
	D = 55		5.8±0.8*	*		5.2±0.5*	*	*	4.9±0.4*	*	*	4.8±0.6		
1065	D = 45									1.3±0.4*				
	D = 75		0.6±0.3*	1.2±0.3*		*	*	*	*		*	0.4±0.3*		
	D =100		0.3±0.2*	*			*		0.6±0.3*			0.4±0.2		
1510	D = 15		0.8±0.3*	0.6±0.3*		*	*	0.8±0.3*	0.5±0.3*	0.3±0.3*	0.4±0.2*	*	2.6±0.3	1.9±0.5
	D = 45			*		3.0±0.4*	*	0.2±0.3*	0.2±0.2*	0.5±0.2*	0.3±0.2*	4.3±0.6*		2.3±0.3
	D = 75		1.1±0.3*	0.4±0.2*		*	*	4.5±0.6*	0.5±0.3*	1.9±0.3*	0.6±0.2*	4.3±0.4*	2.5±0.3	1.7±0.4
	D =100		0.7±0.3*	0.2±0.2*		*	*	*	0.8±0.3*	*	0.9±0.2*	2.8±0.4*	3.2±0.5	2.0±0.3
1539	D = 50						2.3±0.5*		0.4±0.3*	0.4±0.3*	0.0±0.2*	3.0±1.1*	0.8±0.3	0.1±0.2
	D = 75				P.T. 0.7±0.3*		1.2±0.4*		0.3±0.3*	0.1±0.2*	0.5±0.2*	2.1±0.2*	1.0±0.3	1.8±0.4
	D =100				P.T. 1.0±0.4*		*		0.3±0.3*	*	1.2±0.3*	1.7±0.3*	0.3±0.2	
	D =130						1.0±0.4*			0.4±0.2*	*	2.1±0.4*		0.4±0.2
1643	D = 25		1.1±0.3*	0.7±0.2*		*	*	*	0.3±0.2*					
	D = 45		1.6±0.4*	*		*		*	1.0±0.3*					
	D = 75		2.3±0.2*	*		*								
	D =100		*	0.2±0.2*				*	0.5±0.2*					
1929	D = 30		15.8±1.8*	8.3±0.9*					1.0±0.3*	0.4±0.3*		5.7±0.5	10.5±0.5	
	D = 60			3.4±0.4*									7.4±0.9	
	D = 90		1.6±0.3*						*	*			1.1±0.4	
	D =110			3.5±0.5*					0.7±0.2*	2.1±0.3*				
1930	D = 20		1.3±0.3*	0.6±0.2*		*	*	*	*	7.8±0.4*	7.8±0.4*	P. *		
	D = 30			*		*	*							
	D = 60		*	*			*							
	D = 90		1.0±0.3*	0.3±0.2* 0.6±0.3										

TRITIUM IN RAINFALL AND GROUND WATER

Tritium in Rainfall

Before tritium values in ground water can be properly interpreted, it is necessary to have a thorough understanding of the behaviour of tritium in rainfall and of seasonal and latitudinal or time variations.

Tritium is brought into the hydrologic cycle as it transfers slowly from the stratosphere (where it has formed by cosmic ray bombardment of the atmosphere or by hydrogen bomb explosions) to the troposphere. Part is added to the hydrogen inventory, while the bulk combines with hydrogen and oxygen at high altitudes to form water molecules of the form HTO. These behave chemically in identical fashion to normal H_2O molecules and hence the HTO molecules make excellent tracers in hydrological studies. HTO molecules have a mean stratospheric residence time of several years, whereas they are washed from the troposphere within a few weeks.

Prior to the thermonuclear era (1952), the only source of tritium in rainfall was from cosmic ray production and an equilibrium concentration of tritium was established between production and radioactive decay. Such fluctuations as did occur were due to cosmic ray fluctuations; "the continental" effect; seasonal effect and climatic conditions.

As cosmic ray fluctuations have not been great within the time scale for tritium detection, any such fluctuations can be regarded as insignificant.
The "continental effect" results from the scavenging, by low tritium water vapour arising from the oceans (which form the ultimate sink for all water and which are of low activity), of additional tritium from atmospheric moisture as it moves inland. Air moisture from inland sampling sites on the larger continents therefore invariably has more tritium than that at coastal sites. Seasonal variations are caused by the "spring leak" in which jet streaming carries large quantities of tritium-laden stratospheric air to the troposphere in spring, and which, therefore, results in a high concentration of tritium in spring rainfall. Finally, fluctuations in the tritium content of rainwater may be controlled by the climate which determines the amount of precipitable moisture and the rate of condensation and re-evaporation.

The first serious measurements to determine the amount of tritium in rainfall from natural sources were commenced in 1952 and then on a very limited scale and only in the northern hemisphere (thermonuclear testing also commenced the same year and hence there is only scant data available for the pre-thermonuclear era).

The average production of tritium prior to 1952 has been calculated as 3,3 TU by Libby (1954) and as 7 TU by Craig and Lal (1961).

During the period November 1962 to 1958 a number of thermonuclear devices were exploded in the northern hemisphere. These were accompanied by a marked rise in tritium levels in the northern hemisphere and a concomitant, but much lower rise in the southern hemisphere. The moratorium on atmospheric nuclear tests (1958 - 1961) led to a temporary halt in this upward trend, but following the resumption of testing in 1961 and 1962, there was a dramatic rise in maxima of up to 10 000 TU being recorded at Whitehorse, Yukon in April 1963. In the interior of southern Africa, the tritium level (adjusted to give the input for effective recharge) also reached a peak in 1963, and was approximately 9 times the pre-bomb level.

These thermonuclear tests thus disturbed the quasi steady-state in natural tritium and resulted in a series of periodic pulses of tritium in the hydrological cycles which could be traced through surface and ground-water systems.

Tritium in Ground-Water

Water turnover times in the terrestrial part of the hydrological cycle - e.g. lakes and ground-water systems, are generally longer than in the atmosphere and the time scale of tritium ($\pm$ 50 years) has proved to be extremely useful for geohydrological studies.

Tritium in Southern African Rainfall

In the southern hemisphere, Taylor (1966) has shown that southern mid-latitude rain contains no significant tritium contribution from spreading across the equator within the troposphere. This is due to a combination of the highly effective rainout by the tropical rain belts and the short tropospheric fall-out time. The increase in the HTO content of rainwater is due mainly to delayed stratospheric fall-out originating from higher stratospheric regions or the mesosphere caused originally by thermonuclear testing in equatorial regions and later by Soviet testing in Arctic regions.

Seasonal variation is observed in the tritium concentration in rain over the whole of the southern African region. This effect is more marked in the interior where concentrations are higher and spring rains occur. The sampling of rain water in South Africa for tritium measurements has shown clearly (Verhagen et al, 1970) that peaks occur in tritium concentrations in spring and early summer (August - November) falling to a minimum in autumn and, when rain occurs, in winter. Peaks may be four to five times that of the winter minima. A similar periodicity is observed in the rainfall figures, but with maxima occurring four months later. The tritium in precipitation concentration curve and the rainfall curve are therefore similar in structure but out of phase by four months. The effect of this phase shift on ground-water systems will be that replenishment will come after the maximum tritium peak, resulting in a lower average tritium input concentration. This is normally the period in which the soil attains field capacity and all water will not be removed by evapotranspiration before reaching the ground-water table. In the more arid regions, where recharge occurs mainly through the medium of normally dry water courses, and in the vicinity of rock outcrops and gravel fans, ground-water replenishment occurs mainly in severe individual storms, because only they result in sufficient concentration of run-off. This mechanism will again probably occur during the later season precipitation because of heavier mid-late seasonal rainfall and because catchments are more likely to be saturated than earlier in the rainy season.

Pre-bomb tritium levels in precipitation are not known for southern Africa and have therefore to be assumed. A global average for cosmic-ray tritium in precipitation has been calculated at 7 TU by Craig and Lal (1961). Because of the continental environment of the areas in which detailed studies have been carried out (minimum distance to coast about 750 km.), and taking the ratio of present-day concentrations between Pretoria (inland) and Cape Town (coast), a figure of 10 TU for pre-bomb precipitation in Botswana is not unreasonable. The uncertainties in these figures lead to the use of a range of pre-bomb tritium precipitation values. Taking into account the selection mechanism described above, a range of 5-10 TU will be assumed for recharge up to 1955, when the first effect of bomb tritium could have been felt at these latitudes.

TABLE 87

EFFECTIVE RECHARGE TRITIUM CONCENTRATION AS FUNCTION OF YEARS

YEAR	TU
Up to 1955	5 - 10
1956/1957	15
1958/1960	20
1961/1962	30
1963	60
1964	55
1965/1966	50
1967	40
1968/1969	35
1969/1970	30
1970/1971	28
1971/1972	25
1972/1973	20

Estimates for the effective recharge concentration over the years for which figures are available with an extrapolation to 1955, are given in Table 87 . A consequence of these figures is that uncontaminated pre-bomb recharge can have a maximum concentration of about 2 TU at present.

The Use of the Tritium Method in Ground-Water Surveys

In the areas under study, the only points of access to the ground water are by boreholes. Therefore, the maximum amount of information has to be extracted from these points. Recharge may give a degree of age stratification in some water bodies. This stratification may be used to try to elucidate the recharge pattern in the aquifer. Ideally, this can be followed by drilling special boreholes and collecting carefully logged samples, as was done by Davis et al (1967), or by installing filters in the well casing, as reported by Halevy et al (1967). However, these are expensive and time-consuming techniques and are hardly applicable when work of an exploratory or extensive nature is being undertaken. In such a case existing boreholes have to be employed. The boreholes used in this study are all kept well covered to avoid the direct ingress of rain-water. The average tritium concentration in air moisture is at present about 25 TU which, in addition to the very low average humidity, make any serious contamination of the borehole water unlikely.

Spot sampling, by means of a device capable of being operated at any chosen depth, is used as a standard technique in this work. As vertical currents can exist in the standing water column in a borehole, any concentration profile such as exists in the aquifer can be distorted or completely obliterated in the borehole itself (Halevy et al, 1967 and Wurzel and Ward, 1969). The extent of distortion depends on the ratio of the vertical flow in the borehole to the horizontal flow in the aquifer. The sampling procedure itself can also cause mixing. The absence of depth stratification need not therefore imply its absence in the aquifer. On the other hand, the existence of stratification in a borehole indicates a possibly larger stratification in the aquifer itself and may therefore give useful information on the recharge.

When pumped samples are taken these tend to give an average for the whole depth of the aquifer traversed by the borehole for unlined boreholes or those with perforated casing. This implies that water withdrawn from a phreatic aquifer can be regarded as well-mixed and that the part of the reservoir above the bottom of the borehole (from which point pumping usually takes place) can be regarded as a well-mixed reservoir.

The true behaviour of the reservoir itself is, as yet, unknown in all the cases to be discussed below, and one therefore does not have any information on the individual contributions to the water in the borehole. In the absence of a realistic model, the exponential well-mixed model is the simplest to apply in order to extract quantitative information. Using Eriksson's

(1958) notation, we have:

$$R = R_o(1-e^{-k\tau}) \quad \ldots\ldots\ldots\ldots\ 1$$

where R_o is the total recharge rate, R the individual contributions of the recharge to the runoff point, k the aquifer time constant and τ the time required for the different contributions to reach the runoff point.

When we calculate the expected mean concentration $\bar{c}$ of the tracer, we obtain, for the exponential model

$$k = \frac{\bar{c}\lambda}{\bar{c}_o - \bar{c}} = 1/T \quad \ldots\ldots\ldots\ldots\ 2$$

where $\bar{c}_o$ is the average annual concentration in the recharge and λ the tracer decay constant; for tritium $\lambda = 0{,}057\ yr^{-1}$. T is the reservoir residence time (i.e. turnover rate).

The reservoir capacity, V, will therefore be given by

$$V = R_oT \quad \ldots\ldots\ldots\ldots\ldots\ldots\ 3$$

The reservoir volume can therefore be determined from the average tritium concentrations in the reservoir and in precipitation and the recharge rate, which can be found from pumping figures and rest level observations. Conversely, the recharge rate can be determined when the capacity is known.

Once water containing tritium leaves the earth's atmosphere, the tritium decays with a half-life of

12,26 years and, in simple situations, the time the water has been underground can be determined by measuring the tritium content of the ground water. Old waters can thus be expected to have low tritium contents. In the "piston flow" model of Nir (1964) water is regarded as entering a confined aquifer at a localised recharge point. Assuming minimal longitudinal dispersion, then the water which flows at velocity V to a point at a distance x_o from the recharge area, would take $\frac{x_o}{V}$ to reach that point. Thus, knowing the input (from the tritium in rainfall record), and knowing its decay rate, the transit time or "age" of the water, and hence the rate of flow, may be calculated.

$$C = C_o \exp - \frac{0,693\, x_o}{V\, T_{\frac{1}{2}}}$$

$$= C_o \exp - \frac{0,693\, t}{T_{\frac{1}{2}}}$$

where C is concentration of tritium sample at time of collection.

C_o is concentration of tritium when water entered the ground.

V is velocity of ground-water movement.

t is the time between recharge and sampling.

$T_{\frac{1}{2}}$ is the half life of tritium.

x_o is the distance of the sampling point from the recharge area.

The Lobatse Ground-Water Basins

Introduction

(See also separate chapter on Hydrogeology of Lobatse)

The town of Lobatse in Botswana is of considerable economic importance to that country because of its meat industry, residential and trading facilities and rail link. The revenue from the meat industry constitutes far and away the country's most important source of income. Boreholes have been sunk in several ground-water basins in and around the town and previously provided the township's sole water supply. In 1964 a surface dam was completed. This has supplied the town with a large proportion of its total water supply up to the present time. However, persistent droughts have on occasion caused this supply to dry up. This has necessitated the resumption of pumping from the ground-water basins and the sinking of additional boreholes in several basins.

Lobatse Western Basin

This basin lies at the foot of a low range of hills to the west and is bounded to the east by a major fault, (Fig. 172). The aquifer occurs at a depth of 30-50 metres and is overlain by a considerable thickness of colluvial soils and gravel and consists of wad, chert and decomposed dolomite (Transvaal Supergroup) (Fig. 23). Because of the thick soil cover over most of the basin and the depth to the water table, no recharge was thought to occur except through the gravel fans at the foot of the hill slope on the western edge of the basin. Because of the known homogeneity of the aquifer and the apparently clearly defined recharge area, it was concluded from the existing hydrogeological information that this basin could act as a "test bench" for studying the tritium behaviour of a simple aquifer in this environment.

The group of boreholes (61, 467, 629, 665, 917 and 952) all lie in the Government sub-basin (Fig. 172). These boreholes were consistently sampled at different depths between 1969 and 1974 to establish the recharge behaviour of this basin. The results of tritium measurements on a number of these holes in this basin are presented in Table 80-82. The low values encountered here are immediately apparent and are most surprising in view of the immediate proximity of the apparent recharge area. It is clear that there is no significant gradient in tritium concentration either horizontally or vertically. A few boreholes show a suggestion of depth stratification, but, even assuming considerable vertical mixing, the uniformly low results exclude the possibility of appreciable modern recharge, despite the immediate rise in water level following the above-average

1966-1967 rainy season, (Fig. 49)

The simple mean of all the point measurements from this basin gives a figure of 0,8 TU, which can be regarded as an average for all the water in the reservoir.

An early analysis of tritium concentrations found in a number of boreholes of this basin (Verhagen et al, 1970) indicated a considerable discrepancy (a factor of 10) between the (then) assessment of the residence time and the value obtained using the observed tritium concentrations interpreted by using the well-mixed model. Although it was felt that the "classical" estimate was a low one, the large discrepancy between the two methods remained worrying. This descrepancy remained following the updating of the recharge rate, (Jennings 1970).

However, the study of the infiltration through the unsaturated zone as well as the application of a recharge model based on moisture balance calculations, (See section on Lobatse in this thesis), pointed towards at least one source of this discrepancy. This has been recently described by Verhagen et al (1974).

The storage capacity calculations,referred to above, apply to the <u>immediately available</u> water i.e. the saturated zone only. The water balance calculated from the environmental tritium data takes account of <u>all</u> the water in the basin, irrespective of its availability. This includes the water held in storage in the unsaturated zone.

Taking the area of the valley floor over the Western basin to be 3 km x 0,6 km = 1,8 km^2, the average depth to the water table 30 metres, the bulk density of the soil 1,6 x $10^3 kg\ m^{-3}$, and assuming a figure of 8 per cent by weight of water in the unsaturated zone (the value obtained at the bottom of a 4,5m pit in Lobatse), the storage would be:

$3\ 000 \times 600 \times 30 \times 1,6 \times 10^3 \times 0,08 = 6,9 \times 10^9$ kg of water

or $6,9 \times 10^6 m^3$ in the unsaturated zone.

Because of the delay in the soil cover, the water infiltrating along this path will arrive at the water table with an activity of about 0,1 TU (See section on infiltration in unsaturated zone). A significant part of the recharge should therefore be delayed less than that amount as the average concentration of water in the basin is about 0,8 TU. Run-off water from the hill slopes bordering Western Basin enters the coarse scree of the gravel fans at the foot of the hill during heavy downpours. It is postulated that it reaches the water table more rapidly than by normal flow infiltration through the thick soil cover on the flat ground.

It has been estimated from the tritium profile that the infiltration of rainwater into the soil amounts to 7 per cent of mean annual precipitation. The total recharge to the Western basin by this mechanism would be:

$3\ 000 \times 600 \times 545 \times 10^{-3} \times 0{,}07 = 7 \times 10^{4}\ m^{3}\ yr^{-1}$. ($0{,}07 \cdot 10^{5} m^{3} yr^{-}$

The run-off from the hillslope to the west of Lobatse has recently been determined by a gauging weir (See chapter on Lobatse). For a near average rainfall year the total run-off was found to be 4 per cent or $1{,}6 \times 10^{5}\ m^{3}$. As direct observation has established the immediate disappearance of this run-off into the gravel fans, evapotranspiration should be negligible and this figure can be accepted as being the input to the Western basin through the scree zones.

Prior to the commencement of large scale pumping in the Western basin in the 1950's, the deeper-seated water in the Western basin was essentially undisturbed and should therefore have had a vanishing tritium concentration. Taking the recharge rate and saturated zone storage capacity in Tables 29, 32 to be fairly realistic, the water in the aquifer should have been turned over at least once in this period. The present-day tritium concentration of 0,8 TU should therefore, following the above arguments, be derived from the inputs from these two sources. If we denote the tritium concentration of the run-off water (i.e. water that has infiltrated in the gravel fans) on arrival at the water table as X, we can write

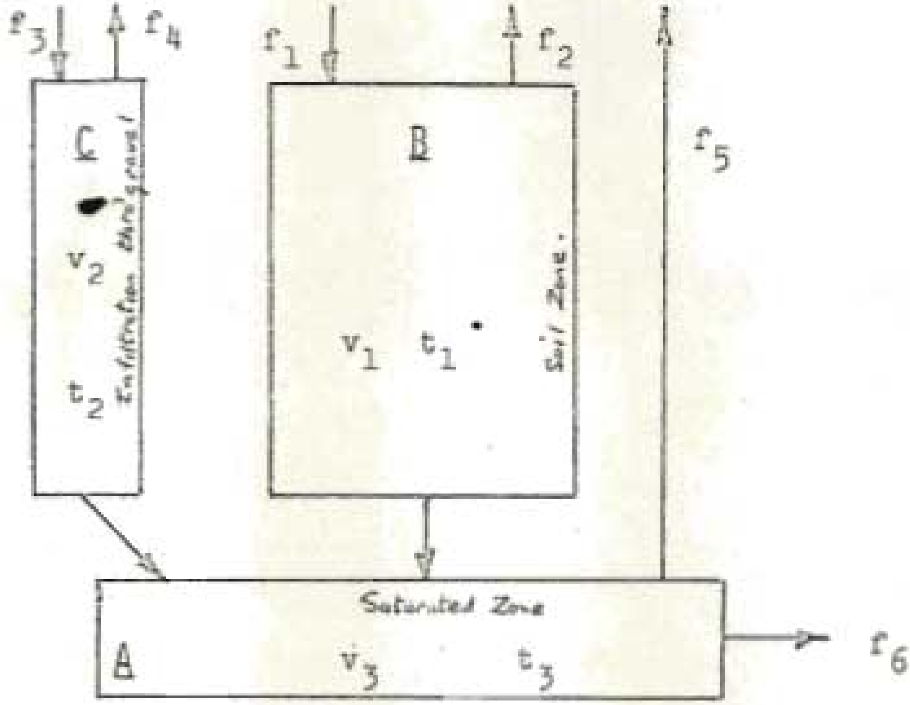
$$(0,7 \times 10^5 \times 0,1) + (1,6 \times 10^5 \times X) = 0,8 \times 2,3 \times 10^5$$

$$\therefore X = 1,1 \text{ TU}$$

This again could, in the absence of major mixing on the way to the water table, be derived only from pre-bomb levels, say 5 TU, which gives a transit time of 27 years for water infiltrating in the gravel fans to reach the water table. A model, as shown diagrammatically in Fig.174, has therefore been derived. (Verhagen, Sellschop and Jennings, 1974).

Three reservoirs are postulated. The larger of the three is B, the unsaturated soil cover; A is the saturated zone and C is the storage incurred by infiltration through the gravel fans into the scree zone. The three reservoirs have turnover times T, t_1 and t_2 and storage capacities V, v_1 and v_2 respectively. The time constant t_2 is the assumed delay of infiltration of the run-off and t_3 is taken as the ratio between storage capacity and recharge as given in Table t_3 is, therefore, a time constant generated by the exploitation of the basin and will depend upon the pumping rate.

The two recharge inputs $f_1 - f_2$ and $f_3 - f_4$ have been determined independently. They must be balanced by the outputs, which are the exploitation (f_5) and subterranean leakage (f_6), if any. With an average depth to the water table of 30 metres, evapotranspiration from the basin should be neglible. The magnitude of the



t_1 = 75 yr
t_2 = 27 yr
t_3 = 4 yr (artificial)

$f_1 - f_2 = 0.7 \times 10^5$ m^3 yr^{-1}
$f_3 - f_4 = 1.8 \times 10^5$ m^3 yr^{-1}
$f_5 = 1.4 \times 10^5$ m^3 yr^{-1}
$f_6 = 1.1 \times 10^5$ m^3 yr^{-1}

$v_1 = 6.9 \times 10^6$ m^3
$v_2 = 4.9 \times 10^6$ m^3
$v_3 = 1.0 \times 10^6$ m^3

Figure 174 : Hydrological model for Western basin
(After Verhagen, Sellschop & Jennings, 1970)

leakage should therefore be:

$$f_6 = (f_1 - f_2) + (f_3 - f_4) - f_5$$
$$= (0{,}7 \times 10^5) + (1{,}6 \times 10^5) - (1{,}4 \times 10^5)$$
$$= 0{,}9 \times 10^5 \ m^3 \ yr^{-1}$$

This value is of course dependent on the accuracy of the assessment of the inputs and exploitation.

In order to explain the apparently contradictory evidence of any immediate rise in the water levels in the basin, without any rise in tritium levels, the writer postulates that older water with tritium values between 1,1 x 0,1 TU (27 to 75 years), is displaced in "piston-like" manner downwards to the saturated zone by the younger recharge waters above. This, therefore, gives valuable evidence of the actual mechanism of the travel of water to the water table.

There remains the question of what happens to this leakage. Natural drainage would reasonably be towards the southeast in the direction of the Peleng River. This could account for earlier reports of springs and perennial pools being present in the Peleng River.

Lobatse Eastern Basin

The Eastern basin seems hydrologically distinct from the Western basin as their rest levels differ by about five metres. All the boreholes in this basin were drilled by the Meat Commission and records were kept since commencement of pumping in 1957. Fairly consistent values of recharge were estimated, monitoring two boreholes (X1 and X4) and a storage capacity calculated (see Tables 29, 31). Abstraction from this basin continued well beyond 1964 (when the Nuane Dam was completed) and rest levels rose dramatically after the 66/67 rains (see Fig. 43).

A feature of the boreholes in the Eastern basin is their generally high tritium content. These are boreholes A7, A10, X4, X1 and 2261 (Fig. 172). An even more striking feature is the pronounced and sustained tritium depth profiles observed in boreholes X1 and X4 and, to a lesser extent, A7. This seems to indicate a marked degree of infiltration in this area, the most likely source being the Peleng River. This effect is also seen further south in boreholes DC No. 1 and later DC No. 3, which are situated quite close to the river bed. However, quite similar features to those in the Eastern basin are seen in the closely adjacent boreholes of the Western basin, notably A2, A3, A5 and, to a lesser extent, A4. Quite marked and very sustained profiles (Tables 82, 83) were observed in borehole A6 over a period of several years. There seems to be little differentiation in recharge characteristics between these two groups of boreholes, the first in the quartzite of the Eastern basin, the latter in the dolomite of the Western basin. Higher tritium concentrations in the range

3,5 - 5,0 TU were found in samples taken during a three day pump test on borehole A2 and during the drilling of borehole 2261 (4,4 TU). It would appear that significant recharge has occurred over a considerable span of time into the ground waters of this area and that this recent water has mixed downwards into the deeper waters, presumably assisted by the sustained pumping. An additional feature seems to be that the faultline does not (at least in the vicinity of the abbatoir) form the efficient aquiclude it was believed to be. The higher rest levels in the vicinity of DC No.1 could indicate a general flow northwards and might constitute a possible source of recharge for both the Western and Eastern basins.

Considerable stratification is also seen in the chemical quality of the waters in the different observation boreholes in this area. The chemical stratification observed in the boreholes might well hold a partial explanation for the persistent tritium stratification observed in the same holes (See Tables 82,83). Higher salinities are always found at the bottom of the hole and this water, which is not so readily replenished, will, because of its greater density, remain near the bottom and thus resist mixing.

The tritium levels observed in the Eastern basin are all clearly post-bomb (>2 TU). It is assumed that the pre-exploitation levels in the deep-seated waters were zero or close to zero, while at present they average about 4TU. Using the recharge rate from Table 29 and the summed tritium input from the piston-flow curve in the section on infiltration through the unsaturated zone, one can calculate the tritium input during the period of exploitation (1957 to present). However, at the same time, tritium was lost from the basin by exploitation. The pumping rate was, on the average, the same as the recharge rate. As a simple approximation, we take the basin's tritium response over this period to be linear (0 - 4 TU) and sum the yearly contributions. This we have to subtract from the input contributions. We therefore get:

$$(438 - 30) \times 4,4 \times 10^4 \text{ TU m}^3 = 4 \times V \text{ TU m}^3$$
$$V = 4,5 \times 10^6 \text{m}^3$$

This should be compared to the storage capacity of 2,9 x 10^5m^3 given in Table 32.

The approximate areal extent of Eastern basin is 3 km^2. The depth of the alluvium is not well known but can be taken to be about five metres on average. This gives a storage capacity in the unsaturated zone of about $5 \times 3 \times 10^6 \times 1,6 \times 10^3 \times 0,06$

$$= 1,5 \times 10^9 \text{ kg of water.}$$
$$\therefore V = 1,5 \times 10^6 \text{m}^3$$

This still leaves a shortfall of effective storage that has not been accounted for of about 2,7 x 10^6m^3.

The north-south fault separating the Western and Eastern basins has been assumed to act as an aquiclude. However, the high tritium concentrations in the vicinity of the abattoir to the west of the fault must, to an extent, be due to leakage from the river bed and from the piezometric high of the Railway Sub-basin. Conversely, undisturbed rest levels further north in the West basin are about five metres higher than found in the Eastern basin. The additional apparent storage might well be due to active leakage of Western basin water into the Eastern basin.

Lobatse Estates South Basin

Situated in Pretoria Subgroup shale and quartzite, this basin has relatively low co-efficients of storage and transmissibility and heavy pumping from the boreholes has resulted in rapid and marked drops in water level. Flooding of the Peleng River, however, as well as cessation of pumping, causes equally rapid and marked recovery.

Depth profile and pumped samples have been taken for tritium analysis during the whole project period and the results are given in Tables 77-79 . Large variations in tritium concentration were evident throughout that period, with some correlation to periods of drawdown and recovery.

Values as low as 0,8 TU have, on several occasions, been observed in the basin which implies that older water is constantly drawn in. This could be derived either from other parts of the basin itself or through leaky barriers from adjoining water bodies. It is significant that such low values were observed at the bottom of Borehole 923, during an all-time high in rest level during 1969. Soon after, in 1970 on renewed drawdown, higher concentrations at depth were observed.

Pumped water from such boreholes as 1010 and 1077 shows fluctuations in tritium concentration, indicating the extreme mixing taking place in this basin. In Borehole 1041 the pronounced stratification observed in the water column in early 1968 diminished after a brief appearance, to the point of disappearing by 1971. It is possible that the stratification seen in 1968 was a remnant of the water level recovery and caused by recharge during the 1966/1967 season.

The simple mean tritium concentration of all measurements done in this basin up to and including August 1969 is 3,6 TU (55 measurements). Between and including September 1969 andMarch 1971 (61 measurements), it is 3,8 TU. The small increase observed shows that:

a) The tritium level was well established by the time observations began - i.e. through the drawdown after 1961 and subsequent recovery, culminating in the 1966/1967 rainy season.

b) The subsequent drawdown further increased the tritium-bearing recharge, leaving the basin at a slightly higher concentration. This would indicate that the tritium concentration has continuously risen since the beginning of exploitation - in other words that the water in the basin is gradually being replaced with recent recharge.

These facts underline the argument put forward earlier that tritium concentrations in deep-seated water in the Lobatse aquifers began to rise significantly only after the beginning of exploitation. This should also make a storage capacity calculation, such as employed for the Lobatse Eastern basin, valid in this case.

A recharge rate (shown in Table 29) of $4{,}0 \times 10^4 m^3$ per year has been calculated. If we add the tritium concentrations under the piston flow input curve (section on infiltration) from 1961 and we eliminate the years 1967 and 1968, as there was no response on the hydrograph, we get a value for the tritium input of

$$323 \times 4{,}0 \times 10^4 \ TU\ m^3$$

However, during this period, water was pumped from the basin at the (then) existing level of tritium concentration. If we again take the tritium response of the basin to have been linear, we have to correct the input to

$$(323-22) \times 4 \times 10^4 \text{ TU m}^3$$

Taking 3,7 TU to be the average value for the whole basin, we obtain a total storage capacity, V_t:

$$V_t = \frac{301 \times 4,0 \times 10^4}{3,7} = 3,2 \times 10^6 \text{ m}^3$$

This is again a factor of nearly 10 higher than the lower limit of storage ($V_1 = 3,6 \times 10^6 \text{ m}^3$) calculated from drawdown for a 30 metres aquifer depth. The actual aquifer depth is unlikely to be more than, say, 60 metres effectively (the drawdown at around 30 metres was very rapid - see Fig. 28), which still leaves a discrepancy of a factor of 5.

The alluvium over the basin itself is very shallow and is generally not more than about 5 metres. The response of the basin (hydrograph; tritium concentrations) is in keeping with this fact. The maximum storage, in the unsaturated zone, taking the same density as for the Western basin, assuming an area of 1 km^2 and, because of its shallowness, a 6 per cent moisture content would be:

$$5 \times 10^6 \times 1,6 \times 10^3 \times 0,06 = 4,8 \times 10^8 \text{ kg}$$

$$\therefore \; V_2 = 0,5 \times 10^6 \text{ m}^3$$

This still leaves most of the storage unaccounted for and the question arises of leakage from adjoining areas. From the east, i.e. across the fault from the Central basin, leakage is unlikely, as rest levels in the Southern basin dip towards the northeast. However, the South basin has been traditionally defined as the developed area to the southwest of the fault. As can be seen in Fig. 173 , further up the valley, towards the township, there is no ground water development. A topographical gradient exists down the valley to the northeast (river drainage). The alluvium higher up in the valley is known to be between 10 and 20 metres deep. Taking an average of 15 metres, an area of 2 x 0,7 km^2 and the same constants as above, we get a weight of water of:

$$15 \times 2 \times 0{,}7 \times 10^6 \times 1{,}6 \times 10^3 \times 0{,}06$$

$$= 2{,}0 \times 10^9 \text{ kg}$$

$$\therefore V_3 = 2{,}0 \times 10^6 \text{ m}^3$$

Assuming, in addition, a saturated zone storage similar to the Southern basin proper gives us a value of:

$$V_4 = 2 \times 0{,}7 \times 3{,}6 \times 10^5 = 0{,}5 \times 10^6 \text{ m}^3$$

If all this water is potentially available to the wells of Southern basin, we should have

$$V_1 + V_2 + V_3 + V_4 = (0{,}36 + 0{,}5 + 2{,}0 + 0{,}5) \times 10^6$$

$$= 3{,}4 \times 10^6 \text{ m}^3$$

which is in good agreement with the value of V_t, calculated from the tritium balance.

This argument is, of course, valid only if there is considerable resistance to flow between the two sections of the aquifer. This should be the case, as the transmissibility in the Southern basin itself is known to be low.

To assess the lowest limit of the tritium concentration being fed to the basin through this mechanism, we calculate the maximum delay and storage in the unsaturated and saturated zones in the adjoining basin. The time constants obtained are 38 years for the unsaturated zone and 25 years for the saturated zone. At such delays, we can assume pre-bomb input, and the output should therefore minimally be 0,3 TU.

The fact that the lowest values measured in Southern basin were 0,8 TU means that more recent water had admixed to these samples, either in the basin itself or from recent infiltration from the river bed.

Lobatse Estates Central Basin

The aquifer of this basin consists of sediments of Pretoria Subgroup quartzites with interbedded shale, calcareous and argillaceous horizons, dipping westwards.

The basin has hillslopes bounding it on the south and east, is separated from the Southern basin by a prominent wrench fault and is thought to be bounded on the north by another fault south of the Peleng River course.

A series of boreholes - 1412, 1429, 1414 and 1379 had been developed in the early 60's. In 1968 an emergency drilling programme was undertaken to supplement the town's water supply, and the boreholes 2239, 2243 2265, 2249, 2250, 2270 2252, 2251, 2271 (see Fig. 173) were drilled. These holes were sited according to detailed geophysical observations which revealed pronounced fractured and weathered zones in the basin.

Tritium concentrations in the Central basin have been consistently low throughout the whole period of the survey, the lowest values being produced by Borehole 1379 at 0,4 ± 0,3 TU. The basin also contains Borehole 1112, which has consistently given amongst the highest tritium concentrations in the whole of Lobatse: 21,3 ± 4,0 TU. (9 measurements). This latter well is rapidly recharged from the river bed and may signify a possible recharge point for the basin.

Well yields in the basin are generally good, especially the new contract holes. The rest level gradient is away from the southern hillslopes and it is thought that, as for the Western basin, the run-off from the slopes constitutes a major source of recharge. This concept was investigated (Verhagen et al 1970) when the new contract holes were being sunk, using a dry drilling process. The first water found in these holes was collected. The tritium concentrations are given in Table 88.

TABLE 88

Tritium concentrations in first water struck

Borehole No	Depth water struck	Tritium TU
2249	50	0,9 ± 0,3
2250	43	1,3 ± 0,4
2265	52	0,0 ± 0,2

Although close to the hillslope, the rest levels were fairly deep and the aquifer overlain by a considerable thickness (approximately 15 metres) of alluvium. At pre-bomb input and 0,4 m yr^{-1} infiltration rate, the aquifer should be recharged at about 0,6 TU in this region.

The variations seen in the Table might be due to local infiltration conditions. On subsequent exploitation (see Table 84) the wells produced consistently low tritium concentrations. More recent water was therefore not drawn in.

A reasonable long-term average tritium concentration for Central basin is 0,7 TU. The turn-over rate is therefore, assuming a well-mixed situation and pre-bomb recharge

$$T = \frac{5 - 0,8}{0,8 \times 0,057} = 93 \text{ yr}$$

which gives a storage capacity for an annual recharge rate of $5,7 \times 10^4$:

$$V = 5,3 \times 10^6 \text{ m}^3$$

The unsaturated zone storage over this basin is likely to be, taking average alluvium depth to be 20 metres, moisture content 8 per cent and area 1,8 km^2 :

$$20 \times 1{,}8 \times 10^6 \times 1{,}6 \times 10^3 \times 0{,}08$$

$$= 4{,}6 \times 10^9 \text{ kg}$$

$$\therefore \quad V = 4{,}6 \times 10^6 \text{ m}^3$$

The difference between these two figures, i.e. $0{,}7 \times 10^6$ m^3 is compatible with an estimated minimum storage of $0{,}4 \times 10^6$ m^3 for the saturated zone, based on drawdown figures (Table 32).

Lobatse Estates North Basin (Fig. 173, Plate 75).

The geological and topographical settings of this basin, as well as its areal extent, are very similar to those of the Central Basin. The storage capacity and recharge rates are therefore taken (Table 33) to be of the same order as those of Central basin.

Some significant tritium variations (Boreholes 1331, 1352) have been seen in this basin, which seems to indicate a shallower alluvium and therefore more direct ingress of rain recharge to the water table than is the case in Central basin. An extreme case is Z388, next to a small surface reservoir, but its high and varying tritium is probably due to local recharge from the adjacent dam.

No quantitative assessment of these results is possible as a recharge rate for the basin has yet to be determined. Water level measurements were shown in Fig. 38.

Stable Isotope and ^{14}C Data - Lobatse

A number of isotopic measurements other than of tritium have been performed on samples from the Lobatse area in the course of this project. They are predominantly radiocarbon results, with an incomplete record of accompanying tritium, ^{14}C, $\delta^{18}O$ and δD measurements. The results are given in Table 88a.

The striking decline in radiocarbon values for Borehole 2270 (Lobatse Estates Central basin) between 1971 and 1973 deserves comment. The well was drilled on a rest level high with the other levels in the Central basin at a lower, fairly uniform elevation. This mound was thought to be associated with a fault, cutting the Peleng River bed, and a guliey in which the well is situated. The enhanced recharge, possibly from the river, is indicated by the high tritium and slightly enriched stable isotope values. On the second sampling in 1973, the well was failing and the ^{14}C concentration dropped. The mound and the very recent water it held had therefore been exhausted.

Other radiocarbon values in the Central basin seem to confirm what tritium failed to detect: that

TABLE 88a

CARBON 14, TRITIUM AND STABLE ISOTOPE DATA, LOBATSE

BH. NO.	LOCALITY	^{14}C (PMC)	AGE	TU	δD‰	$\delta^{18}O$‰	DATE SAMPLED
Z388		85,9±1,8	MODERN				16.2.'73
665		54,0±1,5	3700	1,1±0,2		-5,56±0,09	16.10.'71
1010		29,7±1,0	8500	4,5±0,6	-28,2±0,9	-5,92±0,09	" "
1331		52,0±2,3	4000	1,4±0,4			" "
DC 1 (1378)		46,5±1,1	4850				16.2.'73
1379		54,9±1,5	3550	0,3±0,2	-38,5±1,2	-6,46±0,09	16.10.'71
1379		51,5±1,2	4050				" "
1429		61,6±0,5	2580	1,9±0,4	-42,2±1,8	-7,11±0,09	" "
2254		55,3±2,1	3500	2,6±0,2			" "
2270		115,1±1,7	MODERN	4,2±0,2	-29,7±1,2	-4,85±0,0	" "
2278		63,9±2,0	2290	0,6±0,2	-34,7±1,8	-5,99±0,09	" "
2302		51,6±2,3	4050				16.2.'73
P. 212		52,6±1,4	3900	0,3±0,2	-32,0±0,9	-4,84±0,09	16.10.'71
2271		47,7 0,9					"
1010		30,1±1,5					10.'73
2250		88,3±2,8					"
2262		96,1±1,9					"
2265		85,0±1,9					"
2270		71,6±3,4					"

recharge to this basin is occurring along the hillslope to the south. Older water is found to the north and east, a fact just visible from the tritium values. This lends further credence to the conclusion from the Central basin tritium results that recharge is considerably delayed in the alluvium. Assuming a 15 per cent fossil carbon dilution in the unsaturated zone, the radiocarbon results for wells 2265 and 2250 are about at the upper limit for pre-bomb recharge (age about 20 years).

The two high values in the Northern basin are controlled by different factors. Z388 which has consistently given high tritium concentrations is situated next to a small storage dam which is likely to enhance local infiltration, whilst 2262, close to the hillslope, should reflect significant rapid recharge to the basin.

The radiocarbon values therefore support the heterogeneity of the Northern basin as seen from the tritium concentrations.

The series of results ranging from 46,5 pmc (Railways sub-basin) to 63,9 pmc (Western basin) seem to reflect a mixing of older and younger waters. These values are interpreted as being the result of admixture of recent recharge drawn in by exploitation of the different basins. (In other words, proof of the initial premise that the deep-seated waters were inactive until the basins were exploited).

The most striking example of this mixing process, as seen with tritium, has certainly been the Southern basin. The extreme variability in tritium concentrations led to the rationale that the bulk of the water was being drawn in from beyond the strict confines of the exploited basin. On two samplings, spaced two years apart, well 1010 gave identical radiocarbon values of 30 pmc. This is a very clear indication that the high tritium concentration waters represent but a small part of the effective - and much older - storage available to the wells.

Conclusions Resulting from Isotopic Studies at Lobatse

The main conclusions from this comprehensive research project undertaken by the writer, Professor J. P. F. Sellschop and Dr. B. Th. Verhagen (of N.P.R.U.) are:-

1. Quite distinctively different tritium <u>concentrations</u> as well as <u>variability</u> in concentration is observed in the different basins. These distinctions are in line with the hydrological behaviour of the basins, and are generally consistent with hydrologically distinct units.

2. The variability in some of the basins gives an indication of the extent to which water <u>is mixing</u> in the basin itself, and of whether

other (older) water is being drawn in. This is the case respectively with the Eastern basin and the Lobatse Estates South basin.

3. Higher tritium concentrations have indicated areas of recharge. Such an area was found around the wells DC1 (1368) and DC3 as well as A10, which could be recharged either by the river or from a large gulley to the west. Subsequent to these findings, all the wells in the area were accurately levelled during a period in which no water was pumped. Wells 1368 and A10 had markedly higher water levels than those elsewhere. A recharge area was therefore discovered.

4. The recharge mechanism to a number of these basins was more clearly defined. The seepage through the unsaturated zone over the Western basin was shown to be supplemented by a more rapid ingress of water probably along a scree zone. The rapid recharge to Eastern and Southern basins was linked largely to the flooding of the Peleng River. (Plate 55).

In the Central basin, however, tritium failed to indicate the sources of mechanism of recharge, because of the general lowness of the concentrations. The consistent extreme lowness of tritium concentration of Borehole 1379 (-mean value 0,4 TU) gives some indication of flow to the southwestern part of the basin, whilst Borehole 2270, near a fault cutting the river bed and in a major gully on the hillslope, shows both higher tritium concentration and water level. For the rest, concentrations in the Central basin are quite uniform, indicating good mixing in this highly permeable aquifer (proved by aquifer testing).

5. Calculating <u>storage capacities</u> for the different basins from tritium data provided consistently higher values than those obtained from the drawdown and pumping figures alone. However, infiltration measurements through the unsaturated zone have underlined the importance of storage in that zone. As the turnover rate in a ground water basin, calculated on the premise of the well-mixed model, takes account of <u>all</u> the water, a basis has now been found for a more reasonable correspondence between the two approaches. In addition, it now becomes clear that the "classical" storage calculations, although still lower limit estimates, are closer to a true assessment of the recoverable storage than previously believed.

6. On the basis of the tritium concentrations found in different parts of a basin and at different times, it has been possible to propose a model of the behaviour of Lobatse Western basin. Although the saturated zone storage capacity is still the lower limit estimate, it is felt that this model is basically valid and can be employed in the assessment of similarly situated ground water basins.

7. The value of the model mentioned under 6 has been demonstrated in the assessment of the other Lobatse ground water basins, such as the Central basin. In the Southern and Eastern basins, it has highlighted an additional and extremely important parameter, that of leakage into the basins from adjoining areas.

8. A conclusion of great importance to the assessment of the general ground water situation in Lobatse can be derived from the previous paragraph. Although there exists no regional drainage pattern in the Lobatse area, and the ground water basins such as postulated do show individual characteristics, leakage between several of these basins has now been clearly established.

The tritium survey has therefore indicated that the division of the Lobatse valleys into a number of discrete basins is justified only as a first-order approximation for reasons of convenience of analysis. There exists, however, a degree of hydrological continuity which has to be taken account of in the more accurate assessment of the compartmentalised system.

9. Other isotopic data gathered in the Lobatse region has corroborated a number of the basic features deduced from the tritium survey and other hydrological evidence. The important contribution here is from radiocarbon measurements, which have underlined

a) by the uniformity of the concentrations in most of the Lobatse aquifers, the assumption that the basins were hydro logically inactive before exploitation commenced ;

b) the general drainage pattern in the Central basin and the demonstration of the recharge areas, which tritium failed to do;

c) in excellent fashion the mixing of younger into older water as seen by tritium in the Lobatse Estates Southern basin as well as in the Railway basin.

These facts emphasise the importance of simultaneous measurements of tritium and radiocarbon as well as other isotopes. However, the detailed tritium survey as undertaken could not have been substituted by a more intensive measuring routine for radiocarbon. In a hydrological regime such as found in Lobatse, the basic information can only be forthcoming from a short-lived, conservative tracer such as tritium, even at low levels, with other isotopes providing complementary, and sometimes supplementary, information.

The Serowe Basin

The town of Serowe is situated at the foot of an escarpment to the west and north. It is the largest town in Botswana (pop. 32,000) and the capital of the Bamangwato tribe. It is liberally provided with boreholes, which constitute the only water supply. Fig. 175 shows a sketch map of the village and indicates a number of these boreholes. They have been drilled, mostly to a depth of 91 metres, into a secondary confined aquifer, this being the contact zone between sandstone, and

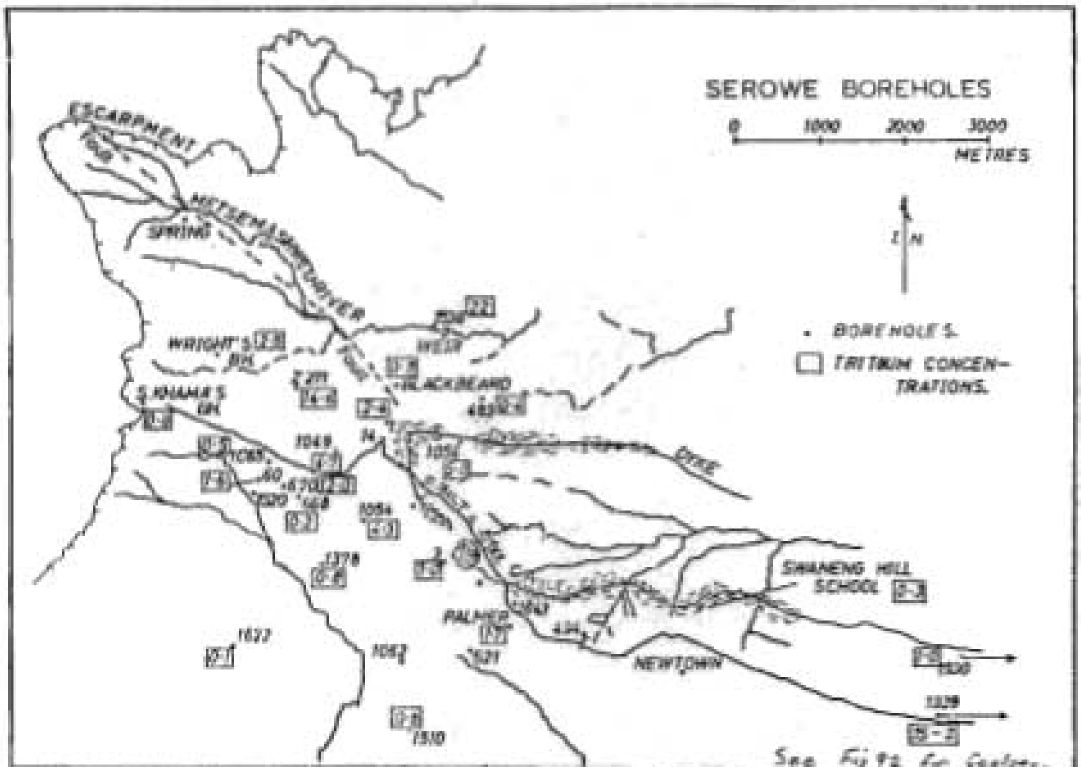


FIG. 175 Serowe Boreholes and Tritium Concentrations.

At first glance, therefore, even in the absence of any supporting information, the environmental tritium data clearly indicate significant recharge to the aquifers. In addition, this recharge is not equally evident in all boreholes, which indicates geohydrological heterogeneity.

The higher tritium concentrations are found in waters lying in an area stretching from west to southeast of Serowe hill, which coincides with the ground water mound in this vicinity. This confirms the postulate that this constitutes an important recharge area.

To the northeast of the fault, tritium concentrations are low in the unconfined sandstone which seems to confirm the poorer infiltration into this aquifer. The fault is therefore a controlling factor in recharge and might facilitate infiltration into the confined aquifer. However, its importance seems to be mainly its separation of two distinct hydrological situations. A striking case of infiltration is demonstrated by the very high tritium concentrations (22 TU) in Borehole 1538, situated next to a dam in the Metsemasweu river, which is now completely silted up by sand. This demonstrates direct and extremely rapid recharge to the shallow aquifer tapped by the borehole.

In the confined aquifer, tritium concentrations tend to drop as one moves away from the fault area to the south and southeast. This could corroborate the postulated ground-water flow away from the recharge area with its high water levels. Recharge through the basalt is determined by the degree of weathering, fissuring etc., and the higher tritium concentrations in some basalt boreholes probably indicate areas of local recharge through the basalt.

Sampling from unused (observation) boreholes using a depth sampler has proved to be a most fruitful technique in the environmental tritium study in Serowe. Large fluctuations in concentration were observed in two boreholes, 670 and 1929 as well as transient depth profiles. (See Tables 85, 86). These results demonstrated direct recharge through the basalt and subsequent slower mixing into the whole ground-water reservoir.

In the case of Borehole 670, the high value of 12 TU coincided with an extreme high in the hydrograph (see Fig. 176). The tritium concentration then dropped along with the hydrograph. Over the same period, extreme stratification was observed in Borehole 1929 which then equalised fairly rapidly and eventually vanished. Interestingly, this was not accompanied by any large rest level fluctuations (less than 0,5 metres). A further point of interest is the fact that Borehole 1929 lies several kilometres to the east of the recharge area in which Borehole 670 is situated. The presence of tritium in Borehole 1929 therefore indicates that significant infiltration occurs in other areas as well as in Central Serowe.

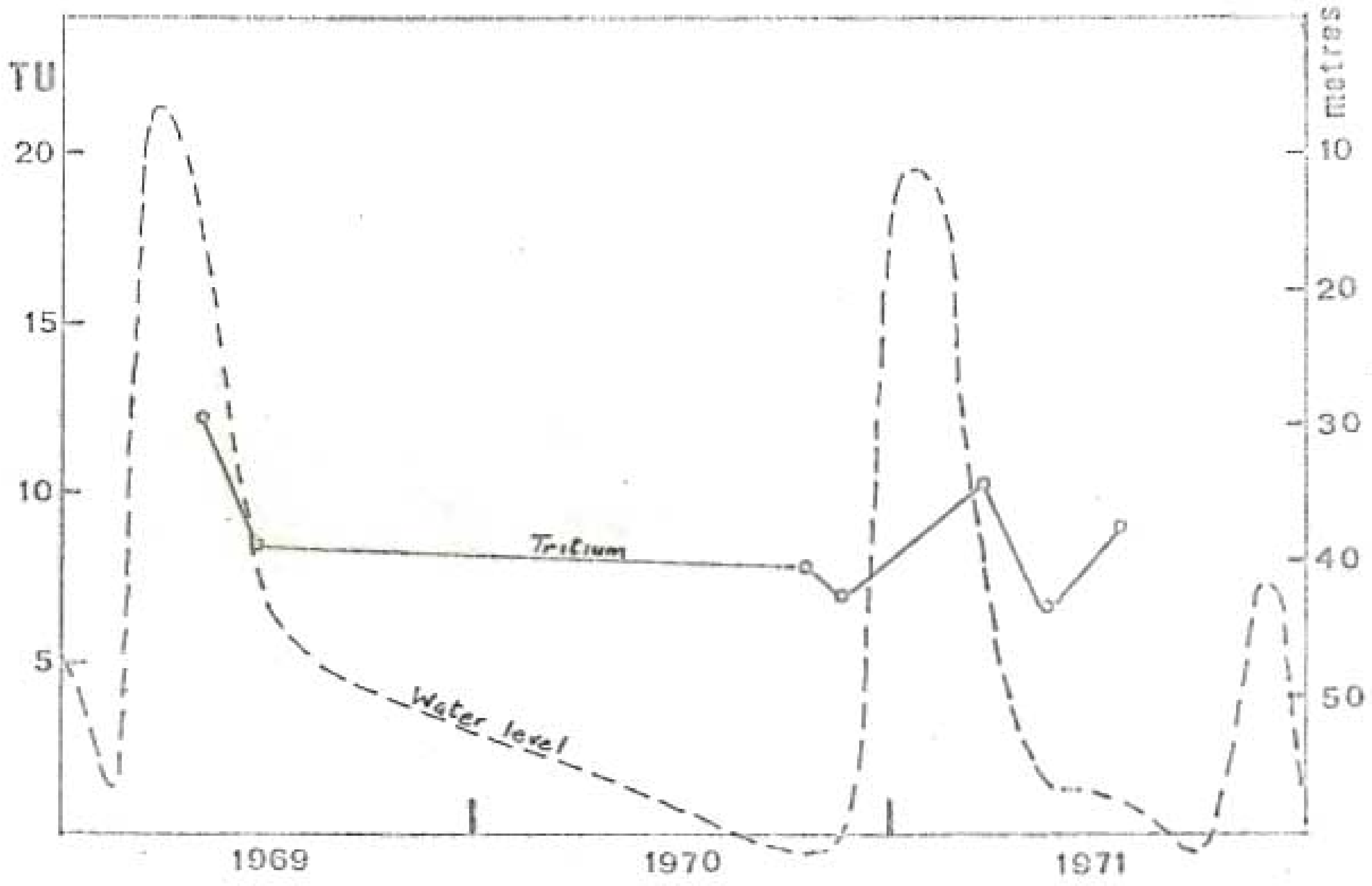


Figure 176 : Bh. 670, Serowe. Hydrograph and ^3H concentration

Borehole 670 is known to be sited in a basin of decomposition in the basalt and during the period of observation described above was being used as an observation hole in the immediate vicinity of two production holes. The interpretation given to the observed tritium concentrations and the hydrograph is as follows:

Tritium concentrations rise immediately on rain recharge. The tritium is fairly rapidly dissipated by both the exploitation and the mixing of the recharged water into the underlying aquifer. The uniformity of the tritium concentrations throughout the column is associated with the large rise in water level in the upper low storage capacity perched basin in the basalt. Exploitation then kept the mixture that developed between younger and older water uniform. The persistence of the higher tritium levels for some time could be associated with a much higher impedance to downward than to internal mixing. (See Table 53, p.420).

In Borehole 1929, hydrological conditions are far more uniform and the tritium profile in the static water column in the hole reflects the downward mixing remarkably clearly. This downward mixing is taken as important evidence (See chapter on Serowe in this thesis) that the lower portions of the sandstone constitute a significant aquifer, in contrast to earlier assumptions (Anon, 1969) that water is confined to the upper (contact) zone.

^{14}C and Stable Isotope Data - Serowe

A small body of additional isotopic data was collected in Serowe during October 1971. This is shown in Table 55(p.425).(See Chapter on Hydrogeology of Serowe).

The radiocarbon results of the first four sampling points indicate rapid recharge. This is consistent with the known hydrogeology which makes recharge likely.

Borehole 1378 at 13,2 pmc has water with a minimum age of about 15 000 yr. The age might be greater as the measureable tritium could indicate that more recent water is being pumped along with the old water. The basalt cover at this site is about 45 metres. No infiltration of any consequence seems to reach the confined aquifer in the vicinity of the borehole . If it is assumed that the water originates from the main recharge area, at a maximum distance of 2 km, the flow rate would be about 0,13 m per year. Unless some geological feature isolates these boreholes from the hydrologically active part of the Serowe ground-water system, this would imply an almost negligible transport of water, i.e. an almost static system. The deuterium and oxygen -18 values for this water are noticeably lower than the range indicated by the four younger waters, possibly indicating a slightly different climatic regime at time of recharge;

alternatively the water is the result of infrequent heavy recharge events.

Recharge and Storage Capacity

The infiltration (rain recharge) rate calculated in the chapter on Serowe is the actual average annual abstraction rate, based on the assumption that no other losses occurred and that the average piezometric levels have not been affected in the long term. This amount ($3,6 \times 10^5 m^3 yr^{-1}$) should therefore be the recharge rate over the whole area from which groundwater is abstracted. This area, to the south and west of the fault can not be easily determined, but is should not be less than $25 km^2$. There is tritium evidence that active recharge is occurring over large sections of this area. The following calculations are made, assuming that water in the sandstone aquifer was in a near static state before major pumping commenced and that present-day tritium levels are the result of exploitation and a drawing in of recent recharge. The present average level is about 0,4TU. (See Serowe depth profiles and pumped samples-Tables 85,86). The period of important exploitation is taken to be 14 years. The loss of tritium due to exploitation over this period should be negligible, at 0-0,4TU, compared to the input. Summing the tritium values under the piston-flow curve (Fig.177) we can write down the tritium balance equation:

$$\frac{428 \times 3,6 \times 10^5}{25} = 0,4 \times V_a$$

$$V_a = 1,5 \times 10^7 m^3/km^2$$

Where V_a is the areal storage capacity of the confined/semi-confined sandstone aquifer. This lies well within the limits of $(0,5-2,6) \times 10^7 m^3/km^2$ calculated from porosity data for the Cave sandstone at Orapa. Because of the similarities in the hydrogeology of the two areas, the figure of $1,5 \times 10^7 m^3 km$ is therefore regarded as being a reasonable figure for Serowe

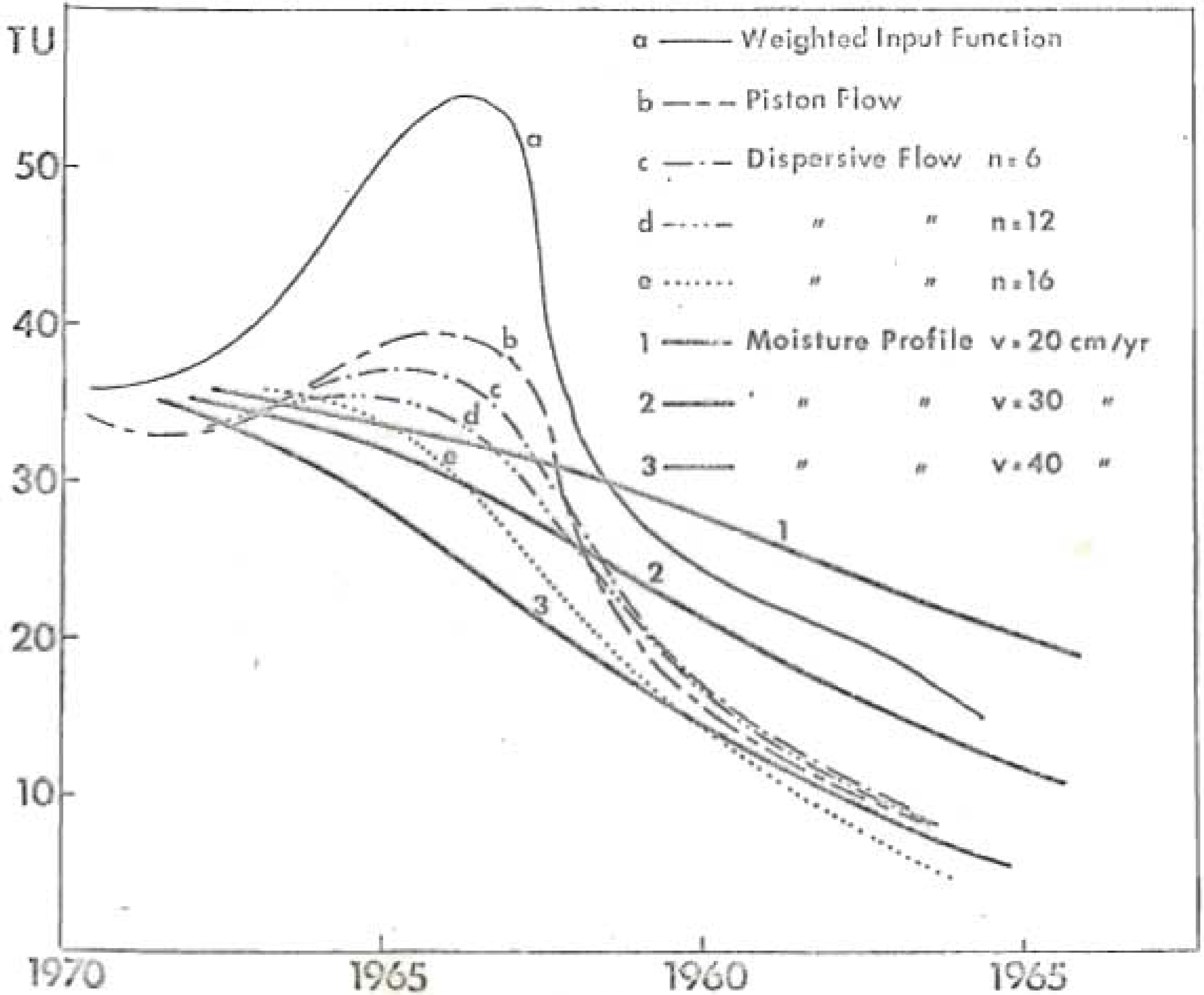


Figure 177 : Rainwater input function for tritium with piston flow and dispersive flow models

Conclusions Resulting from Isotopic Studies at Serowe

Conclusions resulting from this five year isotopic study of the Serowe have recently been given by Verhagen et al (1974). The main conclusions are:-

Conclusions - Serowe Area

1. As in the case of Lobatse, tritium concentrations and their variability confirmed the general hydrological picture in Serowe. To the north-east of the fault, in the unconfined sandstone, low tritium concentrations confirm the poor transmissivity and yield of the aquifer. Immediately to the south and southwest, higher tritium concentrations, variable in time and position, are evident .

2. Tritium concentrations were found to follow variations in rest levels in certain boreholes in the confined and semi-confined aquifer region, proving the direct nature of rainwater recharge in the decomposed zones. The manner in which tritium concentrations varied and the transient nature of depth profiles (such as Borehole 670 and Borehole 1929) showed in a unique fashion the mechanism of mixing of recent recharge with older deeper-seated water. The mixing process furthermore proved the existence of a deeper, primary aquifer in the sandstone,

3. Linking tritium with a parallel tracer, in this case the ground-water chemistry, has provided a powerful tool with which to establish the extent as well as the general (areal) nature of the recharge to the confined and semi-confined aquifer, which appears to be taking place largely through decomposed areas in the basalt.

4. In the correlation of chemistry and tritium concentrations, the importance of repeated measurements was clearly demonstrated. Averaging all low-level tritium concentrations is a powerful method of overcoming uncertainties about contamination of occasional samples.

5. For the first time, it has become possible to assess the magnitude of the available storage capacity in the recharged area of Serowe. This was done by balancing the tritium input against actually observed concentrations in the aquifer. The fact that this exercise provided a figure within the range expected for a geologically similar environment, shows that the method is at least as powerful, if not more so, than laboratory tests of aquifer porosity.

6. Information provided by other isotope data is not in contradiction with the deductions made

from the tritium survey. It must be stated, however, that the paucity of this data might be to blame. High radiocarbon concentrations confirm the rapid infiltration in some isolated cases, whilst the high effective age for Borehole 1378 indicates a slow-flow rate in the cave sandstone, which helps to validate the basis for the calculation of the storage capacity.

Tritium Results from Pump Tests near Selebi-Pikwe

Robins (1972) has noted an interesting variation in tritium content with time during a pump test on Borehole 2403 adjacent to the ephemeral Letlhakane River, near Pikwe. These changes are shown in Table 89.

TABLE 89

VARIATIONS IN TRITIUM CONTENTS - BOREHOLE 2403

Time of sampling			TU	Amount of water pumped in gallons	Tds in ppm
½ hour		after start of test.	1,1 ± 0,3	5 000	3443
8 hours		"	1,5 ± 0,3	80 000	3171
24	"	"	1,6 ± 0,3	240 000	2863
48	"	"	2,5 ± 0,3	480 000	2760
72	"	"	2,8 ± 0,3	720 000	2675

This increase in tritium content with a concomitant decrease in dissolved solids is interpreted by the writer as indicating that younger fresh waters were being drawn into the expanding cone of depression. These younger waters were probably related to recent recharge of the aquifer in the vicinity of the large sandy river bed of the Letlhakane which carries surface run-off for brief periods in most years.

During a similar pump test, carried out by the writer in February 1970 on Borehole 2213, the exceptionally high values of 17,8±1,3 TU were obtained from nearby Boreholes 2216 and 2230.

THE STABLE ISOTOPES

The two principal heavy stable isotopes of water are deuterium (D or ^{2}H) and oxygen -18 (^{18}O) which occur in the form HDO^{16} and molecular $H_2{}^{18}O$ respectively. They occur in natural waters in concentrations of about 320 p.p.m. and 2 000 p.p.m. respectively. Small, but significant, variations are found in the stable isotope content of natural waters which can be measured by a mass spectrometer with a precision of ± 0,01 per cent.

The isotopic composition of a water sample is expressed in terms of per mille (‰) deviation from a standard rather than direct analysis of the absolute ratios.

The standard of reference in general use is an arbitrary point of reference called SMOW (Standard Mean Ocean Water) as originally proposed and defined by Craig (1961a). The data are thus expressed as delta units (δ) defined by $\frac{R - R\ SMOW}{R\ SMOW} \times 10^3$ ‰ where R refers to the isotope ratio $\frac{D}{H}$ or $\frac{^{18}O}{^{16}O}$.

The isotope composition of SMOW is approximately $\frac{D}{H} = \frac{160}{10^6}$ and $\frac{^{18}O}{^{16}O} = \frac{1.98}{1\ 000}$. Where values are negative then the sample contains less of the heavy isotope than SMOW while positive delta values indicate enrichment of the particular stable isotope compared to average sea water.

The use of oceans as a standard is determined mainly because the oceans are the source and sink for all water in the hydrologic cycle and can be regarded as a steady-state system. Whenever water changes state through evaporation, condensation or freezing, an isotopic fractionation occurs which results in the heavy isotopes being enriched in the phase having the lower vapour pressure (i.e. heavy isotopes are less volatile). Thus moisture evaporated from an open water body such as the sea is depleted in deuterium and ^{18}O with respect to the surface water. When moist marine air masses pass over the continents, the first precipitation condensing is relatively close in stable isotope content to that of the sea from which it is derived and the remaining atmospheric moisture is depleted with respect to SMOW. There is thus a continuing depletion of the heavy isotope content due to "prefential rainout" of the water containing the heavy isotopes. Thus the more continental the location, the greater is the depletion in heavy stable isotopes. Craig (1961b) was able to determine a linear relationship for waters not subjected to evaporation between the D and ^{18}O concentrations, $\delta D = 8\delta^{18}O + y$ where y is usually +10. This is shown by the line AB below in Fig. 178.

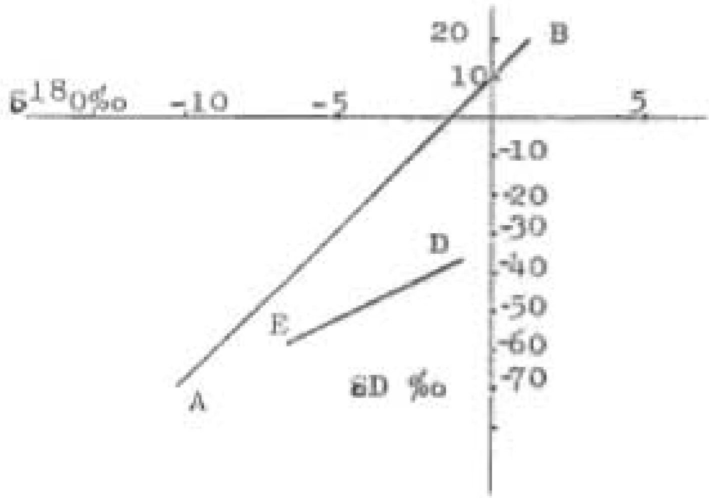


Fig.178. A schematic $\delta D - \delta^{18}O$ Diagram (after Craig,1961b)

Where evaporation has occurred δD and $\delta^{18}O$ values fall off the line of slope 8 and may have a slope of 4 to 6. (e.g. line ED in Fig. 178).

During evaporation the relative fractionation of deuterium and oxygen -18 is dependant on several factors and the ratio of one to the other may be used as a qualitative indication of the process involved. At present it cannot be employed quantitatively to determine the amount of evaporation, because the underlying physical relations are imperfectly understood.

Ehhalt et al (1963) and Vogel et al (1963) mention that rainfall in Southern Africa can be considerably enriched by evaporation during its fall to earth. This can be observed in Botswana, particularly in the hot, early summer months, when light showers can be observed in the sky but which do not reach the ground because of evaporation.

This evaporation does not take place under equilibrium conditions and the relation between D and ^{18}O is then $D = 5\delta^{18}O + k$. Thus waters whose stable isotopes plot off the general line of slope 8 can be presumed to have been subjected to evaporation.

The variation of stable isotope content with temperature is now a well-documented fact (Friedman 1953, Epstein and Mayeda 1953, Dansgaard 1954, 1961 and 1964, and Ehhalt et al 1963). Vogel et al (1963) carried out pioneering work in Southern Africa using stable isotopes. Fractionation is especially sensitive to the temperature of evaporation and condensation (Dansgaard 1964), and the lower the temperature the greater the depletion in heavy isotope content. This temperature effect causes variations with latitude because of the close relationship between mean annual temperature and latitude. Similarly, variations in composition can be related to the altitude of precipitation and thus orographic rainfall can be clearly distinguished from that falling on nearby lower-lying areas. These various factors that affect the temperature of condensation greatly complicate the interpretation of stable isotope data from single storms, but integrated monthly rainfall samples show a consistency over long periods. As hydrologic systems tend to smooth the variability of the input, streams show much less variability than rainfall while ground waters show very little or no seasonal change in their stable isotope content. This lack of variability makes stable isotope analysis very valuable in characterising different ground waters and relating them to the source and season of recharge. Thus, from a practical point of view, the use of stable isotopes in geohydrology can determine whether the water was derived from local rainfall; whether the precipitation occurred at high altitude; the season of recharge; whether the water had been subjected to considerable evaporation or whether the water had come from a different latitude. In particular, it is possible to determine whether ground waters are recharged locally by present-day rainfall or from influent flow from rivers or lakes or from rainfall from some previous period (e.g. a cold

Pleistocene pluvial epoch). The origin of spring waters can also often be easily resolved by a study of their stable isotope content. As light rainfall differs considerably in δD content from that of heavy downpours it is also possible to determine the type of rainfall which results in recharge of boreholes:

Stable Isotope Measurements in Botswana

Surface Waters

Results of sampling of surface waters are given in Table 90 :-

TABLE 90

CHOBE - OKAVANGO RIVER SYSTEMS - ISOTOPE DATA

DATE OF SAMPLING	LOCALITY	δD SMOW	TRITIUM IN TU	REMARKS
8.5.70	Chobe R. Kasane	-20,34	23,8±1,5	River in full flood
11.3.70	Thamalakane R Mathlapaneng Bridge	+21,56		
15.4.70	" "	+43,15		
13.3.70	Thamalakane R Maun	+ 5,72		
15.4.70	" "/Boro R junction	+52,95		
15.4.70	Boro drift (upstream of above)	+49,23		
20.4.70	Kunyere R	+32,50		
20.4.70	" "	+33,39		
10.5.70	" "	+36,36	27,2±2,2	
12.5.70	Boro River		20,8±1,2	
[illegible]	[illegible]		[illegible]	

The large difference in δD for waters of the Okavango system and that of the Chobe River is readily explained by the fact that the Chobe River was in full flood with waters derived from summer rainfall on the inland catchment areas in Angola, whereas the waters sampled from the Okavango system were all sampled from the lower drainages from the Okavango swamp at a stage just prior to the annual flooding. These waters had been subjected to considerable evaporation in the large shallow swamp land occupied by the Okavango delta during the hot, late summer period.

TABLE 91

LAKE NGAMI ISOTOPE DATA

DATE OF SAMPLING	LOCALITY	δD SMOW	TU
20.4.70	Lake Ngami	+36,59	
20.4.70	Lake Ngami	+37,53	
12.5.70	Lake Ngami	+58,36	29,5 ± 1,6

Note the enrichment in δD (Table 91) following an extra 23 days of evaporation over this large but very shallow lake.

TABLE 92

LAKE XAU - Mopipi Pan Area

ISOTOPE DATA

Date of Sampling	Locality	δD SMOW	TU
8.5.70	Lake Xau	+68,74	30,3±1,6
8.5.70	Mopipi Pan	+38,69	23,7±2,5
26.6.70	Mopipi Pan		31,1±1,7
21.8.70	Mopipi Pan		32,0±2,0

The reason for the difference in the above two adjacently situated, shallow lakes (Table 92 , one an artificial lake covering 2320 ha created for Orapa Diamond Mine Water supply), is probably that water for the Mopipi Pan was pumped several months earlier (July, 1969 - December, 1969) from the Lake Xau overflow into Mopipi Pan at peak flood time and was then subjected to less evaporation in the much deeper (6,4m), vegetation free, Mopipi Pan than the shallow Lake Xau (1 - 2m) where greater evaporation and transpirative losses probably occurred. The author thus feels that this may be utilized to give an empirical formula for the quantitative determination of the amount of evaporation of water from a free water surface. Rates of evaporation for the period since the filling of the Mopipi Pan in December, 1970 have averaged about 17,78 cm per month but doubled during the summer of 1972/1973 when abnormally hot, dry and windy weather prevailed.

Ground-waters

TABLE 93

BOREHOLES NEAR OKAVANGO SWAMPS - ISOTOPE DATA

Date of Sampling	Locality	δD SMOW	TU
27.4.70	T.F.C. Borehole	-6,14	7,0±0,6
12.5.70	T.F.C. Borehole	-8,27	
20.4.70	Setateng Borehole	-28,84	

This slight difference in the T.F.C. Borehole above in Table 93 may indicate recent recharge from D depleted peak flood Okavango Swamp waters. Thus further research may yield fruitful data on the use of stable isotopes to provide data on rates of recharge and possibly even to obtain quantitative data on recharge quantities. The lighter isotope content of the Setateng borehole indicates greater recharge by unevaporated Okavango flood waters than the T.F.C. borehole.

TABLE 94

WELL NEAR LAKE NGAMI - ISOTOPE DATA

Date of Sampling	Locality	δD SMOW	TU
20.4.70	Vlotoma's well near Sehitwa	-3,16	(0,9±0,3- 18.7.70 2,0±0,3)

This well shows D enrichment relative to other ground-waters due to recharge from evaporated surface waters.

TABLE 95

ISOTOPE DATA -

WELLS AND BOREHOLES EAST OF MAUN AND ORAPA

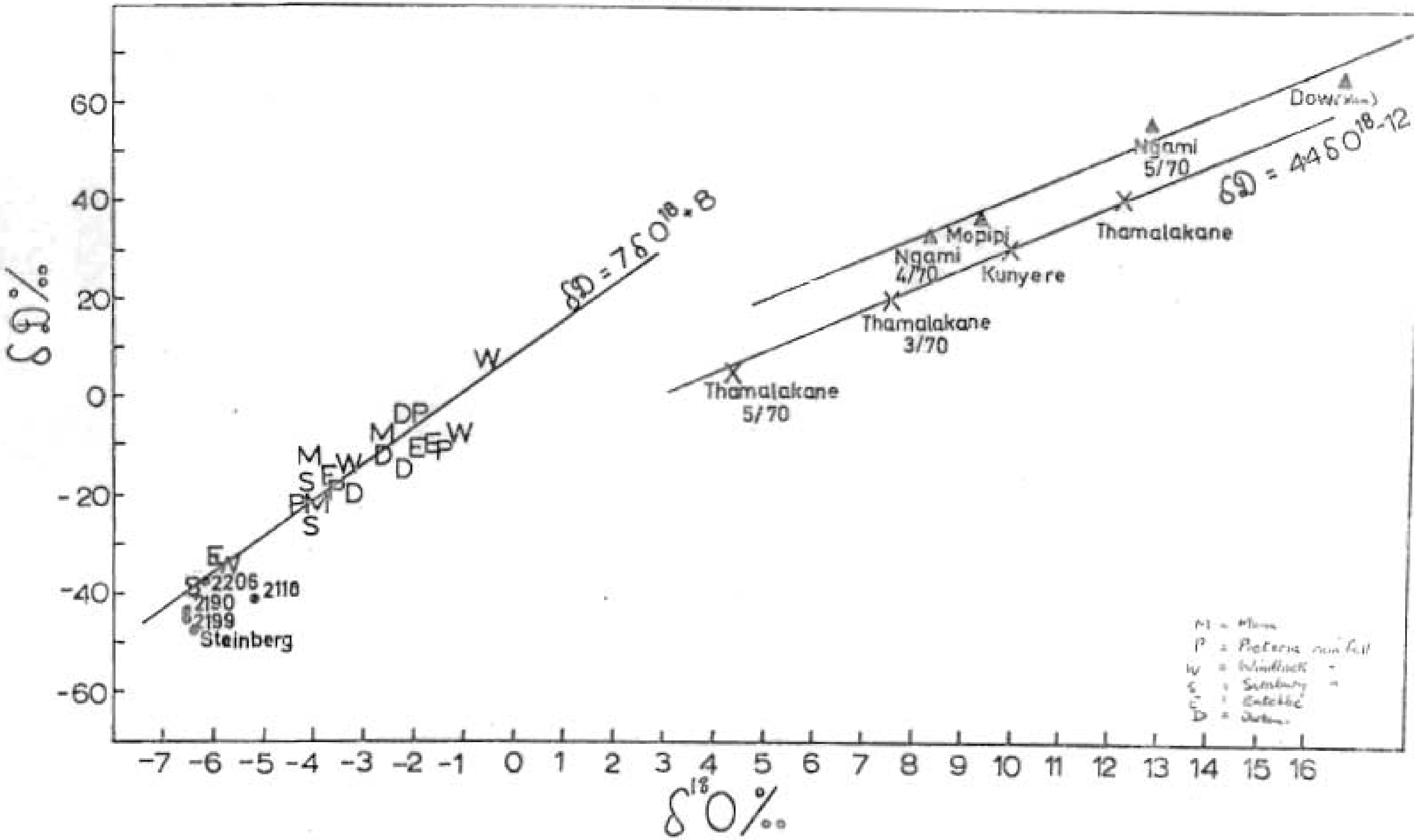
Date of Sampling	Locality	δ D SMOW	T
15.4.70	Tshipidi No. 1 well	-50,25	
12.5.70	Tshipidi No. 1 well	-47,50	3,3±0,4
15.4.70	Tshipidi No. 2 well	-42,63	
12.5.70	Tshipidi No. 2 well	-54,96	4,5±0,6
15.4.70	Phefodiafoku well	-52,61	
12.5.70	Phefodiafoku well		3,7±0,5
Orapa Boreholes and Wells			
7.5.70	Bh 2118 Orapa	-41,46	
7.5.70	Bh 2152 " pumped water	-43,62	
7.5.70	Bh 2174 " " "	-47,03	2,8±0,3
7.5.70	Bh 2179 " " "	-53,45	1,7±0,3
7.5.70	Bh 2183 " " "	-45,58	2,0±0,2
7.5.70	Bh 2184 " " "	-44,58	3,5±0,3
7.5.70	Bh 2185 " " "	-46,72	2,7±0,3
7.5.70	Bh 2190 " " "	-45,08	
7.5.70	Bh 2192 " " "	-40,80	
7.5.70	Bh 2193 " " "	-46,35	1,8±0,3
7.5.70	Bh 2199 " " "	-43,80	
7.5.70	Steinberg Bh " "	-45,66	4,5±0,4
7.5.70	Landing strip" " well, Orapa	-44,72	
7.5.70	Township NO. 10 Orapa " "	-43,61	
7.5.70	Township No. 9 Orapa " "	-44,77	
9.5.70	Bh 2199 Depth = 50' " "	-47,06	2,9±0,4
9.5.70	Bh 2199 D=100' " "	-45,45	2,4±0,4
9.5.70	Bh 2199 D=219' " "	-46,84	
9.5.70	Bh 2199 D=300' " "	-49,56	18,4±0,8
9.5.70	Bh 2206 D=50' " "	-45,64	3,3±0,3
9.5.70	Bh 2206 D=100' " "	-42,64	1,9±0,2

All the above boreholes from Orapa and from wells east of Maun (Table 95) show remarkably little variation in δD content thus indicating quite clearly that they have a common or similar source of origin (either present day rainfall or rainfall during some past Pleistocene pluvial recharge period). The marked difference between the enriched waters of the Okavango, - Lake Ngami - Boteti, - Lake Xau system clearly rules out the hypothesis of recharge from these waters. The differences between the Orapa ground waters, surface waters from various rainfall stations in Southern Africa, the highly evaporated waters of Lake Ngami, Lake Xau, Mopipi and the Thamalakane and Kunyere Rivers (Okavango outlets), are clearly shown in Fig.179 . Comparison of the δD values, found in Botswana, with values obtained elsewhere in the world (Friedman, 1953; Horibe and Kobayakowa, 1960) show that average values, given as between +15‰ and -15‰ for δ D, are considerably exceeded in Botswana.

Comparison with D Values for Present Day Rainfall

Comparison of the considerable amount of data for rainfall in Southern Africa collected for the world network (International Atomic Energy Agency 1969,1970,1971) shows clearly that heavy falls of rain at inland stations in general contain the lightest isotopic content e.g. during the period 1961 - 1967 the lightest monthly δ D content of -84,2, -66,4 and -63,2‰ at Salisbury (Rhodesia) were associated with some of the heaviest monthly rainfalls of 225, 185 and 145 mm respectively. During the same period the lightest isotopic δ D content in Windhoek (South West Africa) was -115, -57,0 and -48,3‰ δ D. At Pretoria, the lightest isotopic content was -35,4‰. δ D. By extrapolation

FIG 179



δD‰
δ^{18}O‰
60
40
20
0
-20
-40
-60
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
δD = 7δO^{18}+8
δD = 4.4δO^{18}-12
Dow
Ngami 5/70
Mopipi
Ngami 4/70
Kunyere
Thamalakane
Thamalakane 3/70
Thamalakane 5/70
2206
2116
2190
2199
Steinberg
M
P
W
S
E
D

706

heavy rainfall in Botswana should fall somewhere between that for Pretoria which had weighted δ D means for 1962 and 1963 of -17,35 and -19,98 respectively and that of Windhoek which had weighted means for the same period of -14,2 and -32,46 δD‰ respectively. It is interesting to note that the total annual rainfall for Windhoek in 1963 was more than double (753mm) the mean annual rainfall (370mm), while in 1962 the rainfall (242mm) was 65% of the mean annual rainfall. The annual rainfall for Pretoria for 1962 and 1963 (612 and 600mm respectively) represents 82 and 80% respectively of the mean annual rainfall of 746mm.

The fairly large difference between mean δ D values for groundwater in the Orapa area (-47,6%o) and known weighted mean rainfall values for similar climates e.g. Pretoria and Windhoek, indicates a strong possibility that the ground waters stem from a former period, possibly a pluvial associated with Pleistocene glaciation or could be derived from exceptionally heavy reainfall and hence low temperatures associated with an unusual southward migration of the zone of Inter Tropical Convergence.
Vogel and Bredenkamp (1969) carried out stable isotope measurements on rainfall at Upington southwest of the southern tip of Botswana for the 1966/1967 and 1967/1968 rainy seasons and arrived at a weighted mean of δ D =-21,2%o. They were thus able to conclude that 33 samples of ground water from the Kalahari area south of the Botswana border with an arithmetical mean δ D content of-36,97%. were not recharged during 1966/1967 or 1967/1968 but were probably recharged during an earlier period of excessive rainfall and low evaporation.

Comparison between stable isotope tritium and ^{14}C data on waters from Orapa area

TABLE 96

BOREHOLES SAMPLED FOR D, ^{14}C AND T- ORAPA

Borehole No.	Carbon-14 pmc	Tritium TU	δD_{SMOW}
2153	10,1±0,3	0,6±0,3 to 1,9±0,5	-43,62 (2152)
2175	9,3±0,5	0,0±0,1	-47,03 (2174)
2182	15,0±0,4	0,4±0,2	-45,58 (2183)
2184	22,6±0,3	1,7±0,4 to 3,5±0,3	-44,58
2199	9,1±0,5	0,7±0,3	-43,80
2206	20,2±0,8	0,8±0,2	-42,64 to -45,64
Steinberg's	86,2±2,0	2,8±0,3	-45,66
		Arithmetical mean	-44,8

The most striking evidence afforded by a comparison of isotope data (see Table 96) on waters from boreholes in the Orapa area is that there is remarkably little difference in deuterium values yet there are marked differences in the amount of ^{14}C present varying from old waters (9,1 per cent modern carbon - pmc - to 86,2 pmc) while tritium variations tend to mirror those of ^{14}C. The most important conclusions that can be made from the above data therefore are:(1) that ground waters in the Orapa area range in age from over 17 000 years to modern, though (2) they are mostly "old", (3) they have measureable amounts of tritium indicating some recent recharge and (4) yet water which can be regarded as modern (Steinberg's), has a nearly identical deuterium content to that of waters (e.g. 2199) that are over 17 000 years old. From this the important conclusion can be reached that intermittent recharge has taken place over the time scale of carbon- 14 (i.e. ± 50 000 years) under climatic conditions varying very little from that of the present day but that actual recharge only occurs during times of excessive rainfall and consequently during cool climatic conditions when little evaporation takes place.

Comparison between stable isotopes, tritium and ^{14}C data on waters from the Kweneng area

TABLE 97

BOREHOLES SAMPLED FOR D, ^{14}C AND T-KWENENG DISTRICT

Borehole	Description	δD SMOW	Tritium TU	^{14}C
314	Letlhakeng	-31		15,52±0,25
763	Kadijwe	-41		82,6±0,42
780	Tsoto	-45		4,92±0,18
858	Morwamosu	-32	0,8±0,4	31,92±0,20
1028	Phuduhudu	-35	) 5,3±0,7	15,18±0,45
1102	Mabutsane	-32	) 6,4±1,0	86,39±0,55
1221	Khekwe	-30	0,7±0,4	28,24±0,31
1616	Kgorwe	-29		45,64±0,31
Arithmetic mean		-34,37		

Of eight boreholes sampled (Table 97), six of these with ^{14}C ranging from 15,52 to 86,39 pmc have δD values ranging from -29 to -32 per mille. The other two have values of -41 and -45 ‰ with ^{14}C values of 82,61 and 4,92 pmc respectively. From the above table it can be seen that the mean δD value of -34,37‰ for the Kweneng area is isotopically heavier than that of the Orapa area (mean δD = -47,61) and is similar to the mean value of -36,97‰ obtained by Vogel and Bredenkamp (1969) in the

The Orapa area is situated just south of latitude 21 degrees S., is approximately 360 km northeast of the Kweneng area and thus falls near the southern limit of the Inter Tropical Convergence Zone. The lighter isotopic content of the ground water at Orapa could thus be explained by heavier storms (associated with a southward migration of the zone of the Inter Tropical Convergence), falling at Orapa with consequent slight evaporative losses prior to infiltration compared with the areas further south in the southern Kahalari areas.

CARBON-FOURTEEN

The carbon-fourteen (^{14}C) dating method first gained prominence when its value in dating archaeological remains was realised (Libby, 1946). Munnich (1957) was the first to adapt the ^{14}C method to the dating of ground water when he discovered that dissolved bicarbonate in recent ground water, like all living organic matter, contained ^{14}C at a fairly fixed level. Ground water containing dissolved carbonate species could thus be dated in similar fashion to other substances containing carbon, such as bone. The early work of Munnich was followed by papers by Munnich and Vogel (1959), Brinkmann et al (1959, 1960), Munnich and Vogel (1960), Vogel and Ehhalt (1963), Vogel (1967, 1969, 1970), Wendt et al (1967), Munnich et al (1967), Geyh (1970), Pearson and Hanshaw (1970), Thilo and Munnich (1970), Mazor et al (1974) and others.

^{14}C is the radioactive isotope of carbon. It has a half-life of 5 730 years and thus, because of its exponential decay, age measurements up to 50 000 years can be made. Although the use of carbon dating for the dating of archaeological remains is now well known, its potential in the ground water field has so far undeservedly received relatively little recognition by the ground water hydrologist. ^{14}C is produced in the upper atmosphere by the interaction of cosmic-ray produced neutrons with atmospheric ^{14}N and decays by beta emission. $^{14}N + n \longrightarrow {}^{1}H + {}^{14}C$. ^{14}C is also produced by thermonuclear testing. The ^{14}C atoms are rapidly oxidized to form radioactive carbon dioxide molecules which mix with inert normal carbon dioxide and then mix through the dynamic carbon cycle including the atmosphere, oceans, plants and all living matter. All living materials, including substances such as water, which react with carbon dioxide within the atmospheric exchange reservoir, contain an equilibrium concentration of ^{14}C to ^{12}C of $1 : 10^{12}$ denoted by 100% which decreases with time once the materials are removed from the reservoir e.g. water leaving zone of aeration and infiltrating to the ground-water zone or following the death and burial of some former living organism. This constant ratio is referred to as modern ^{14}C content. Since 1952 a considerable amount of ^{14}C has been added to the atmospheric reservoir by the testing of nuclear devices, so that present equilibrium levels are now greater than "modern". Thus, provided the cosmic ray flux remains constant, all carbon in materials in the exchange reservoir will have a known amount of ^{14}C regardless of time or geographic location and by measuring the ^{14}C content of the material, a measure of time elapsed since removal from the equilibrium cycle can be obtained. Theoretical considerations, coupled with comparison of

^{14}C derived ages with ages derived from independant methods suggest that the cosmic ray flux has remained virtually unchanged for the past 100,000 years and hence reliance can be placed on the ^{14}C dating method.

Ground water contains carbon in the form of carbon dioxide (CO_2) and bicarbonate ions (HCO_3) - and rarely in carbonate form CO_3^{--}, for ground waters of normal pH. Rainwater contains dissolved CO_2 which forms carbonic acid. When this water passes through the soil zone it also absorbs CO_2 derived from respiration and plant decay and by reacting with lime (calcium carbonate) in the soil it hydrolyses to HCO_3 ions. The extra CO_2 derived in the soil zone explains how ground water, which theoretically cannot dissolve more than 1 to 2 milliequivalents per litre of calcium bicarbonate from the amount of CO_2 in the atmosphere, can dissolve up to 10 ME/litre of calcium bicarbonate.

$$Ca\,CO_3 + CO_2 + H_2O \rightleftharpoons 2HCO_3^- + Ca^{++}$$

$$CO_2 + H_2O + CaCO_3 \rightleftharpoons Ca^{++} + 2HCO_3^-$$

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons 2HCO_3^- + Ca^{++}$$

Water infiltrating to replenish ground water supplies thus acquires some radioactive ^{14}C atoms. For ground water dating the zero time datum is the time the water enters the ground water system and is coincident with the last ^{14}C source with which the water was in contact, which is generally the soil air.

When this water percolates beyond the root zone, the dissolution process ceases and no further ^{14}C is added to the ground water. In addition to the above, calcium carbonate of non-biogenic origin contributes to the bicarbonate in ground water and hence contains no radioactive ^{14}C. Part of the bicarbonate is therefore of non-biogenic origin and hence the ^{14}C content of water (prior to 1952) varies from 50 to 100% of that of the modern ^{14}C content of living material. To date ground water accurately, it is necessary to know what proportion of the total carbon present was derived from soil air. Experience has shown that the initial ^{14}C content of dissolved bicarbonate (HCO_3) is about 85% $\pm$ 5% of that of living plants, i.e. 85% "modern". Thus knowing the initial percentage of modern ^{14}C, analyses of the apparent ages of ground water can be made following acidification and absorbtion of CO_2 in an alkaline solution. This is processed in a laboratory and the ^{14}C concentration measured in sensitive and highly sophisticated gas counters.

The main uses of ^{14}C in ground water studies are age dating (ages up to 50,000 years); determining flow rates of ground water by dating the water at different points in the same aquifer,and as an aid to calculating the contributions of different components to a ground water blend.

History of use of ^{14}C in Botswana

Following an approach by the writer to Professor J. C. Vogel, head of the Natuurkundig Laboratorium of the Rijks - Universiteit in Groningen (Netherlands), it was agreed in August 1965 to carry out a limited research programme in Botswana in which approximately 15 samples per year would be analysed. Following this agreement, several visits to the southern and central Kalahari areas were made to collect water samples in 1967, 1968 and 1970. Further sampling in 1971 and 1972 was carried out by joint teams from the Geological Survey and from the Nuclear Physics Research Unit of the University of Witwatersrand. (Mazor et al, 1974).

Sampling

Prolonged contact of ground water with the atmosphere results in isotopic exchange between the carbon dioxide in the air and the dissolved bicarbonate in the ground water and results in the ^{14}C content of the water being increased. Care was therefore taken to ensure that the borehole being sampled was pumped for a sufficient period to remove all water in the borehole column which is likely to have been in contact with the air. Care was also taken to see that the water was in an airtight container.

Apparatus and Analysis

Initially all water samples were collected in tightly sealed 44 gallon drums and were brought back to the Geological Survey Chemical Laboratory where the sample was concentrated and sent in dried form as barium carbonate to Holland for counting.

Following the visit of Dr. J. C. Vogel to Botswana in May 1968, a much simplified version of the original laboratory apparatus was constructed and is shown in Fig. 200 . This consists of a 60 or 100 litre container connected by 2 tubes to a 200 ml plastic flask filled with 3N Na OH solution. The acidified water is circulated using a modified aquarium pump which runs off a 12 volt car battery which is converted to alternating current by a small electronic converter. The carbon dioxide liberated by the acid is absorbed in the alkali within 4 to 5 hours. Samples can thus be easily concentrated in the field and it is then only necessary to send the 200 ml flasks to the laboratory for analysis. This is done by liberating CO_2 gas which is introduced to sensitive gas counters and the concentration measured.

CARBON-FOURTEEN SAMPLING IN BOTSWANA

Two areas in Botswana were sampled for ^{14}C age measurements in relatively great detail: viz. the

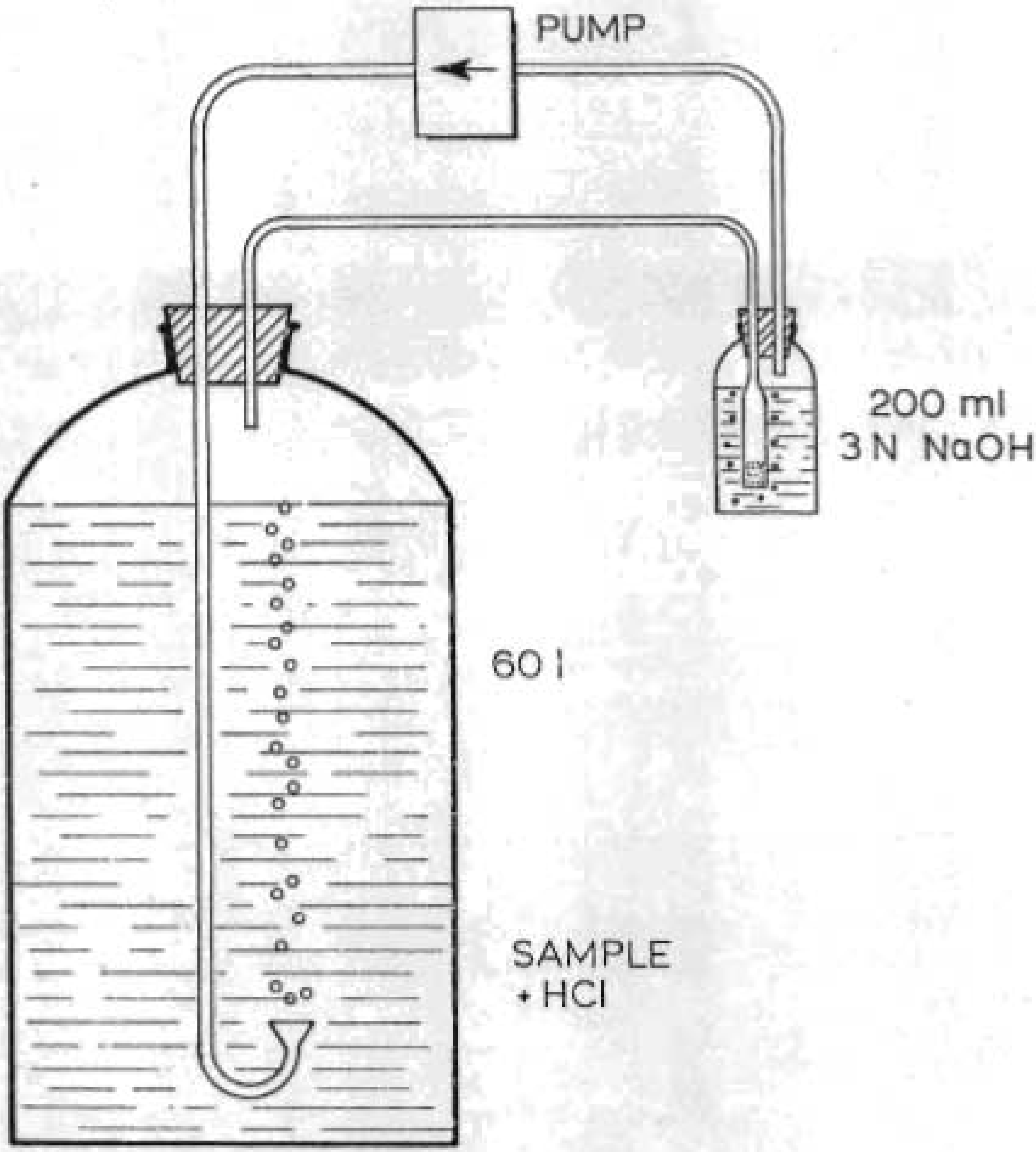


FIG. 180.

^{14}C APPARATUS

western Kweneng district (Central Kalahari) and the Molopo State Lands and western Bangwaketsi District areas in the southern Kalahari. These two areas were selected because of the relatively intense cattle ranching being carried out there. This ranching is completely dependent on ground water for stock drinking purposes and, as the areas are known to be mantled by a thick cover of Kalahari Beds, it was vitally important to know whether the waters being used were fossil or whether they were being periodically replenished.

The Kweneng District

The area selected for detailed hydrogeological investigation in the western Kweneng area stretches from Letlhakeng, northwest of Molepolole, westwards for 160 km to the Morwamosu - Phuduhudu area across the sand-covered and fairly well-grassed Kalahari plain. (Fig.11, Plate 66).

A total of 49 ^{14}C determinations were carried out in this area while 23 tritium and stable isotope measurements were made in the same area. As there were no contour maps for the area, carefully controlled barometric levelling was carried out in the area just west of Letlhakeng, and maps showing iso-piezometric levels, depth to base of the Kalahari Beds and topographic contours were drawn up (Figs.12, 13 and 14). See also chapter on hydrogeology of Central Kalahari.

Details of the results obtained in this area are given in Table 98.

TABLE 98

ISOTOPIC MEASUREMENT - CENTRAL KALAHARI

mple	Locality	Depth water struck in m	^{14}C pmc	Age (years)	Tritium T U	δD °/oo	$\delta^{18}O$ °/oo
) *	Bh1102 Mabutsane		92,1±2,2	Post 1952	10,8±1,2		
32	" " (May 1968)		86,39±0,55	"	6,4±1,0		
2	Bh281 Khakhea		90,6±1,4	"	2,0±0,3		
3	Bh Lehoko		89,0±2,3	"	0,9±0,3		
33	Bh765 Kadijwe (May 1968)		82,61±0,42	234			
2	Bh473 Tshane		80,4±1,4	430			
3	Bh1838 Tshane		79,6±1,7	530	3,9±0,4		
)	Bh738 Masope		75,6±1,5	950	0,5±0,2		
)	Bh Kang,Vet.		67,7±1,2	1830	0,0±0,2	-41,9±1,2	-6,34±0,09
19	Bh770 Mamatlhaku		66,28±0,54	2010			
312	Bh705 Rasefifi (Jun 1970)		64,83±0,58	2180			
7	Bh786 Lone Tree		61,4±1,5	2620	0,2±0,2	-35,2±1,2	-6,02±0,09
)	Bh1320 Kyuma Tshisane		59,4±1,0	2950		- 8,3±1,2	-0,52±0,09
315	Bh1765 Kwakadi (Jun 1970)		58,16±0,5	3060			
20	Bh1764 Monwane		58,86±0,55	2960			
7	Bh671 Maitlo & Phuduhudu		55,3±2,1	3500	2,6±0,2		
316	Bh764 Sekuku (Jun 1970)		55,29±0,57	3460			
RNS 182	Bh1766 Mohuswe		53,8±0,5	3670	0,9±0,3		
)	Bh1243 Moleleme		52,3±1,6	3950			

B2	Bh712	Ditshegwane (May 1968)	51,93±0,39	3960			
B14	Bh1626	Tshetswe (Jun1970)	51,90±0,58	3970			
3	Bh1572	Hanahai	48,3±1,7	4550	1,2±0,3	-40,0±1,3	-7,2±0,09
2	Bh1768	Polompshwe	48,0±1,2	4600	0,1±0,2		
0	Bh	Kang	47,3±1,1	4750		-43,7±1,2	-6,6±0,09
B21	Bh1768	Polompahwe (June 1970)	47,17±0,51	4740			
3	*Bh1616	Kgorwe Pan 2	47,0±1,1	4750	1,2±0,5		
B5	Bh1616	" "	45,64±0,31	5000		-29	
B17	Bh1828	Kwenashadi	44,49±0,45	5210			
4	*Bh849	Metokwe	44,4±1,1	5250	0,2±0,2		
B22	Private Bh.	Khuchwe (Jun 1970)	42,21±0,50	5250	0,2±0,2		
B6	Bh849	Metokwe (May 1968)	39,33±0,23	6190	0,5±0,3		
B24	Bh849	Metokwe (Jun 1970)	38,6±0,72	6350			
8	Bh1827	Tswane	34,9±1,1	7200			
5	*Bh858	Morwamosu(May 1968)	32,6±1,0	7700	0,7±0,3	-35,1±0,9	-5,92±0,09
39	Bh858	Morwamosu(May 1968)	31,92±0,20	7871	0,8±0,4	-32	
37	Bh1221	Khekwe	28,24±0,31	8856	0,7±0,4	-30	
5	*Bh1221	Khekwe	28,9±1,2	8700			
B23	Gunter's Bh		20,6±0,5	11380			
B1	Bh314	Letlhakeng (May 1968)	15,52±0,25	13664		-31	
5	Bh2308	14km W of Ncojane	15,2±0,5	13850	1,5±0,3		
B 8*	Bh1028	Phuduhudu(May1968)	15,18±0,45	13842		-35	
8	Bh1028	Phuduhudu	10,2±0,7	17100	2,6±0,4	-34,8±1,2	-5,77±0,09
B11	Bh716	Mantswabise (Jun 1970)	12,86±0,48	15180			

1	Bh1867 Kala e Tswago (Jun 1970)	8,5±0,4	18500	0,0±0,3		
B18	" " "	5,32±0,27	22290			
2	Bh546(338) Takatshwane	5,5±0,4	22400		-40,6±1,2	-7,03±0,09
B4	Bh780 Tsoto (May 1968)	4,94±0,18	22855		-45	
1	Bh1344 Phuduhudu	4,8±0,5	23200	0,7±0,2		
B25	Bh1128 Kekenye	4,41±0,25	23670			
1	Bruwer's Bh	3,1 ±0,2	26730	0,2±0,2	-41,3±1,2	-5,6±0,09
B13	Bh Dikgatlong	1,8±0,2	30,870	2,2±0,2	-	-
6	Bh. 2222 Ncojane	1,3±0,5	33700	2,2±0,2	-	-

All samples numbered RB or GRNS analysed by Dr. J.C. Vogel.

All other samples analysed by N.P.R.U. (After Mazor et al, 1974).

* Indicates independent sampling and analysis by different laboratories.

Hydrogeology of Kweneng Area

The area from Letlhakeng to Morwamosu (See Fig. 8), is underlain by the Ecca Group (Karoo Supergroup) and is overlain by a progressively greater thickness of Kalahari Beds as one proceeds westwards. (See Fig. 10). This area was selected for detailed hydrogeological study partly because it contains some of the best grazing land in Botswana and hence is of vital importance to the economy and partly because of the apparent simplicity of the hydrogeology of the area. Prior to the commencement of the study it was presumed that recharge took place in the vicinity of exposures of porous Ecca sandstones around Letlhakeng and to the east of Letlhakeng and that ground water then moved slowly in a westerly direction towards the Morwamosu area with no contribution from the pre-Karroo rocks known to occur further to the south. As it was known that the Ecca sandstone aquifer was confined by an increasing thickness of Kalahari Beds it was also presumed that this aquifer became confined i.e. of artesian type, to the west of Letlhakeng and hence simple "piston flow" assumptions could be made to determine the velocity of ground water movement in a westerly direction.

Discussion on results

Results obtained from the research programme have produced some surprising results both regarding the age and possible source of recharge. Prior to the commencement of work in the area, it was presumed that water encountered in the western Kwaneng District was probably "fossil" as the area was covered by a considerable thickness of Kalahari Beds and as writers such as Martin (1961) and van Straten (1955) had indicated that the possibility of recharge to the ground water table was extremely remote indeed. Furthermore, it was presumed that recharge only took place in the vicinity of Letlhakeng village where Ecca Series sediments were known to crop out. Following the levelling and carbon-fourteen programme, it became immediately evident that, because of higher water levels and younger water ages further west no recharge could take place in the vicinity of Letlhakeng.

The marked ground water mound further west (See Figs. 13,15 and Chapter on Central Kalahari) indicated clearly that flow is taking place radially from this area. The ^{14}C data corroborates this data in excellent fashion with the youngest waters occurring in proximity to the highest water levels. The marked age difference in the boreholes at Tsoto and Kalaetswago reflects a difference in geology and hence an entirely different aquifer. (Water was encountered in shale instead of the usual standstone.) It is interesting to note that the core boreholes drilled in the vicinity of the ground water "high" show that although the Kalahari

Bed cover in this area is 25 to 30 m thick, there is only a very thin veneer of Kalahari type sand with a considerable thickness of calcrete and calcrete conglomerate underlying the surface sand layer. This is thus not in conflict with the earlier contentions that present day rainfall cannot infiltrate through Kalahari sand exceeding 10m in thickness.

Assuming that water infiltrating in the Kadijwe-Mamatlhaku-Monwane—Sekuku-Kwakadi area is the source of recharge for the Metokwe-Khekwe-Morwamosu areas (mean ^{14}C age of water - 7666 years) in the western Kweneng, then the flow rate from the Kgorwe-Polompswe-Kuchwe area (mean ^{14}C age of 5127 years) just west of the recharge area to the Metokwe area will be

$$\frac{100{,}000 \text{ (approximate distance)m}}{7666-5127 \text{ year}}$$
$$= \pm 40\text{m per year.} \quad \text{(Fig.15).}$$

The presence of "modern" water at Mabutsane (Bh 1102,RB10) where the ^{14}C age shows more than 85% modern ^{14}C and therefore indicates recharge in post-thermonuclear times (i.e. post 1952) was another surprising result of the ^{14}C sampling programme. A subsequent tritium dating gave $5{,}3 \pm 0{,}7$ TU which confirms the young age given by the ^{14}C method. The very pure quality of the water from this borehole can also now be explained by assuming that recharge is still taking place in this area where outcrops of pre-Karroo, Waterberg Supergroup sediments are known to occur. This raises the question of whether recharge is not taking place all along the zone underlain by Waterberg sediments stretching all the way from Mabutsane past Kwakala, Seletsa pan to Molepolole (Fig. 11). This possible recharge zone could then be slowly feeding water northwards into the Karoo Supergroup. The presence of saline water in the marginal Karoo areas could be explained by impermeable barriers such as dolerite dykes inhibiting the movement of fresh ground water. The presence of a dolerite dyke has been proved in the core borehole at Bajwane (Recorder borehole) while magnetic traverses have indicated that the dykes are present in the area.

The presence of relatively old water at Kekenye (Bh 1128, RB25) in proximity to Metokwe could be accounted for by explaining an easterly source of recharge which is obstructed just east of Kekenye by a dolerite dyke known to be present from magnetic traverses.

Relatively "old" water is present north of Letlhakeng at Dikgatlong (Bh 702, RB 13) where the second oldest recorded water in Botswana is present (30 870 years). Old water is also present at Kang, Phuduhudu, Kala e Tswago, and Mantswabise. The oldest water found to date in Botswana comes from Ncojane. This has a probable age of 33 700 years.

<u>The use of ^{14}C for estimating the aquifer permeability and transmissibility</u>

One of the most valuable uses of the ^{14}C method is for estimating aquifer permeabilities. Darcy's Law states that the filter velocity is equal to the permeability (K) multiplied by the hydraulic gradient. The actual velocity of water in the aquifer is equal to the filter velocity divided by the porosity, as water can only flow in the intergranular spaces. Therefore, if the hydraulic gradient is known, and if the porosity can be estimated (or measured from cores) it is possible to determine the regional permeability using ^{14}C ages.

Now it has been shown that v (the actual velocity of flow) = 40m per year $= \frac{40}{365}$ m/day

From Darcy's Law $v(\text{filter}) = K \frac{dh}{dL}$

where $v\ (\text{actual}) = \frac{\text{filter velocity}}{\text{porosity}}$

$v\ (\text{filter}) = v\ (\text{actual}) \times \text{porosity}$

$\therefore$ Filter velocity $= K \frac{dh}{dL} = \frac{40}{365} \times \frac{5}{100}$

Now, assuming a porosity of 5%

Substituting for filter velocity $\frac{40}{365} \times \frac{5}{100} = K \frac{1}{1670}$

$$\therefore K = \frac{40.1670.5}{365.100} \text{ m per day}$$

$$= 9{,}15\text{m per day}$$

Assuming an aquifer 100m thick (W)and T (coefficient of transmissibility) then:

$$T = KW$$
$$= 9,15.100$$
$$= 915m^2 \text{ per day}$$

Summary and conclusions

^{14}C studies in the Central Kalahari have indicated that

1. the main recharge area appears not to be in the immediate vicinity of Letlhakeng but further west than originally thought - this has been amply corroborated by isopiezometric data and the drawing up of flow networks.

2. In general there is a progressive increase in the age of ground water within the Ecca subgroup the further one proceeds westwards.

3. The age dating of the ground water indicates a flow rate of approximately 40m per year in a westerly direction.

4. From 3 above and assuming a porosity of 5%, a coefficient of permeability (K) of 9,15m per day was calculated.

5. Knowing the thickness of the aquifer, the coefficient of transmissibility (T) can then be calculated and hence the quantity of water moving through any section of the aquifer can be calculated. A value for T of $915m^2$ per day was calculated.

6. Interpretation of the presence of very small but measurable amounts of tritium indicate that recent recharge had taken place prior to 1952. The presence of tritium combined with the calculated flow rate of 40m per year from the ^{14}C data indicates that recharge is taking place by direct infiltration through the Kalahari Beds, or by infiltration in the Matsap Beds to the south, and then by gravity flow into the Karoo Beds further to the north.

7. The stable isotope data indicates recharge having occurred during a period of intense rainfall with low evaporation.

Molopo State Lands and Western Bangwaketse Areas (Southern Botswana)

Hydrogeology

The greater part of the western Bangwaketse and Molopo State Lands is covered by a superficial cover up to 168 m thick consisting predominantly of sands of Kalahari type, marl, calcrete, silcrete and minor ferricrete. Cemented fluviatile sand and gravel (calcretised) are occasionally exposed in the fossil rivers and in numerous boreholes. The bedrock underlying these relatively young superficial deposits rarely crops out. However the relatively large number of deep water boreholes drilled in the area to support the intensive cattle ranching have enabled a fairly comprehensive picture of the distribution of these older formations to be built up.

TABLE OF FORMATIONS

Cretaceous to Quaternary Deposits	Kalahari Beds	Sand, silcrete, calcrete, marl, sandstone, conglomerate.
Waterberg Supergroup		Quartzite sandstone & minor shale.
Transvaal Supergroup	Pretoria Group	Shale siltstone, quartzite and andesitic lava.
	Dolomite Group	Dolomite, chert, banded ironstone & minor shale.
	Black Reef Group	Quartzite & shale.
Ventersdorp Supergroup		Shales, pyroclastics?
Dominion Reef System		Felsite.
Basement Complex	Kraaipan Formation	Banded ironstone, chert, minor altered mafic lava & agglomerate.
	"Old Granite"	Mainly granite with minor schist & amphibolite.

Intrusive Rocks

Ultramafic and mafics

Diabase/dolerite

Gaborone-type granite.

Water bearing properties of various formations in southern Botswana.

Apart from the intrusive mafic and ultramafic rocks (which yield blank or saline boreholes) and the Waterberg sediments which generally yield saline water south of Khakhea but yield fresh water to the north and northeast of Khakhea, all the other formations, including the Kalahari Beds, in southern Botswana, give moderate to high yields of moderate quality water which is eminently suitable for cattle ranching. Very high yielding boreholes in the Kalahari Beds have been obtained in basal Kalahari gravels. The gravels appear to occur mainly in very broad, deep pre-Kalahari valleys.

Carbon-fourteen sampling in Southern Botswana (See Fig.201).

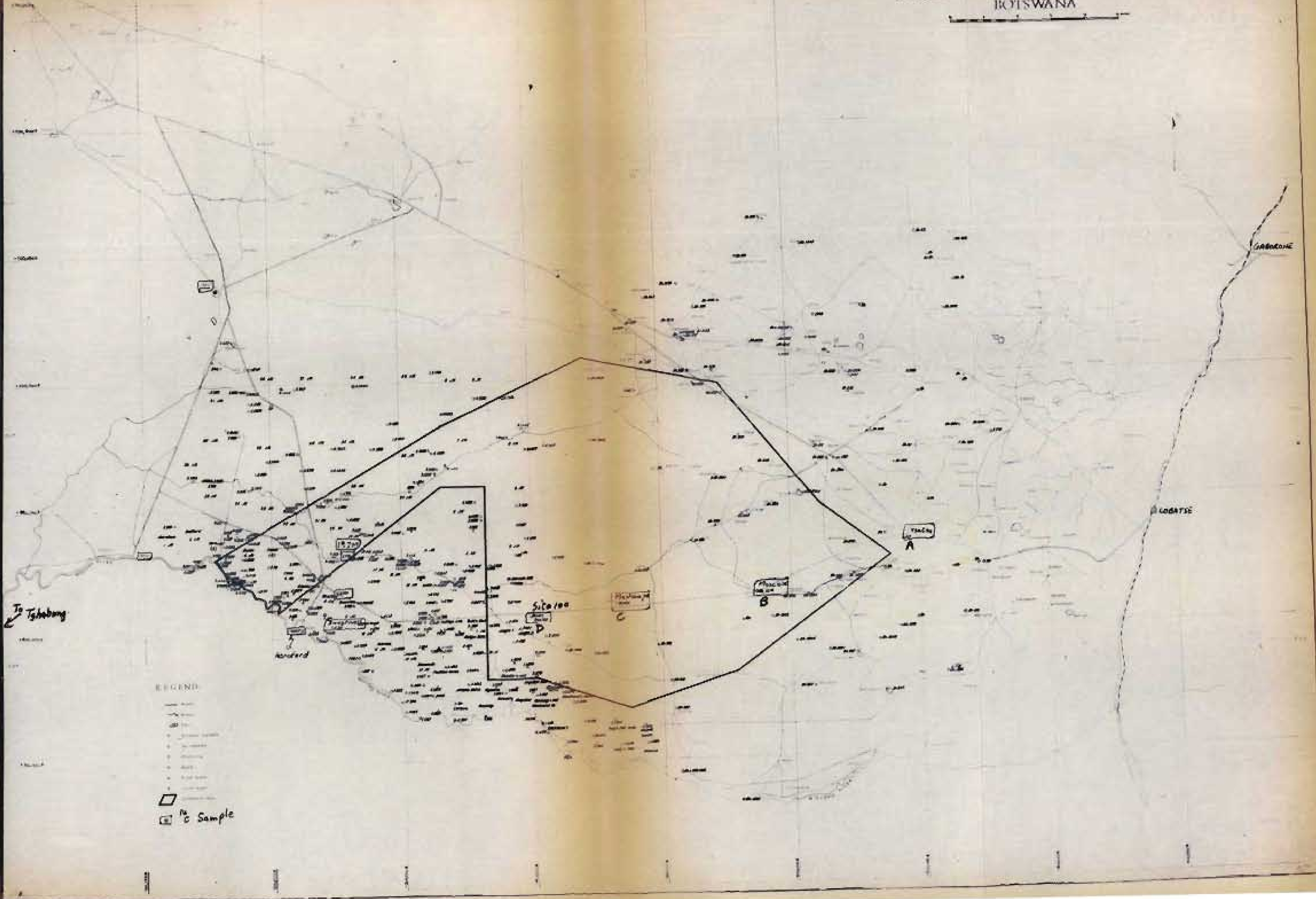
Results of sampling in the western Bangwaketse and southern State Lands are given below in Table 99 :

TABLE 99

^{14}C ISOTOPIC MEASUREMENTS - SOUTHERN KALAHARI

SAMPLE NO.	LOCALITY AND BH NUMBER	^{14}C pmc	PROBABLE AGE IN YEARS (± 400 YRS)	TU	DEPTH WATER STRUCK IN M
* 82	Khakhea Bh 281	90,6±1,4	Post 1952	2,0±0,3	33 (0)
* 80	Lebaleng, Molopo River	89,5±1,8	"	4,2±0,4	?
5504	Hereford (Farms JM), Molopo Bh. P 457	80,22±0,7	470	-	100 (111)
81	Werda	79,3±1,4	550	1,6±0,3	?
5920	Farm 19JM, Molopo Bh.Z776	76,3±0,96	870	-	
5562	Tsatsu Bh 1253	76,11±0,87	890	-	55 (0)
* 79	Tsabong Police Bh	66,0±2,3	2030	15,7±0,8	(0)

FIG. 181 ^{14}C SAMPLING LOCATIONS – S. KALAHARI



5564	Moselebe Bh 1574	62,47±0,57	2480	-	83 (65)
5383	Monmouth Ranch Bh Z 692	21,36±0,32	11100	-	106 (172)
5563	Farm 21 JM Bh Z 842	11,9±0,38	15800	-	
5565	Mashampa Bh 1615	10,9±0,31	16000	-	124 (148)
5921	Site 100 Farm, Bh Z 429	6,77±0,42	20350		159 (180)
5766	Farm 8 JM Bh Z 306	4,32±0,17	24000		122 (157)
5383	Inverness Farm Bh Z 351	4,04±0,18	24400		113 (126)

* After Mazor et al (1974)

Discussion of results

The positions of all boreholes sampled for ^{14}C measurement in southern Botswana are shown on Fig. 201 . It can be quite clearly seen that four areas - Khakhea Pan, Tsatsu (Bh 1253), Bh Z.776 on the Moselebe valley on Farm 19 JM and along the Molopo River have very high ^{14}C values indicating recharge in these areas within the past 1000 years. This data fits well with the known hydrogeology of these areas i.e. local concentration of surface run-off occurs in all four areas by flow down the Molopo; by localised concentration of run-off in the Moselebe Valley; by concentration of run-off in the large depression formed by Khakhea Pan and by localised concentrations of run-off in hollows in the dolomite (Transvaal Supergroup) near Tsatsu. It is interesting to note that two of the above group with high ^{14}C values are in areas of deep Kalahari Beds cover (+60m). This provides further proof that recharge can take place through a considerable thickness of Kalahari Beds and is in direct conflict with evidence supplied by Martin (1961) and van Straten (1955) though admittedly this recharge occurs in areas where unusually large concentrations of water, for the Kalahari, are concentrated.

All other boreholes sampled show varying ^{14}C contents (21,36 to 4,04 pmc) but all are relatively very old. There appears, from the limited amount of sampling, to be a gradual increase in age from the area of rock outcrop at Tsatsu westwards beneath a thickening cover of Kalahari Beds. Assuming the section A B C D to be the flow direction then the ^{14}C ages were used to calculate the velocity of ground water flow as follows:-

A	Tsatsu Bh	^{14}C Age	890	(See Fig. 202).	
B	Morenane Bh	"	2480	Difference B-A = 1590 years	
C	Bh 1615	"	16000	Difference C-B = 13520	"
D	Bh 2429	"	20350	Difference D-C = 4350	"

Distance A - B = 37km = 37000m

B - C = 30,59km = 30590m

C - D = 16,26km = 16260m

$\therefore$ Ground water velocity A-B = $\frac{3700}{1590}$, B-C = $\frac{30590}{13520}$,

C-D = $\frac{16260}{4350}$

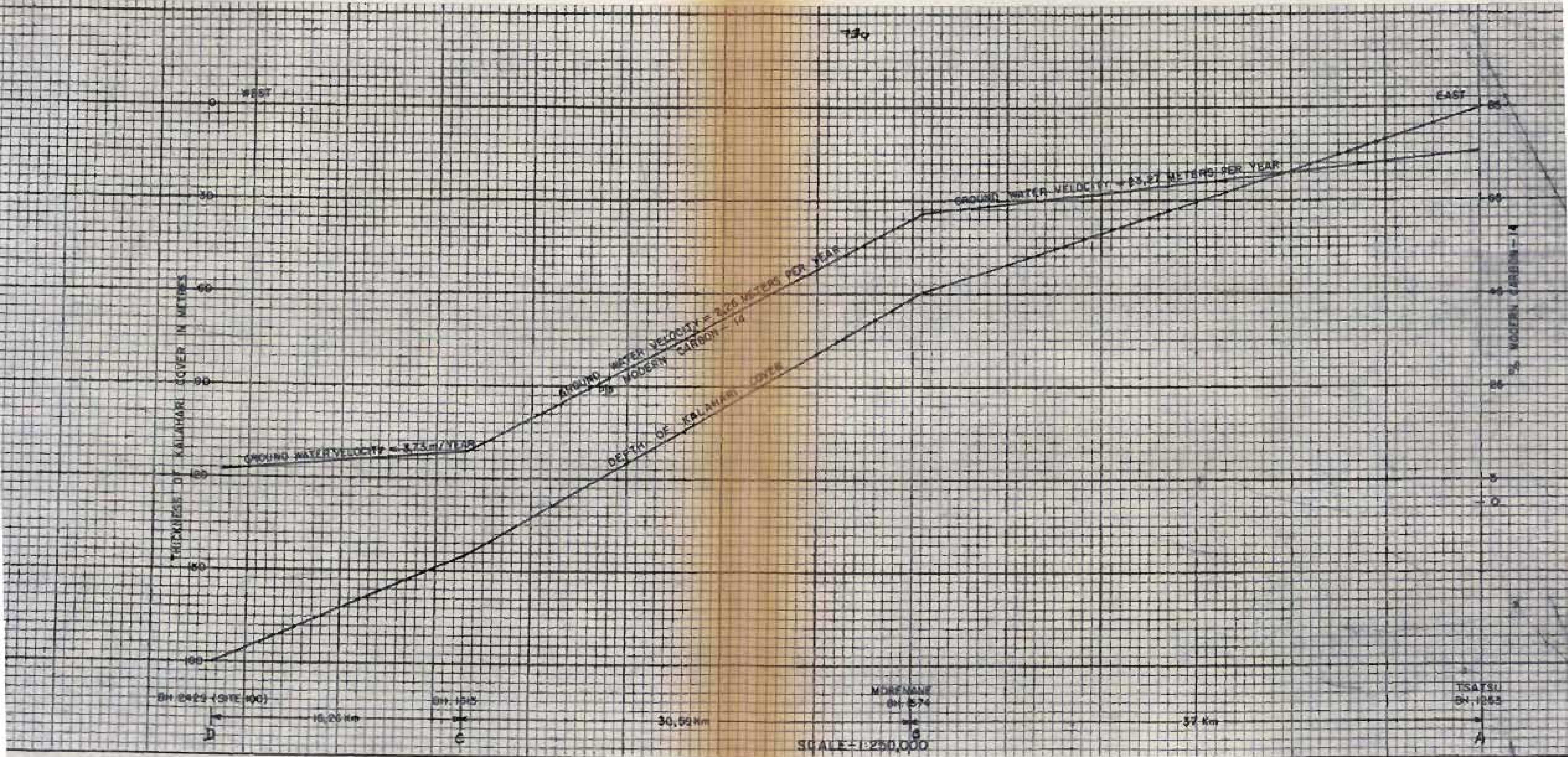


Fig. 181 DIAGRAM SHOWING RELATIONSHIP BETWEEN ^{14}C CONTENT AND DEPTH OF KALAHARI BEDS IN W. BANGWAKETSE (SEE FIG. 20)

A-B = 23,27m per year B-C = 2,26m per year

C-D = 3,73m per year (See Fig.202).

Fig.202 shows how there is a decrease in age of the ground water in the western Bangwaketse District with a decrease in the thickness of the Kalahari Beds.

^{14}C Sampling in Other Areas in Botswana

Serowe

Results have been discussed in the Chapter on the "Hydrogeology of Serowe". These results indicate that post 1952 recharge is taking place in the area of the unconfined Cave Sandstone aquifer.

Serowe - Orapa

^{14}C measurements along a line of observation boreholes between Serowe and Orapa and in the vicinity of Orapa itself have shown that in general the waters encountered on the basalt/Cave Sandstone contact are generally old (± 20 pmc) but that recharge is apparently occurring in proximity to Tshepe and Makoba boreholes where ^{14}C values are much higher (about 78 pmc).

Northern Kgalagadi

^{14}C measurements in the northern Kgalagadi are shown in Table 100:

TABLE 100

SHOWING ISOTOPIC DATA IN N. KALAHARI

(After Mazor et al, 1974)

MPLE	LOCALITY	^{14}C	PROBABLE AGE (YRS)	TU	$\delta D^o/oo$	$\delta O^o/oo$	DEPTH WATER STRUCK IN M
54	Bh Z 1231 Burton's Farm, Ghanzi	99,1±2,2	Post 1952	5,1±0,6	-54,4±1,2	-8,46±0,09	±9
63	Bh 1614 Gweta	97,6±1,5	"	1,2±0,3	-39,7±1,2	-6,03±0,1	±5
62	Bushman Pits	97,4±2,2	"	8,0±1,8	-42,8±1,2	-7,73±0,1	±9
64	Zoroya PWD Camp Bh 1721?	91,9±2,2	"	10,3±1,1	-34,6±1,6	-5,42±0,1	10
56	Kuke Bh 487?	66,8±1,7	1930	0,6±0,6	-54±1,2	-8,9±0,09	30
53	Bh1572 Hanahai	48,3±1,7	3950	1,2±0,3	-40,0±1,2	-7,2±0,09	53

These measurements show that post-bomb recharge is taking place in the shallow ground water table areas of the northern Kalahari and Ghanzi areas. In the Kuke and Hanahai areas where older waters are found, about 24m of Kalahari sand mantles the pre-Cambrian Ghanzi Formation sediments in which the water was encountered. The high ^{14}C values are generally backed up by relatively very high tritium values indicating also that considerable post 1952 recharge has occurred.

Okavango - Lake Ngami Area

Results of ^{14}C measurements in proximity to the Okavango Swamps and Lake Ngami are shown in Table 101 .

TABLE 101

ISOTOPIC MEASUREMENTS IN OKAVANGO - LAKE NGAMI AREA *

SAMPLE	LOCALITY	^{14}C pmc	AGE	TU	δD‰	$\delta^{18}O$‰
60	Bh 1242, Toteng	98,7±1,8	Post '52	16,9±1,7	+3,3±1,2	+1,83±0,09
58	Tsau	68,3±1,3	1750	0,9±0,2	-17,1±1,2	-2,9 ±0,09
57	Sehitwa, Tribal Bh	54,3±1,2	3600	1,2±0,3	-4,8±1,2	-0,56±0,09

* After Mazor et al (1974)

The Toteng borehole is situated on the banks of the Kunyere River which flows strongly for a number of months of the year and is thus replenished annually by direct infiltration by the annual floodwaters.

Both Tsau and Sehitwa are situated at no great distance from perennial surface water in the swamps and from Lake Ngami respectively and yet both samples of ground water show relatively low ^{14}C and very low tritium contents indicating a low permeability for the recent sediments present in these areas. This low permeability deduced by ^{14}C dating is confirmed by numerous boreholes with poor quality water away from the actual edge of permanent water in the Swamps.

Lobatse

Results of ^{14}C sampling at Lobatse were discussed earlier in the section on tritium in this chapter.

Relationship between age of water, depth water encountered and thickness of Kalahari Beds

Figure 203 shows a plot of the age of ground water against both depth water was encountered and the thickness of the Kalahari Beds. This shows clearly that, in general, waters become progressively older beneath increasing Kalahari cover and with an increase in the depth at which water was encountered below surface.

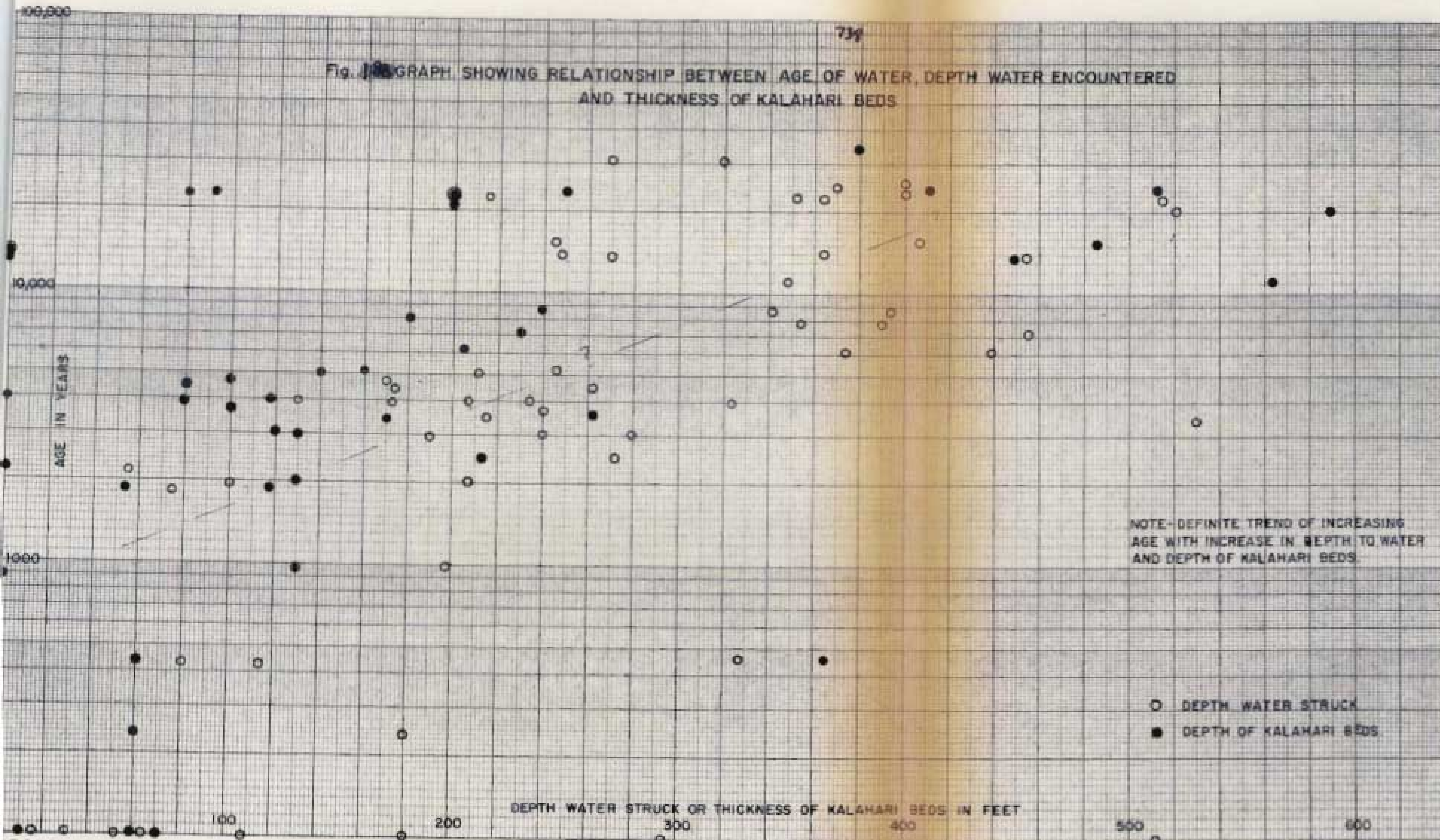


Fig. [illegible] GRAPH SHOWING RELATIONSHIP BETWEEN AGE OF WATER, DEPTH WATER ENCOUNTERED AND THICKNESS OF KALAHARI BEDS

Relationship between age of ground water and the bicarbonate content expressed in percentage milliequivalents

Figure 204 shows a graph of age of ground water plotted against percentage milliequivalents of bicarbonate (HCO_3^-) ion. This shows an apparent positive correlation between decreasing bicarbonate content and increasing age in ground water.

Repeat sampling of ground water for ^{14}C analysis

Results of repeat sampling for isotopic measurements are given below in Table 102 .

TABLE 102

BOREHOLES SAMPLED MORE THAN ONCE IN THE KALAHARI FOR ISOTOPIC MEASUREMENTS

			SAMPLE NO	DATE	^{14}Cpmc	TU
	Bh1102	Mabutsane	17.5.68	6.4.67	86,39±0,55	5,3±0,7
+	Bh "	"		28.6.72	92,1 ±1,4	6,4±1,0
	Bh1768	Polompswe		?.6.70	47,17±0,51	
+	Bh "	"		27.2.72	48,0 ±1,2	0,1±0,2
	Bh1616	Kgorwe		17.5.68	45,64±0,31	
+	Bh "	"		27.2.72	47,0 ±1,1	1,2±0,5
	Bh 849	Metokwe		17.5.68	39,33±0,23	0,5±0,3
	Bh "	"		?.6.70	38,6 ±0,72	
+	Bh "	"		27.2.72	44,4 ±1,1	0,2±0,2
	Bh 858	Morwamosu		17.5.68	31,92±0,20	0,8±0,4
+	Bh "	"		28.2.72	32,60±1,0	0,7±0,3
	Bh1221	Khekwe		17.5.68	28,24±0,31	0,7±0,4
+	Bh "	"		27.2.72	28,9 ±1,2	-
	Bh1028	Phuduhudu		17.5.68	15,18±0,45	
+	Bh "	"		28.2.72	10,2 ±0,7	2,6±0,4

+ Data analysed by Nuclear Physics Research Unit.

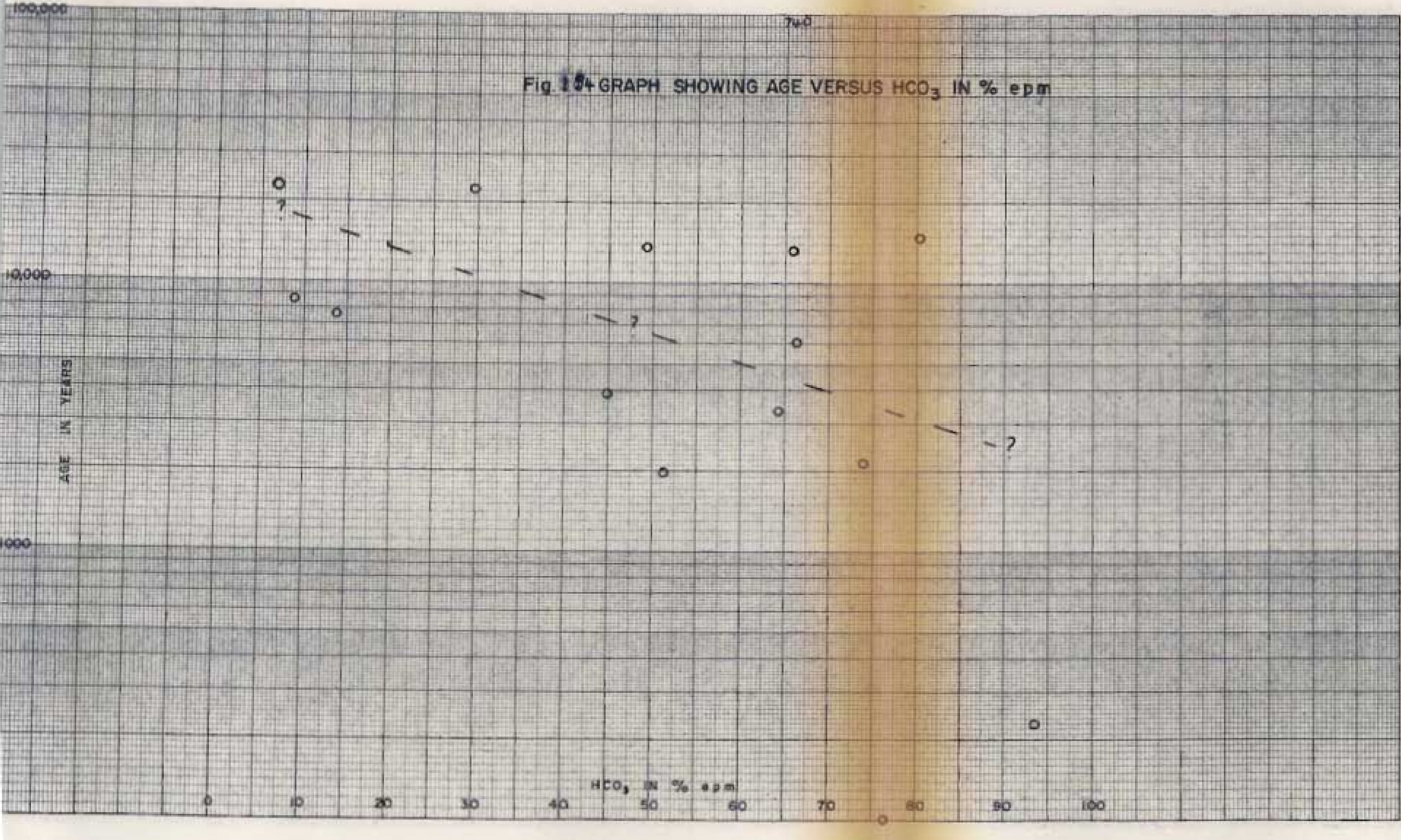


Fig. 134 GRAPH SHOWING AGE VERSUS HCO_3 IN % epm

Repeat sampling of the same boreholes for isotopic measurements shows excellent agreement especially when it is borne in mind that the repeat analyses were done by a different laboratory. The only boreholes showing any differences on repeat sampling are Bh 1102 (Mabutsane) which showed an increase of about 5,5 per cent modern carbon and a marked increase from 6,4 to 10,8 Tritium Units. It is thus obvious that recharge of this borehole took place between 1968 and 1972. Bh 849 (Metokwe) shows an increase of about 5,9 pmc and it is thus possible that recharge to this borehole occurred between 1970 and 1972. No explanation for the decrease in ^{14}C content in Bh.1028 Phuduhudu can be offered other than that analytical error is responsible for the discrepancy. Another possibility is that the borehole could have been confused with another borehole (No.537) with the same name.

<u>Limitations of ^{14}C Method</u>

The ^{14}C dating method for ground water has the disadvantage that, unlike the tritium method, the carbon analysed is present in dissolved compounds rather than as part of the water molecule. The carbonate chemistry of the water thus plays a major role in the interpretation of the data and imposes a number of limitations on the reliability of this method. Of these limitations, the possibility of isotopic exchange with "dead" carbonate; the amount of dilution with non-radioactive compounds; dilution by post thermonuclear period carbon (greater than 100% of standard ^{14}C) cause the most concern. However experience has shown that little dilution with non-radioactive carbon compounds occurs and it is felt that the ^{14}C method of dating ground water, especially where relative age comparisons in a limited area are made, can produce valuable and reliable data.

MOVEMENT OF SOIL MOISTURE IN THE UNSATURATED ZONE

Introduction

In order to obtain a better understanding of the movement of rainwater through the thick colluvial soil covering the western Lobatse (dolomite) basin,a deep pit was excavated on level ground adjacent to the Geological Survey headquarters and approximately mid-way between the hillslope and the major fault separating the eastern and western ground-water basins. This area contains a sparse grass cover and a few low bushes.

Virtually no plant roots were obseserved in the 4,7 m pit excavated to obtain representative samples of soil The pit was excavated immediately prior to the 1970/1971 rainy season.

No rain fell during the period of excavation and hence no contamination of the deeper soil horizons could have taken place by direct ingress of rainfall or run-off into the pit.

Samples weighing 3 to 4 kg were collected at ±30 cm intervals as the pit progressed and were stored in large, tightly stoppered glass containers. A further set of samples was collected from the opposite wall of the pit after the pit was completed. Prior to the collection of samples, the first 20 cm or so of the wall was sliped away.

Portions of these samples were then weighed and placed in a stainless steel container fitted with a Liebig condenser and a collection vessel. The system was made vacuum tight, and pumped to a low pressure through a trap which was kept at a temperature of -80 degrees C. The steel vessel was then heated to 400 degrees C and the bulk of the soil water transferred to the flask in about $1\frac{1}{2}$ hours. A small amount of water collected in the cold trap was also added to the remainder of the water collected. In this way an estimated 90 per cent of the water was removed from the soil.

After extraction of the moisture from the soil the samples were electrolytically enriched and the tritium content measured. The resulting tritium profile was then related to the known history of precipitation and its tritium content (input function) over the last 20 years.

By applying suitable corrections for radioactive decay and dispersion to the known and extrapolated tritium input function, theoretical profiles were obtained which could then be matched to the observed profiles. In this way the infiltration velocity and, from the measured moisture content, the percentage infiltration were obtained.

Another approach is to compare the total amount of tritium known to have been precipitated to the amount found in the profile. This again gives the percentage infiltration.

Theoretical Profiles

Figure 177 shows a smoothed curve (a) which depicts the known and exprapolated tritium concentrations in Southern African rainfall over the past twenty years.

By correcting for decay to 1970,a curve (b), which represents the ideal or piston flow profile that would have been

expected without dispersion, was obtained.
When a binomial approximation to the Gaussian dispersion function (Verhagen et al, 1974) is applied to the piston flow model, individual values are multiplied by factors.

$$\binom{n}{x} = \frac{n\,!}{x!\ \ (n-x!)}\ p^x\ q^n$$

The resulting distribution was made symmetrical by putting p=q=0,5. The dispersion factor n was varied to give a number of cases:

n = 6
n = 12
n = 16

which seems to cover the curve shapes obtained from the measured tritium profiles.
The profiles were then plotted at different assumed infiltration rates and the best fit to the curves was assumed to indicate the best flow velocity. It is noteworthy that the fit becomes better at greater depths, i.e., the flow becomes less model-dependent. This is ascribed to the fact that, near the surface, evapotranspiration removes significant amounts of moisture from the soil during dry periods. Heavy rains (such as during 1966/67) which fall during the descent of atmospheric tritium concentrations (negative slope of the input function) could invade layers representing higher tritium rainfall years. At greater depth, more thorough dispersive smoothing has taken place and secondly, the water originates from periods with less abrupt changes in tritium concentration.

It is at such depths (usually greater than 3 metres) that the most reliable fits, and the best criteria for a year assignation are obtained. (Verhagen, Sellschop & Jennings 1974)

Results - Lobatse

Results of the sampling in the 4,7 m deep pit at Lobatse are plotted in Figure 185. This shows a progressive decrease in tritium from 34 TU at 60 cm to 15 TU at 4,6 m. The weight percentage of water in the soil varied from 5 percent near the surface to 8 cent at the bottom of the pit. The increase in moisture content with depth can be ascribed to evapotranspiration removing moisture from the near surface zone. From Figure 177, it can be seen that the best fit to the profiles gives an infiltration rate of 40 ±5 cm per year. If the bulk density of the soil is taken to be 1,6 gm per cubic centimetre and taking the average moisture content for the profile to be 6 per cent, then the downward flux will be 38 mm per year. For an average rainfall of 545 mm this represents an infiltration ratio of 7 percent. This compares reasonably well with the figure of 4 per cent described in the chapter on Lobatse. At an infiltration rate of 40 cm per year, the residence time for moisture in the unsaturated zone in the Lobatse western basin would be $\frac{3000}{40}$ = 75 years.

Results - Kalahari Area

Figure 186 shows an example of a soil moisture and tritium profile in a Kalahari sand-covered area near Mabutsane (G.4). The first 30 cm contained no moisture.

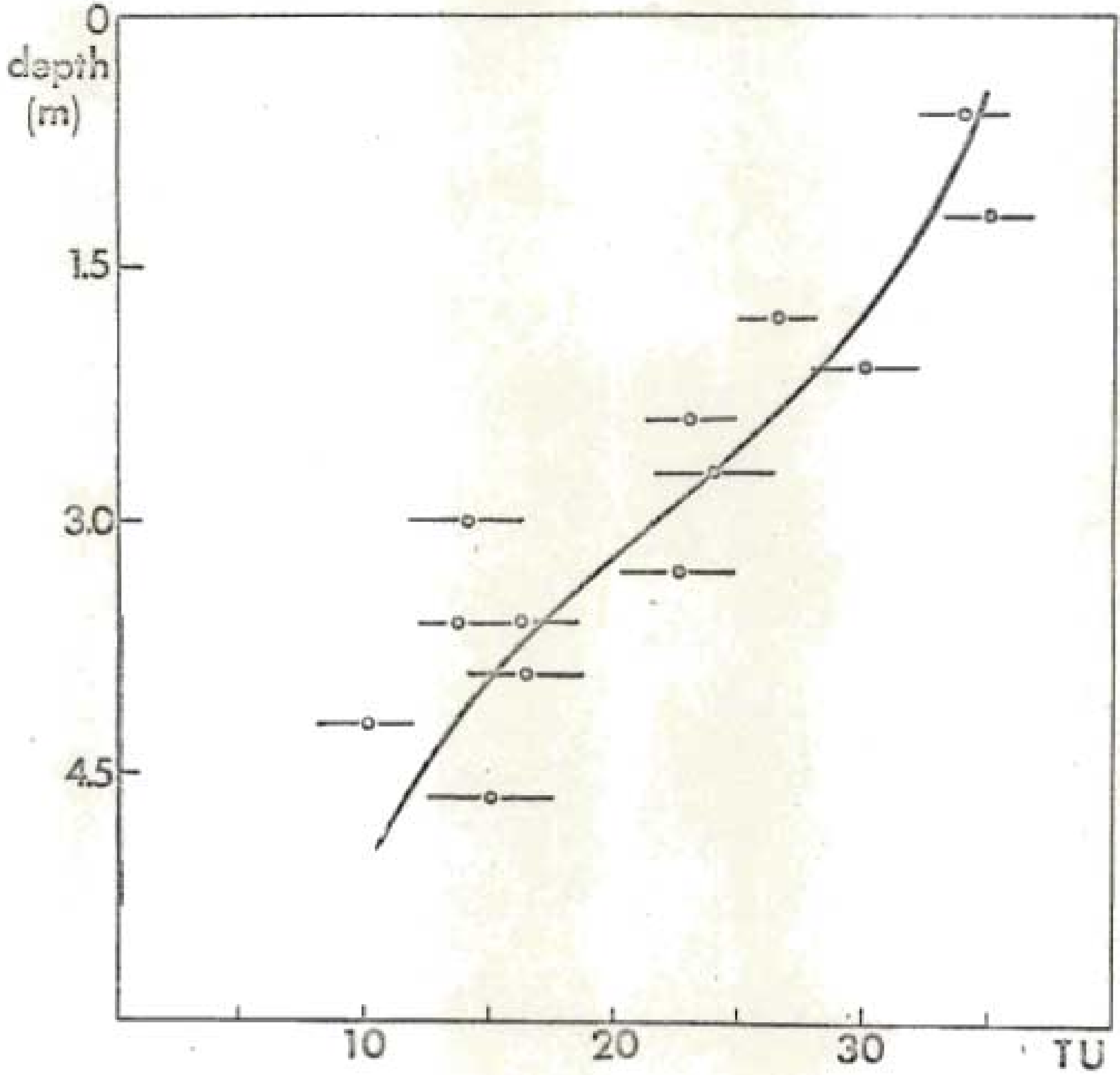


Figure 185 : Tritium in soil moisture profile : Lobatse, 1970

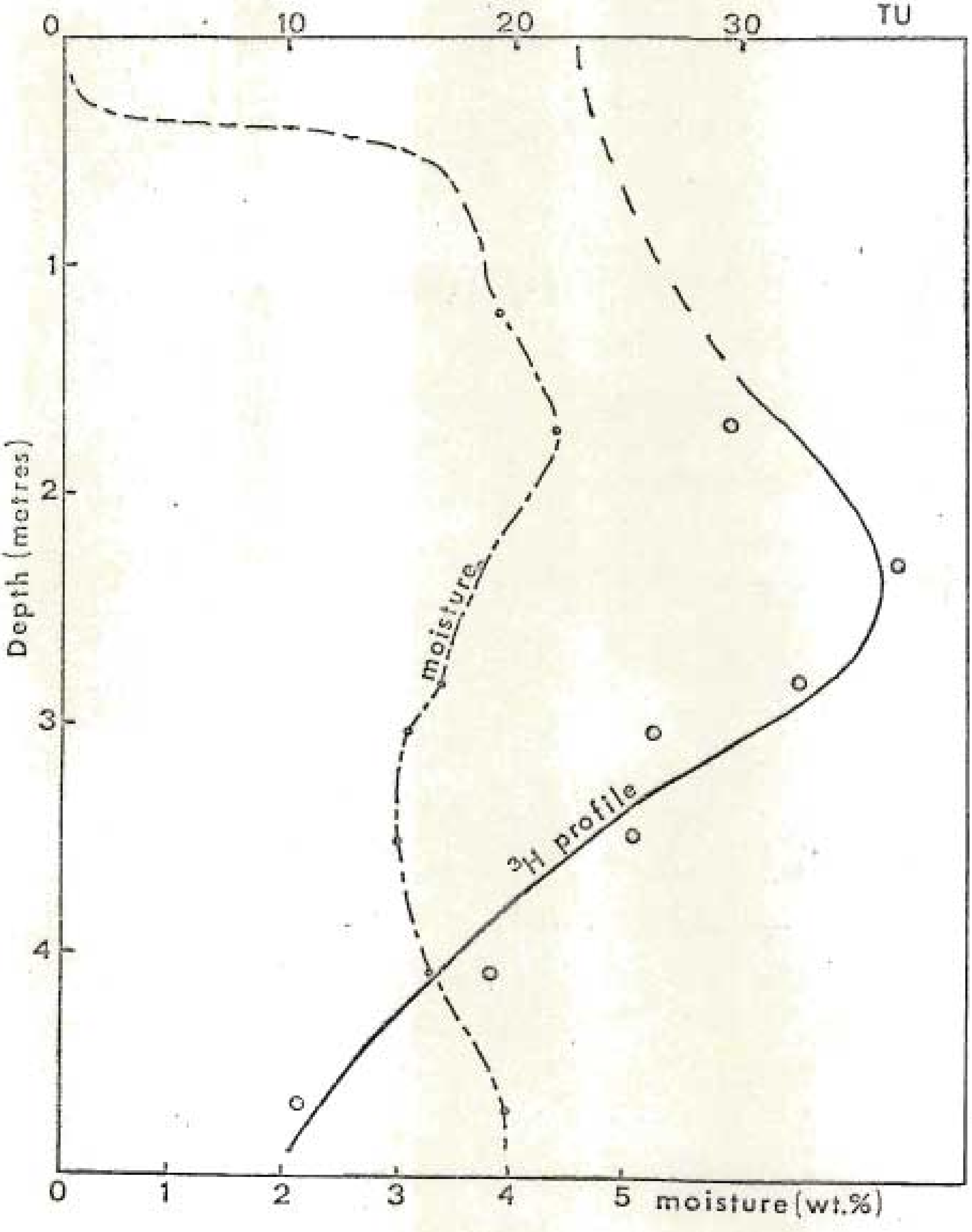


Figure 186 : Tritium sand moisture profile : Mabutsane, July 1972 (After Verhagen et al, 1974).

Thereafter this increased to between three and four per-cent for the remainder of the profile to 5 m. The tri-tium content varied from about 37 TU at about 2,3 m to 11 TU at 4,7 m.

Employing the same type of analysis as was used for the Lobatse profile, an infiltration rate of 31 cm per year was obtained and using a bulk density for Kalahari sand of 1,6 gm cm^{-3} an equivalent water column (downward flux) of 18 mm per year was obtained. This represents 5,4 per cent of the annual rainfall of 330 mm or using the total tritium method, 5,2 per cent.

Further profiles from the same locality near Tshonya Pan (G5, Figure 187), were sampled by the writer just prior to the rainfall season in 1969 and again in 1970. In addition to soil moisture and tritium measurements, deuterium measurements were also made and are plotted on the same profile. Both tritium and deuterium pro-files show clearly defined peaks which can probably be related to individual rainy seasons. By comparing the sharp peak of isotopically lighter values (i.e. large negative values) present on the δ D curve for 1969 with that for 1970, it can be seen that the peak has moved downwards by 1,25 feet (41 cm) in one year. This compares well with the values of 40 cm for Lobatse and 31 cm for Mabutsane. The moisture content at the bottom of the pit varies from 1 to $1\frac{1}{2}$ per cent.

The two δ D profiles provide further interesting informa-tion on the probable depth to which evaporation takes place. Both show marked enrichment (positive δ D values) up to depths of $1\frac{1}{2}$ feet (49 cm) which appears to be the approximate depth to which evaporation can take place.

Conclusions

Soil and sand samples from pits up to depths of 5 m have shown that present day rainfall penetrates to at least this depth. The above calculations of the rate of downward movement of moisture through the unsaturated zone are thus somewhat speculative as it is assumed that this continues to move downwards at the same rate. Further research using samples from greater depths is therefore required. However, there is widespread isotopic evidence from the northern Kalahari (Verhagen et al, 1974) that the shallow ground waters are being directly recharged by rain. Other evidence has been provided by the writer (Chapters on Isotopes and Hydrogeology of Central Kalahari) that some modern rainfall is probably reaching the water table in areas of even deeper Kalahari Bed cover. This could therefore have important connotations in calculating an average safe yield for ground water for the whole of Botswana.

p.750a.

Fig. 187

TRITIUM, SOIL MOISTURE AND STABLE ISOTOPE PROFILES – TSHONYA PAN

GROUND-WATER LEVELS AND FLUCTUATIONS

Water-level observations have been made using more than twenty six automatic water-stage recorders and at over 100 further boreholes (equipped with digital recorders or which are measured manually by electrical water-stage meters) at intervals varying from one day to once every two months. The earliest systematic water level measurements date from 1955, while a fairly comprehensive programme of measurement was commenced in the Lobatse area in 1957. The first two automatic water-stage recorders were purchased and installed on boreholes 629 and 1071 in Lobatse in July 1959. The number of recorders has been progressively increased since then.

The acquisition of long term data on the response of water levels to changes in storage is of vital importance for the understanding of hydrogeological problems in any hydrogeological research programme. Data collected to date in Botswana shows a number of types of water level fluctuations in response to such factors as recharge from rain, natural recession, pumping, earth-tides, atmospheric pressure and earthquakes.

These water level fluctuations have been classified into long-term or short-term fluctuations.

Long-term fluctuations

Natural Recession Curves

The decline of water levels in the absence of recharge depends on:

(1) The capacity of the aquifer to transmit water i.e. its coefficient of transmissibility, T.

(2) The storage coefficient, S.

(3) The hydraulic gradient (Heath and Trainer, 1968)

Examples of natural recession curves are not commonly encountered in Botswana, probably mainly due to the lack of observation boreholes away from the influence of pumped boreholes or other complicating factors.
Fig. 28 shows a natural recession curve (before end of 1960 only) for borehole 1071 in the Lobatse Estates south basin prior to the commencement of heavy pumping from the basin.
Figures 72 - 75, 188 show recession hydrographs for Mahata, Makoba, Tshepe, Mashoro, Bosupswe and Serwe. Robins (1972) has noted that all curves barring Makoba and Serwe show a natural recession with a constant drop of 0,16m per year, while the water level at Makoba is dropping 1,14m per year due to local pumping.
The writer feels, however, in view of the fact that all the observation boreholes quoted above are in close proximity to boreholes used for cattle watering purposes, that these could be pumping recession curves, or a recession resulting from a combination of natural loss and pumping. Another natural recession curve is shown in Fig. 189

Fluctuations caused by seasonal changes

Because of the distinct wet and dry seasons and the great variability in rainfall with consequent seasonal and variable nature of recharge, hydrographs in Botswana often show marked long term seasonal fluctuations.

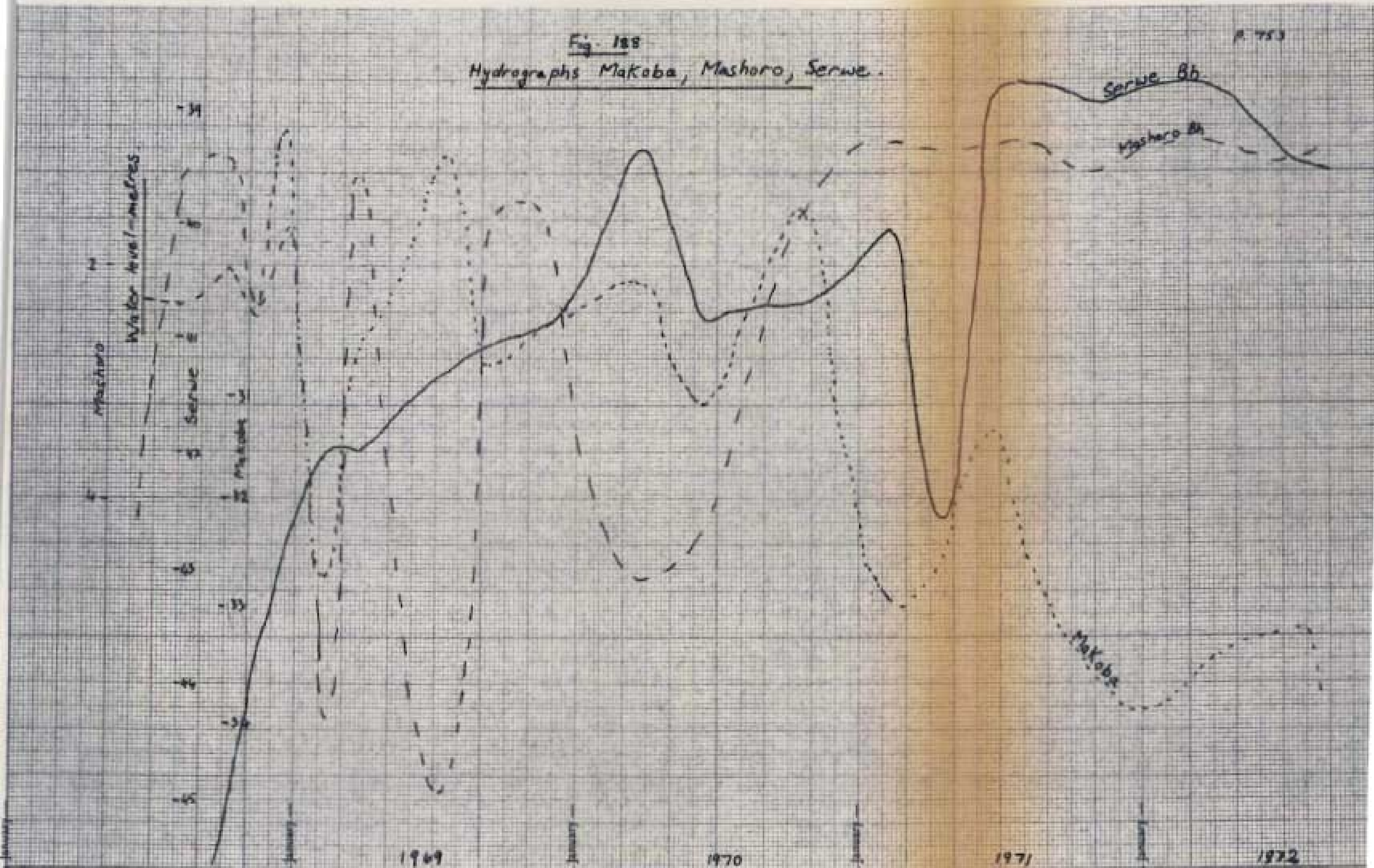


Fig. 188
Hydrographs Makoba, Mashoro, Serwe.
p. 753
Serwe Bh
Mashoro Bh
Makoba
Water level - metres
Mashoro
Serwe
Makoba
1969
1970
1971
1972

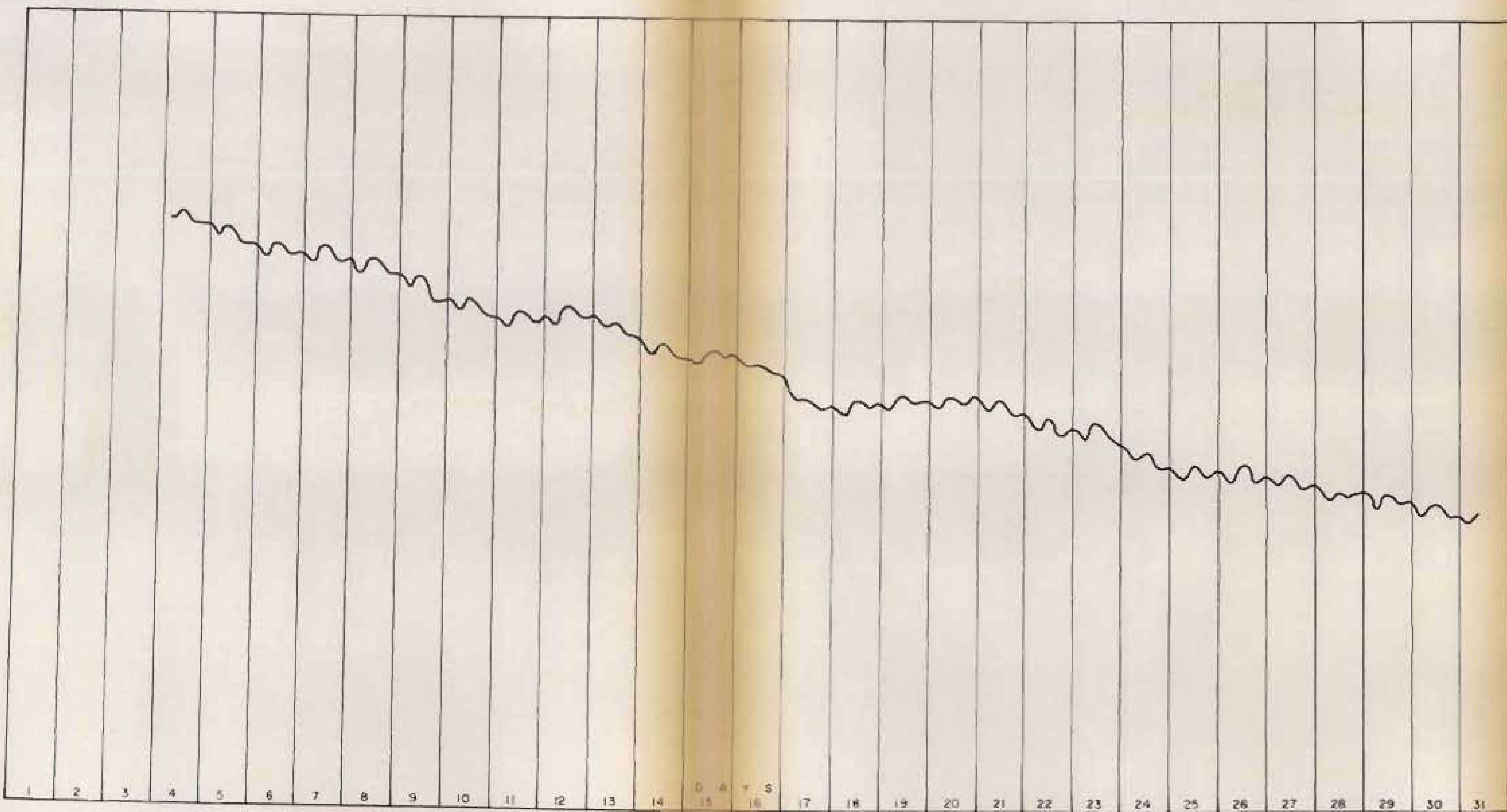


Fig. 189 HYDROGRAPH BH.1917—NATA
SHOWING NATURAL RECESSION AND DIURNAL AND OTHER BAROMETRIC EFFECTS.

Sometimes the effects of changes due to replenishment by rainfall are masked by superimposed changes due to pumping. The writer has consequently calculated and plotted cumulative departure curves using departures from the long term mean monthly rainfall values and from the "safe yield" for Lobatse. (Tables 103 and 104). These departure curves were then plotted on the hydrographs for boreholes A6 (Z.1661), x 4 (P. 772), 1071 and 1412. (Figs. 26-28, 31). The hydrographs represent typical hydrographs in the Lobatse eastern and western and the Lobatse Estates south and central basins respectively.

As can be seen, there is often an excellent correlation between the hydrograph and the departure curves. This shows quite clearly that seasonal variations in rainfall are the main cause of the sharp fluctuations in water level, while general trends correspond with the pumping departure curves. Further details on long-term water level data are given in the chapters on Serowe, Lobatse and Orapa.

Fluctuations caused by pumping

Periodic pumping of ground water causes a drawdown in the water level, followed by a rise in level once pumping is stopped. However, a single or a number of boreholes pumping from an aquifer at a rate which exceeds that of the recharge, will cause a progressive decline in water level which could ultimately lead to the complete de-watering of the aquifer. Study of the long-term trends in water levels can be extremely useful for estimating specific yield of an aquifer, and as an aid to predicting the probable effect of future withdrawal abstractions,

TABLE 103

CUMULATIVE DEPARTURE CURVE FROM MEAN MONTHLY PRECIPITATION IN INCHES - LOBATSE

(For Mean Monthly Rainfall see Table p.757)

MONTH	1954/5 RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE	1955/6 RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE
JULY	-	- 0,22	-0,22	-	-0,22	+4,13
AUG.	-	- 0,08	-0,30	-	-0,08	+4,05
SEPT.	-	- 0,49	-0,79	-	-0,49	+3,56
OCT.	0,09	- 1,72	-2,51	4,69	+2,88	+6,44
NOV.	4,06	+ 1,40	-2,11	2,90	+0,24	+6,68
DEC.	2,83	- 0,97	-3,08	4,91	+1,11	+7,79
JAN.	5,83	+ 2,03	-1,05	0,82	-2,94	+4,85
FEB.	11,10	+ 7,34	+6,29	9,31	+5,50	+10,35
MARCH	1,43	- 1.61	+4,68	1,33	-1,71	+8,64
APR.	1,42	- 0,45	+4,23	-	-1,87	+6,77
MAY	0,04	- 0,64	+3,59	1,70	+1,06	+7,83
JUNE	0,90	+ 0,76	+4,35	-	-0,14	+7,69

TABLE 103

CUMULATIVE DEPARTURE CURVE FROM MEAN MONTHLY PRECIPITATION IN INCHES - LOBATSE

		1956/7			1957/8		
MONTH	MEAN RAINFALL (35 YRS)	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE
JULY	0,22	-	-0,22	+7,47	3,11	+2,89	7,55
AUG.	0,08	-	-0,08	+7,39	-	-0,08	7,47
SEPT.	0,49	0,34	-0,15	+7,24	2,96	+2,47	9,94
OCT.	1,81	2,60	+0,79	+8,03	3,31	+1,50	11,44
NOV.	2,66	1,37	-1,29	+6,74	3,90	+1,84	13,28
DEC.	3,80	2,18	-1,62	+5,12	4,14	+0,34	13,62
JAN.	3,76	2,57	-1,19	+3,92	5,79	+2,03	15,65
FEB.	3,81	5,21	+1,40	+5,33	2,43	-1,38	14,27
MARCH	3,04	2,73	-0,31	+5,02	2,39	-0,65	13,62
APRIL	1,87	0,24	-1,63	+3,39	2,06	+0,19	13,81
MAY	0,64	0,16	-0,48	+2,91	-	-0,64	13,17
JUNE	0,14	1,89	+1,75	+4,66	-	-0,14	13,03

TABLE 103

CUMULATIVE DEPARTURE CURVE FROM MEAN MONTHLY PRECIPITATION IN INCHES - LOBATSE

	1958/9	(25,36in)		1959/60	(16,93in)	
MONTH	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE
JULY	-	-0,22	12,81	0,21	-0,01	12,31
AUG.	-	-0,08	12,73	-	-0,08	12,23
SEPT.	1,10	+0,61	13,34	-	-0,49	11,74
OCT.	1,79	-0,02	13,32	0,69	-1,12	10,62
NOV.	3,12	+0,46	13,78	2,15	-0,51	10,11
DEC.	4,76	+0,96	14,74	5,20	+1,40	11,51
JAN.	5,26	+1,50	16,24	2,86	-0,90	10,61
FEB.	2,13	-1,68	14,56	1,89	-1,92	8,69
MARCH	2,39	-0,65	13,91	2,36	-0,68	8,01
APR.	2,06	+0,19	14,10	1,18	-0,69	7,32
MAY	-	-0,64	13,46	0,09	-0,55	6,77
JUNE	-	-0,14	13,32	0,30	+0,16	6,93

TABLE 103

CUMULATIVE DEPARTURE CURVE FROM MEAN MONTHLY PRECIPITATION IN INCHES - LOBATSE

1960/1 (29,42in) 1961/2 (19,66in)

MONTH	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE
JULY	0,38	+0,16	7,09	0,63	+0,41	16,93
AUG.	0,15	+0,07	7,16	0,23	+0,15	17,08
SEPT.	0,13	-0,36	6,80	-	-0,49	16,59
OCT.	1,56	-0,25	6,55	0,76	-1,05	15,54
NOV.	4,03	+1,37	7,92	2,15	-0,51	15,03
DEC.	7,02	+3,22	11,24	1,90	-1,90	13,13
JAN.	1,55	-2,21	9,03	3,12	-0,64	12,49
FEB.	5,06	+1,25	10,28	2,51	-1,30	11,19
MARCH	1,73	-1,31	8,97	3,04	0,00	11,19
APR.	7,05	+5,18	14,15	5,32	+3,45	14,64
MAY	2,39	+1,75	15,90	-	-0,64	14,00
JUNE	0,76	+0,62	16,52	-	-0,14	13,86

TABLE 103

CUMULATIVE DEPARTURE CURVE FROM MEAN MONTHLY PRECIPITATION IN INCHES - LOBATSE

	1962/3	(15,99in)		1963/4	(15,05in)	
MONTH	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE
JULY	-	-0,22	13,64	-	-0,22	7,31
AUG.	0,05	-0,03	13,61	-	-0,08	7,23
SEPT.	0,11	-0,38	13,23	-	-0,49	6,74
OCT.	0,80	-1,01	12,22	5,05	+3,24	9,98
NOV.	5,31	+2,65	14,87	3,44	+0,78	10,76
DEC.	0,96	-2,84	12,03	0,15	-3,65	7,11
JAN.	4,37	+0,61	12,64	3,39	-0,37	6,74
FEB.	0,28	-3,53	9,11	1,25	-2,56	4,18
MARCH	1,05	-1,99	7,12	1,61	-1,43	2,75
APR.	1,18	-0,69	6,43	0,02	-1,85	0,90
MAY	0,90	+0,26	6,69	-	-0,64	0,26
JUNE	0,98	+0,84	7,53	0,14	-0,00	0,26

T A B L E 103

CUMULATIVE DEPARTURE CURVE FROM MEAN MONTHLY PRECIPITATION IN INCHES - LOBATSE

1964/5 (15,32in) 1965/6 (15,51in)

MONTH	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE
JULY	-	-0,22	0,04	0,05	-0,17	-5,21
AUG.	-	-0,08	-0,04	-	-0,08	-5,29
SEPT.	-	-0,49	-0,53	-	-0,49	-5,78
OCT.	2,32	+0,51	-0,02	0,40	-1,41	-7,19
NOV.	0,81	-1,85	-1,87	1,64	-1,02	-8,21
DEC.	5,08	+1,28	-0,59	0,53	-3,27	-11,48
JAN.	2,91	+0,85	+0,26	4,90	+1,14	-10,34
FEB.	1,35	-2,46	-2,20	5,09	+1,28	-9,06
MARCH	0,33	-2,71	-4,91	-	-3,04	-12,10
APRIL	2,52	+0,65	-4,26	0,51	-1,36	-13,46
MAY	-	-0,64	-4,90	0,40	-0,24	-13,70
JUNE	-	-0,14	-5,04	2,39	+2,17	-11,53

TABLE 103

CUMULATIVE DEPARTURE CURVE FROM MEAN MONTHLY PRECIPITATION IN INCHES - LOBATSE

	1966/7	(35,52in)		1967/8	(22,92in)	
MONTH	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE
JULY	-	-0,22	-11,75	-	-0,22	1,45
AUG.	-	-0,08	-11,83	1,26	+1,18	2,63
SEPT.	0,68	+0,19	-11,64	0,02	-0,47	2,16
OCT.	1,24	-0,57	-12,21	2,01	+0,20	2,36
NOV.	0,79	-1,87	-14,08	1,12	-1,54	0,82
DEC.	5,91	+2,11	-11,97	2,78	-1,02	-0,20
JAN.	9,67	+5,91	- 6,06	1,31	-2,45	-2,65
FEB.	5,97	+2,16	- 3,90	2,48	-1,33	-3,98
MARCH	2,64	-0,40	- 4,30	7,23	+4,19	+0,21
APRIL	8,48	+6,61	+ 2,31	3,98	+2,11	2,32
MAY	0,14	-0,50	+ 1,81	1,29	+0,65	2,97
JUNE	-	-0,14	+ 1,67	0,07	-0,07	2,90

TABLE 103

CUMULATIVE DEPARTURE CURVE FROM MEAN MONTHLY PRECIPITATION IN INCHES - LOBATSE

	1968/9	(15,90in)		1969/70	(13,36in)	
MONTH	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE
JULY	-	-0,22	2,68	-	-0,22	-3,69
AUG.	0,05	+0,03	2,71	0,08	0,00	-3,69
SEPT.	-	-0,49	2,22	0,06	-0,43	-4,11
OCT.	0,05	-1,76	0,46	1,96	+0,15	-3,96
NOV.	2,48	-0,18	0,28	0,31	-2,35	-6,31
DEC.	2,78	-1,02	0,74	4,36	+0,56	-5,75
JAN.	1,31	-2,45	3,19	3,00	-0,76	-6,51
FEB.	2,48	-1,33	4,52	1,70	-2,11	-8,62
MARCH	3,26	+0,22	4,30	0,78	-2,26	-10,88
APRIL	2,57	+0,70	3,60	0,91	-0,96	-11,84
MAY	0,92	+0,28	3,32	0,20	-0,44	-12,28
JUNE	-	-0,14	3,46	-	-0,14	-12,42

TABLE 103

CUMULATIVE DEPARTURE CURVE FROM MEAN MONTHLY PRECIPITATION IN INCHES - LOBATSE

1970/1 (22,79in) — 1971/2 (26,92in)

MONTH	RAINFALL (1970/1)	DEPARTURE FROM NORMAL (1970/1)	CUMULATIVE DEPARTURE (1970/1)	RAINFALL (1971/2)	DEPARTURE FROM NORMAL (1971/2)	CUMULATIVE (1971/2)
JULY	0,02	-0,2	-12,62	-	-0,22	-12,25
AUG.	-	-0,08	-12,70	-	-0,08	-12,33
SEPT.	0,42	-0,07	-12,77	0,52	+0,03	-12,30
OCT.	0,29	-1,52	-14,29	2,92	+1,11	-11,19
NOV.	3,07	+0,41	-13,88	3,71	+1,15	-10,04
DEC.	4,37	+0,57	-13,31	1,46	-2,34	-12,38
JAN.	7,44	+3,68	- 9,63	9,15	+5,39	- 6,99
FEB.	2,67	-1,14	-10,77	2,50	-1,31	- 8,30
MARCH	1,23	-1,81	-12,58	5,67	+2,63	- 5,67
APR.	2,72	+0,85	-11,73	0,87	-1,00	- 6,67
MAY	0,56	-0,08	-11,81	0,01	-0,63	- 7,30
JUNE	-	-0,22	-12,03	0,10	-0,04	- 7,34

TABLE 103

CUMULATIVE DEPARTURE CURVE FROM MEAN MONTHLY PRECIPITATION IN INCHES - LOBATSE

	1972/3	(16,61in)		1973/4		
MONTH	RAINFALL	DEPARTURE FROM NORMAL	CUMULATIVE DEPARTURE	RAINFALL	DEPARTURE FRM NORMAL	CUMULATIVE
JULY	-	-0,22	-7,56	-	-0,22	-13,27
AUG.	-	-0,08	-7,64	-	-0,08	-13,35
SEPT.	0,55	+0,06	-7,58	1,68	+1,19	-12,16
OCT.	0,27	-1,54	-9,12	3,69	+1,78	-10,38
NOV.	2,25	-0,41	-9,53	4,54	+1,88	- 8,50
DEC.	1,64	-2,16	-11,69	2,29	-1,51	-10,01
JAN.	2,54	-1,22	-12,91	8,05	+4,29	- 5,72
FEB.	3,99	+0,18	-12,73	4,34	+0,53	- 5,19
MARCH	3,02	-0,02	-12,75	4,05	+1,01	- 4,18
APR.	2,35	+0,48	-12,27	2,42	+0,55	- 3,63
MAY	-	-0,64	-12,91	0,07	-0,57	- 4,20
JUNE	-	-0,14	-13,05	-	-0,14	- 4,34

TABLE 104

CUMULATIVE DEPARTURE CURVE FOR LOBATSE E. BASIN (XI.) FROM LONG TERM MEAN RECHARGE RATE OF 0,80 MILLION GALLONS PER MONTH

	1957			1958			1959			1960			1961		
J	-			0,90	+0,10	+1,01	2,14	+1,34	+ 6,91	1,07	+0,27	+13,53	0,53	- 0,27	+15,29
F	-			0,84	+0,04	+1,05	1,89	+1,09	+ 8,00	1,59	+0,79	+14,32	0,96	+0,16	+15,45
M	-			0,69	-0,11	+0,94	1,71	+0,91	+ 8,91	1,72	+0,92	+15,24	0,97	+0,17	+15,62
A	-			0,91	+0,11	+1,05	1,60	+0,80	+ 9,71	1,56	+0,76	+16,00	0,87	+0,07	+15,69
M	-			1,44	+0,64	+1,69	1,46	+0,66	+10,37	1,12	+0,32	+16,32	0,92	+0,12	+15,81
J	-			1,27	+0,47	+2,16	1,73	+0,93	+11,30	0,95	+0,15	+16,47	0,93	+0,13	+15,94
J	-			1,35	+0,55	+2,71	1,56	+0,76	+12,06	0,70	-0,10	+16,37	1,15	+0,35	+16,29
A	-			1,78	+0,98	+3,69	1,68	+0,88	+12,94	0,52	-0,28	+16,09	1,22	+0,42	+16,71
S	-	0	0	1,26	+0,46	+4,15	0,98	+0,18	+13,12	0,83	+0,03	+16,12	1,28	+0,48	+17,19
O	0,43	-0,37	-0,37	1,39	+0,59	+4,74	1,35	+0,55	+13,67	0,80	0	+16,12	1,00	+0,20	+17,39
N	1,24	+0,44	+0,07	1,16	+0,36	+5,10	0,61	-0,19	+13,48	0,54	-0,26	+15,86	1,06	+0,26	+17,65
D	1,64	+0,84	+0,91	1,27	+0,47	+5,57	0,58	-0,22	+13,26	0,50	-0,30	+15,56	0,60	-0,20	+17,45

NOTE: Column 1 = Monthly pumping figure.
Column 2 = Departure from mean of 0,80 million gallons.
Column 3 = Cumulative departure from mean.

TABLE 104

CUMULATIVE DEPARTURE CURVE FOR LOBATSE E. BASIN (XI.) FROM LONG TERM MEAN RECHARGE RATE OF 0,80 MILLION GALLONS PER MONTH

	1962			1963			1964			1965		
J	0,55	-0,25	+17,20	0,78	-0,02	17,52	0,41	-0,39	14,62	1,32	+0,52	14,30
F	0,87	+0,07	+17,27	0,78	-0,02	17,54	0,38	-0,42	14,20	1,16	+0,36	14,66
M	0,92	+0,12	17,39	0,85	+0,05	17,59	0,97	+0,17	14,37	1,72	+0,92	15,58
A	0,80	0	17,39	0,82	+0,02	17,61	0,82	+0,02	14,39	0,70	-0,10	15,48
M	1,10	+0,30	17,69	0,70	-0,10	17,51	0,81	+0,01	14,40	0,67	-0,13	15,35
J	0,89	+0,09	17,78	0,79	-0,01	17,50	0,69	-0,11	14,29	0,61	-0,19	15,16
J	0,90	+0,10	17,88	0,71	-0,09	17,41	0,54	-0,26	14,03	0,74	-0,06	15,10
A	0,75	-0,05	17,83	0,40	-0,40	17,01	0,66	-0,14	13,89	0,59	-0,21	14,89
S	0,90	+0,10	17,93	0,24	-0,56	16,45	0,78	-0,02	13,87	0,55	-0,23	14,66
O	0,68	-0,12	17,81	0,26	-0,54	15,91	0,78	-0,02	13,85	0,84	-0,04	14,62
N	0,58	-0,22	17,59	0,33	-0,47	15,44	0,49	-0,31	13,54	0,90	+0,10	14,72
D	0,75	-0,05	17,54	0,37	-0,43	15,01	1,04	+0,24	13,78	0,60	-0,20	14,52

TABLE 104

CUMULATIVE DEPARTURE CURVE FOR LOBATSE E. BASIN (XI.) FROM LONG TERM MEAN RECHARGE RATE OF 0,80 MILLION GALLONS PER MONTH

	1966			1967			1968			1969		
J	0,91	+ 0,11	14,63	1,18	+0,38	16,45	0,83	+,03	17,27	0,4e	-0,4	16,87
F	0,92	+ 0,12	14,75	1,09	+0,29	16,74	0,80	0	17,27	0,4e	-0,4	16,47
M	0,92	+ 0,12	14,87	0,91	+0,11	16,85	0,8e	0	17,27	0,4e	-0,4	16,07
A	0,80	0	14,87	1,11	+0,31	17,16	0,8e	0	17,27	0,4e	-0,4	15,67
M	0,64	- 0,16	14,71	1,10	+0,30	17,46	0,8e	0	17,27	0,4e	-0,4	15,27
J	0,90	+ 0,10	14,81	0,99	+0,19	17,65	0,8e	0	17,27	0,4e	-0,4	14,87
J	0,75	- 0,05	14,76	1,01	+0,21	17,86	0,8e	0	17,27	0,4e	-0,4	14,47
A	0,95	+ 0,15	14,91	0,86	+0,06	17,92	0,8e	0	17,27	0,4e	-0,4	14,07
S	0,86	+ 0,06	14,97	0,84	+0,04	17,96	0,8e	0	17,27	0,4e	-0,4	13,67
O	1,17	+ 0,37	15,34	0,83	+0,03	17,99	0,8e	0	17,27	0,4e	-0,4	13,27
N	1,19	+ 0,39	15,73	-	-0,80	17,19	0,8e	0	17,27	0,4e	-0,4	12,87
D	1,14	+ 0,34	16,07	0,85	+0,05	17,24	0,8e	0	17,27	0,4e	-0,4	12,47

TABLE 104

CUMULATIVE DEPARTURE CURVE FOR LOBATSE E. BASIN (XI.) FROM LONG TERM MEAN RECHARGE RATE OF 0,80 MILLION GALLONS PER MONTH

	1970			1971			1972		
J	-	-0,8	11,67	0,60	-0,2	2,79	0,32	-0,48	-1,23
F	-	-0,8	10,87	0,47	-0,33	2,46	0,20	-0,60	-1,83
M	-	-0,8	10,07	1,06	+0,26	2,72	0,20e	-0,60	-2,43
A	-	-0,8	9,27	0,73	-0,07	2,65	0,20e	-0,60	-3,03
M	-	-0,8	8,47	0,81	+0,01	2,66	0,23	-0,57	-3,60
J	0,01	-0,8	7,67	0,46	-0,34	2,32	0,22	-0,58	-4,18
J	0,38	-0,8	6,87	0,35	-0,45	1,87	0,20e	-0,60	-4,78
A	0,23	-0,8	6,07	0,41	-0,39	1,48	0,20	-0,60	-5,38
S	-	-0,8	5,27	0,22	-0,58	0,90	-	-0,80	-6,18
O	-	-0,8	4,47	0,14	-0,66	0,24	-	-0,80	-6,98
N	0,09	-0,71	3,76	0,29	-0,51	-0,27	0,09	-0,71	-7,69
D	0,03	-0,77	2,99	0,32	-0,48	-0,75	-	-	-

* NOTE: Column 1 for each year denotes montly pumping figure in million gallons, column 2 denotes departive from mean of 0,80 million gallons per month, column 3 indicates cumulative departure.

or even give warning prior to the complete depletion of an aquifer (see chapter on Lobatse).
Examples of long-term trends are given for borehole No. 901 (Railway Basin, Lobatse), for boreholes A6, 629 (Western Basin, Lobatse), for borehole X4 (Eastern Basin, Lobatse), for borehole 1071 (South Basin, Lobatse Estates, Fig. 28) borehole 1412 (Central Basin, Lobatse Estates, Fig. 31) and for a group of observation boreholes extending across the Kalahari from Letlhakeng to Morwamosu (Figs. 27, 39, 17; also 66, 93).
The hydrograph for the Majwane borehole is an excellent example of a combination of recession due to overpumping in the area and of rises in the water level, probably caused by occasional recharge (Fig. 17).

Short Term Fluctuations

Hydroseisms

The term "hydroseism" includes all seismically induced water level fluctuations other than tsunamis (Vorhis, 1967) while he defines a "seismic seiche" as a symmetrical seismically induced water-level fluctuation.
Hydroseisms in water boreholes have been reported by da Costa (1964), La Rocque (1951), Parker and Stringfield (1950), Vorhis (1967) and many others.
In Southern Africa hydroseisms have been recorded by Olivier (1972), Jennings (1970), while Vorhis (1967) quotes van Eeden (1965) as recording hydroseisms on three observation-well recorders in South Africa following the disastrous Alaskan earth-

quake of March, 1964. Van Wyk (1965) also noted a hydroseism in a borehole at Windhoek, South West Africa, following the same earthquake (Vorhis, 1967).
Olivier (1972) noted vertical disturbances of 0,1 feet, 0,15 feet and 0,25 feet in boreholes near the Fish River - Orange River tunnel following the Ceres-Tulbagh earthquake on 29th September, 1969, 2nd October, 1969 and 14th April, 1970 when shocks of 6,3, 4,1 and 5,7 respectively on the Richter scale were recorded. He noted, furthermore, that a disturbance of the semi-diurnal fluctuation pattern for a period of six days preceding the earthquake of 14th April, 1970.

Hydroseisms in Botswana

Lobatse

The Ceres-Tulbagh earthquake also had a clearly discernable effect on the regular semi-diurnal fluctuations of borehole 1325 situated in the Lobatse Estates southern ground water basin some 1088 km from Tulbagh. This borehole is 116,76m deep, water was encountered from 32m onwards and the original water level was 13,7m, but, at the time of the earthquake, was approximately 33,2m. The borehole was sunk through 12,19m of alluvium into a succession of shale and quartzite (Daspoort Stage, Pretoria Group, Transvaal Supergroup). The borehole was cased with steel lining.
A study of the hydrograph for September and October (see Fig. 48) shows that for thirteen days preceding the earthquake on 29th September 1969, there was a steady overall rise in water level, amounting to about 15cm, on which the regular semi-diurnal fluctuations were superimposed. At approximately 2000 hours on

29th September (closer estimation of the exact time was not possible because of the scale of the recorder chart (12mm to one day), a sudden drop of 3,0 cm was recorded, followed by a rise of 33,9 cm over a period of just under six hours. This was followed by a steady decline in water level for forty-six hours, interrupted briefly by a minor rise in water level conforming to portion of the regular semi-diurnal fluctuation. The decline in water level amounted to 39cm. This was followed on 2nd October by two further rapid rises, totalling 31,2cm and 22,8cm respectively, each followed by a more gradual decline in water level. It is interesting to note that each of the three major rises in water level resembled the mirror image of the form of water level fluctuation caused by a pumping event such as that shown in the same hydrograph (Fig. 48) on 20th October 1969. It is also interesting to note that the general rise in water level preceding the earthquakes, was followed by a period with no overall change in water level until the pumping event on the 20th. The semi-diurnal fluctuations for the period 29th September to 3rd October were also completely disrupted.

During this period, the only appreciable rainfall recorded was 10,5mm but as it was the first significant rainfall in the new season, no run-off occurred and hence the fluctuations cannot have been caused by recharge. There was also no pumping from the basin during the same period.

Ghanzi

The only other observation borehole in Botswana to show a hydroseism was borehole 1128 located in Ghanzi village and

situated in shale and quartzite of the Ghanzi Formation.
The hydrograph of this borehole normally showed marked semi-diurnal fluctuations caused by pressure changes with superimposed minor fluctuations caused by a number of pumping boreholes within a radius of 300 to 400m (see Fig.190).
However, on 12th September, 1969, a disturbance of the regular semi-diurnal fluctuations commenced and continued till 10th October 1969. At approximately 2000 hours on 29th September, a small but sharp rise and fall in water level, totalling 2,4cm, occurred and was followed on both 30th September and 1st October by an abnormally rapid rise in level each of 4,8cm accompanied on each occasion by minor fluctuations in water level (see Figs.191 and 192).
Unfortunately no hydrograph is available for this borehole from 2 - 4th October 1969. However normal, semi-diurnal fluctuations only recommenced on 10th October. Should it be found that disturbances of the normal tidal fluctuations in boreholes occur regularly prior to major seismic events, this could prove of enormous help in aiding the prediction of future catastrophic earthquakes.

Water Level Fluctuations Due to Changes in Atmospheric Pressure

Prior to carrying out a detailed aquifer evaluation pump test in Lobatse, regular measurements of water levels were accurately taken using an electrical depth gauge. These levels were plotted on the strip chart showing atmospheric changes as recorded by a micro-barograph for the same period. It can be seen (Fig.117) that there is an excellent correspondence between the daily atmospheric pressure maxima and the greatest depression of the

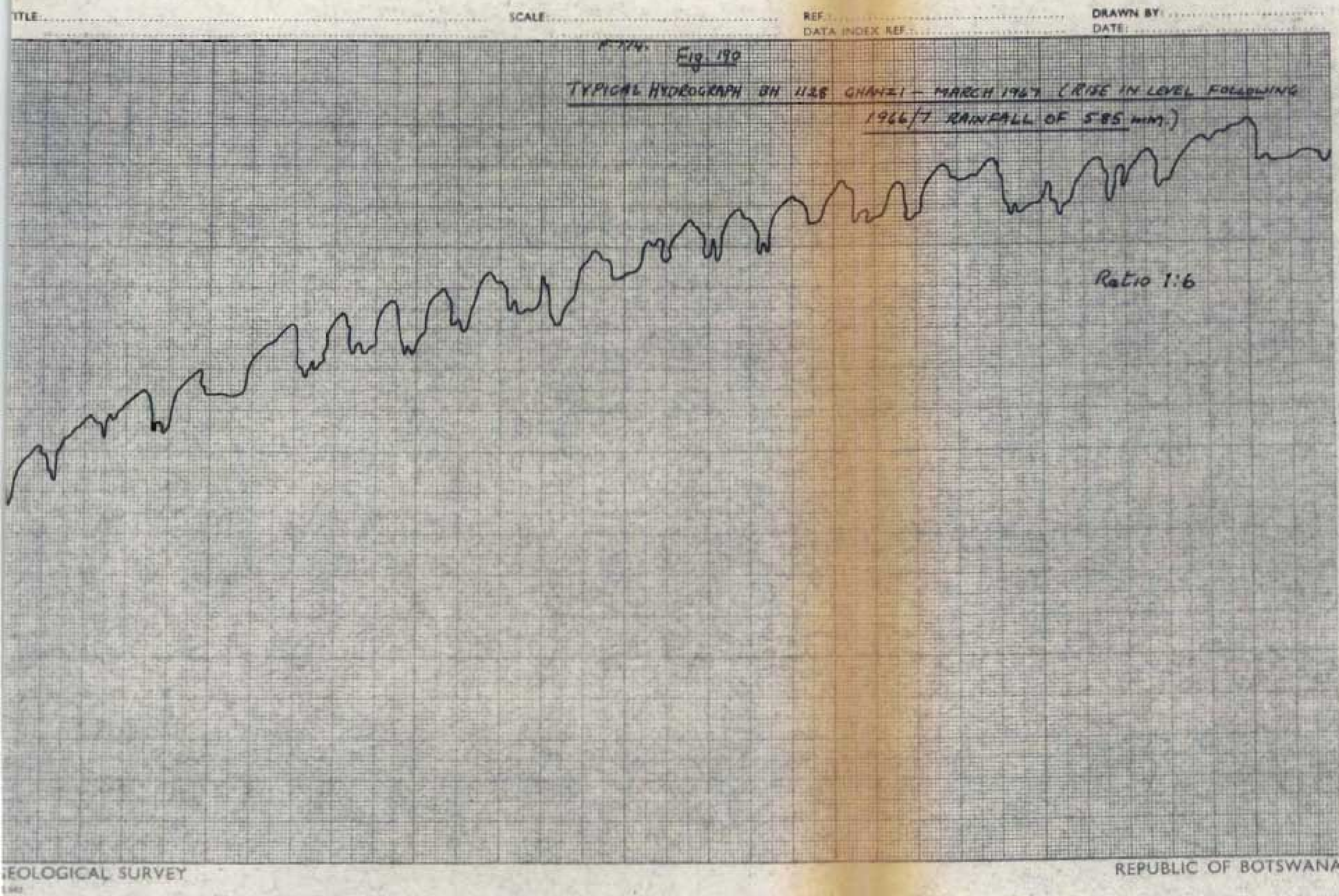

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Fig. 190
TYPICAL HYDROGRAPH BH 1128 GHANZI – MARCH 1967 (RISE IN LEVEL FOLLOWING 1966/7 RAINFALL OF 585 mm.)
Ratio 1:6
GEOLOGICAL SURVEY
REPUBLIC OF BOTSWANA

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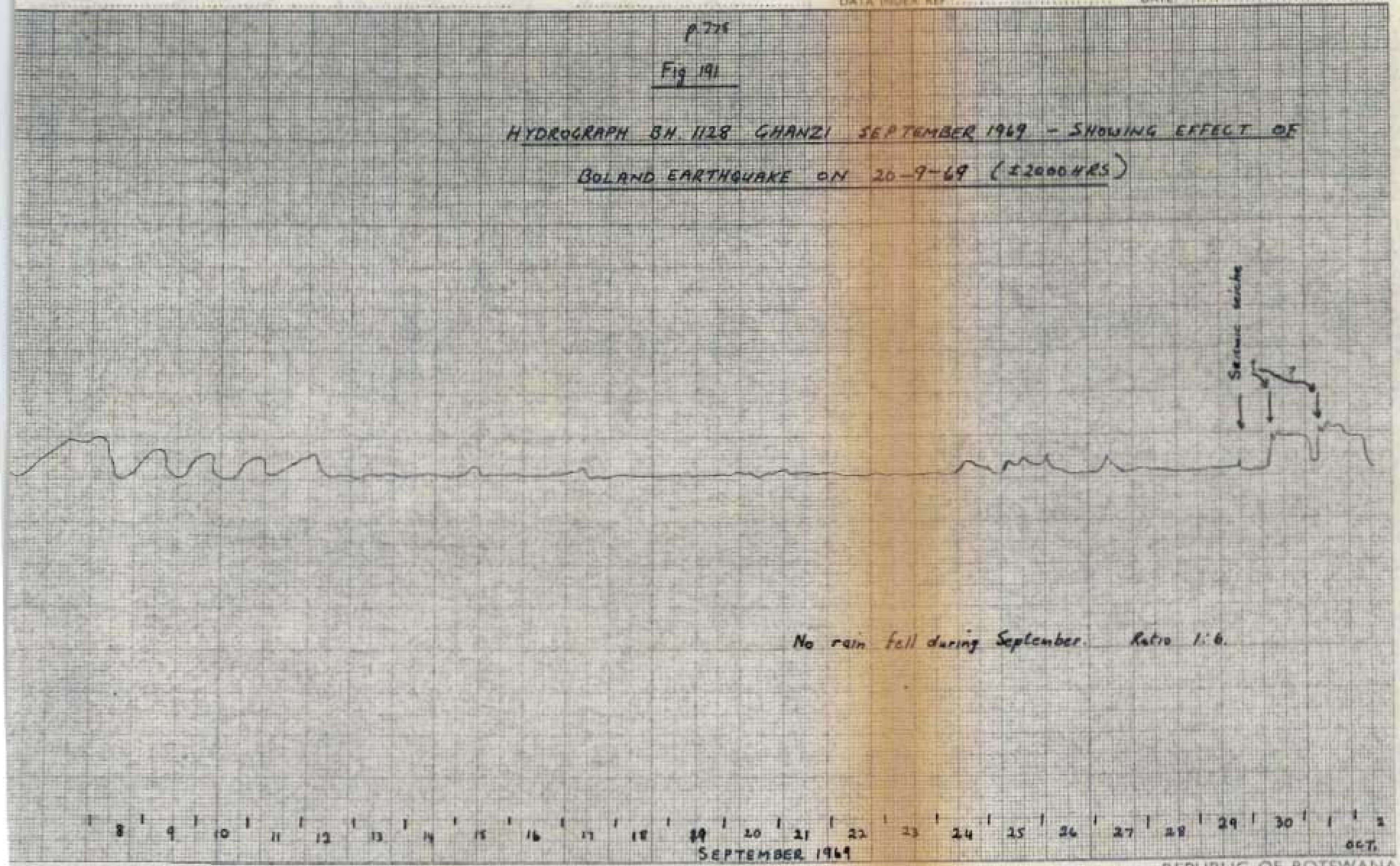

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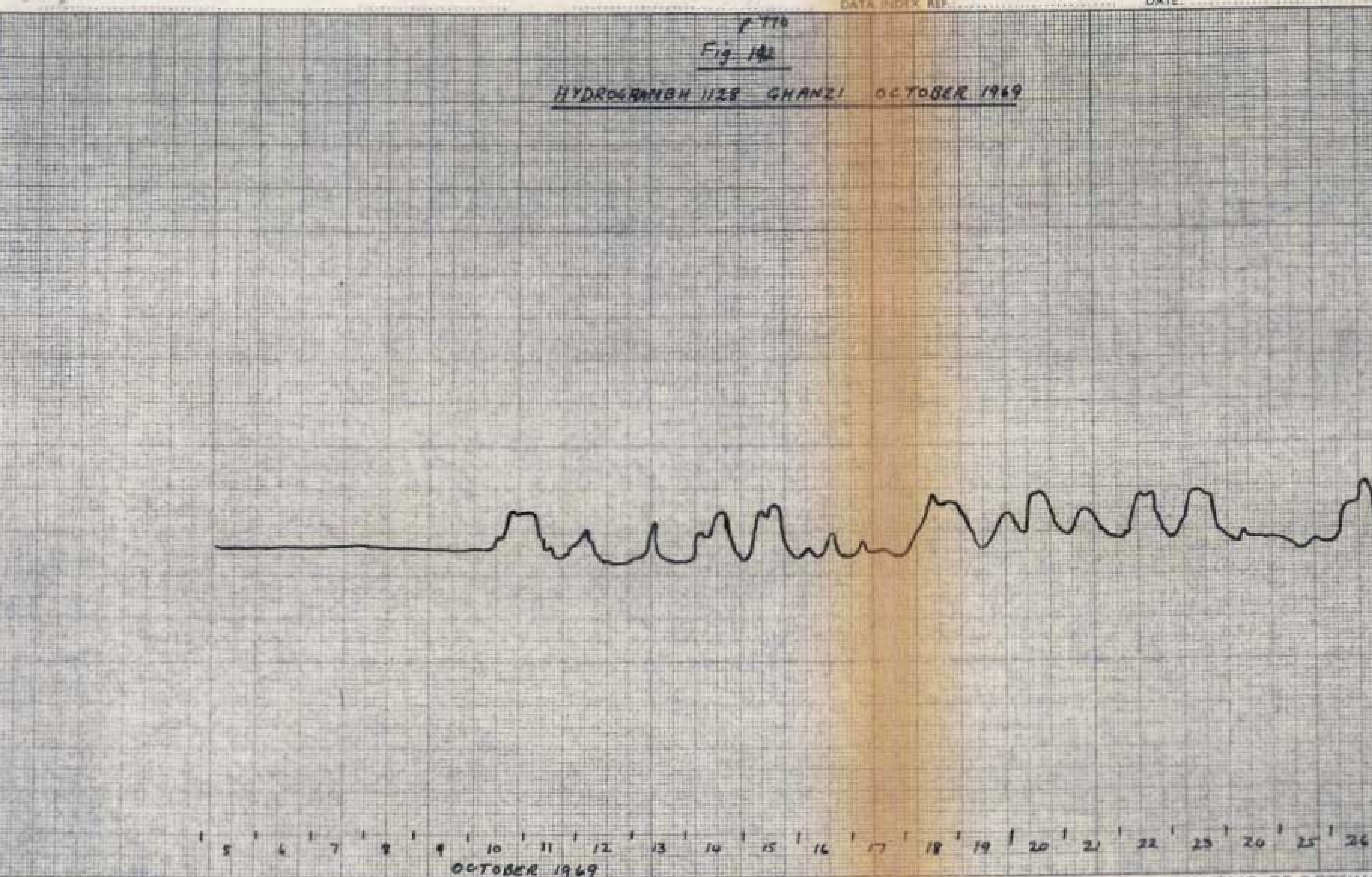


GEOLOGICAL SURVEY

REPUBLIC OF BOTSWANA

piezometric surface in boreholes A.4, A.7 and A.10. The magnitude of the water level fluctuations varied from 0,01 feet (3mm) to 0,06 (18,3mm). Other examples of typical water level fluctuations due to diurnal pressure fluctuations are shown in Figs. 190, 193.

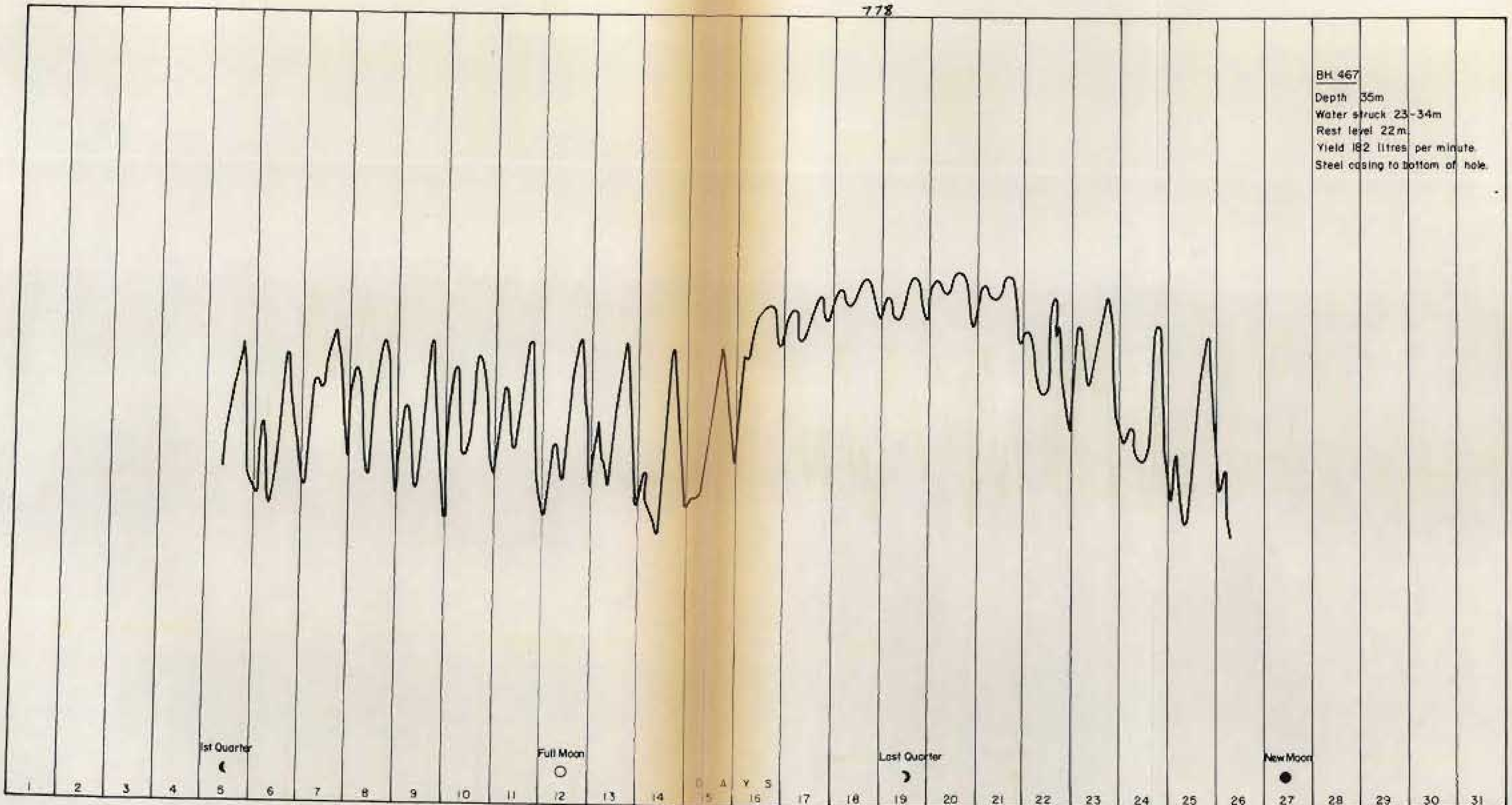
Water Level Fluctuations caused by Earth Tides

Semi-diurnal fluctuations of water level ascribed to earth tides have been described by van Wyk (1963) and others. Van Wyk (1963) showed that these result from earth-tides produced by the attraction of the moon and the sun.

Similar earth-tidal fluctuations in water-level have been observed in numerous boreholes in Botswana. Examples of such tidal fluctuations are given in Figs. 193, 194, 195, 196, which also coincide with the various phases of the moon. It can be clearly seen that these fluctuations attain their greatest amplitude at new and full moon and minimum amplitude during periods coinciding with the first and last quarters of the moon.

Water Level Changes due to Rapid Infiltration to the Water Table

Figures 98 and 99 show typical examples of rapid rises in water level following heavy rain in Serowe, Figs. 47, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, show typical hydrographs reflecting rapid response to heavy rain in Lobatse. The sympathetic response in boreholes in the Western basin is clearly shown in Fig. 45. Figs. 197 - 199 show an interesting, and almost immediate response, in borehole 2124, of the water table at about 10m to flood waters flowing past the adjacent large,



RATIO 1:6

Fig. 193 HYDROGRAPH BH. 467 – LOBATSE WEST BASIN – DECEMBER 1966
SHOWING TIDAL FLUCTUATIONS (UP TO 30cm) SUPERIMPOSED ON DIURNAL FLUCTUATION.

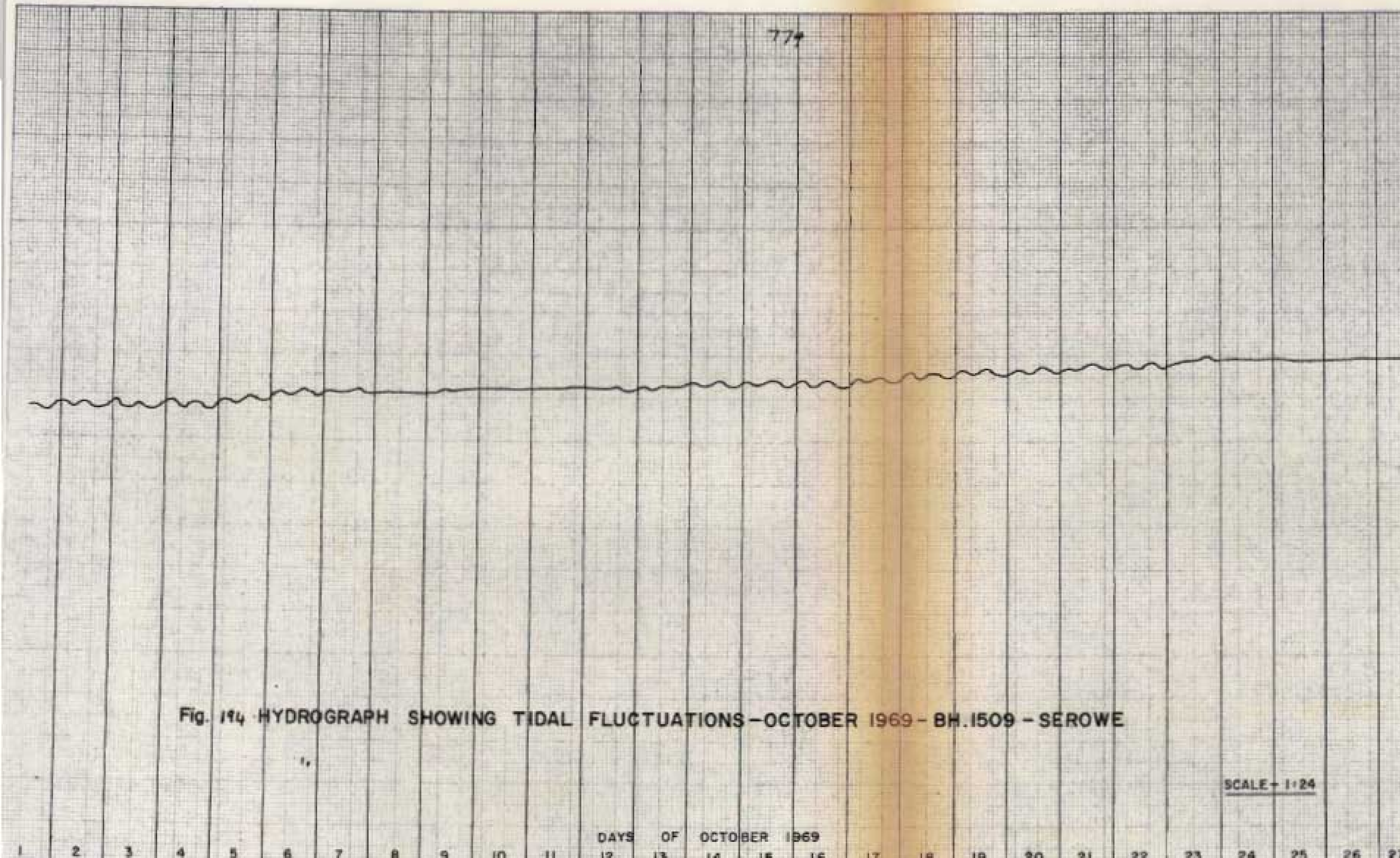
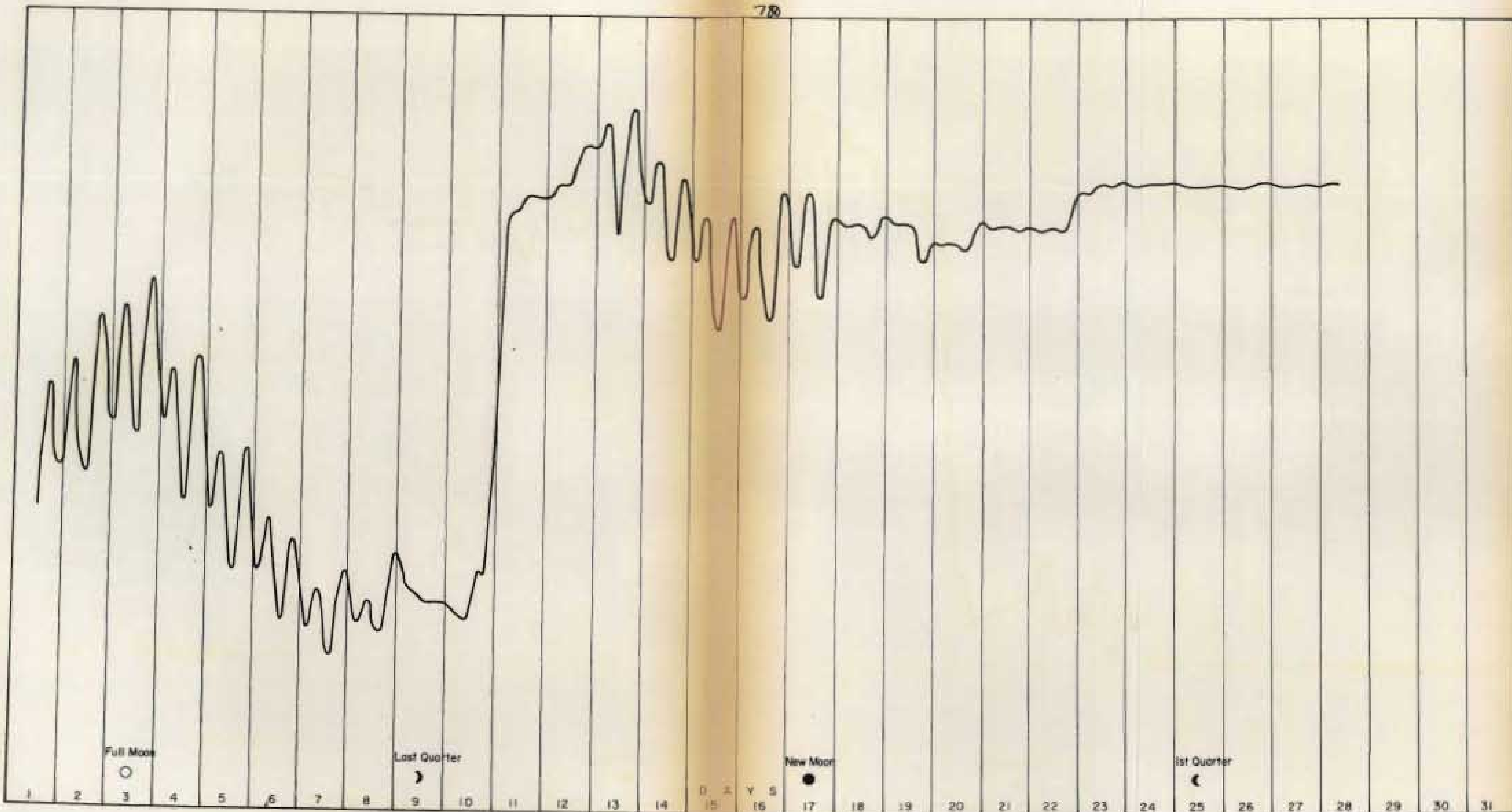


Fig. 14 HYDROGRAPH SHOWING TIDAL FLUCTUATIONS - OCTOBER 1969 - BH.1509 - SEROWE

FIG. 195.



RATIO 1:2

Fig. 195 HYDROGRAPH BH. 1463 – LOBATSE ESTATES NORTH BASIN – OCTOBER 1963
SHOWING RECHARGE EVENT (10th) AND TIDAL FLUCTUATIONS.

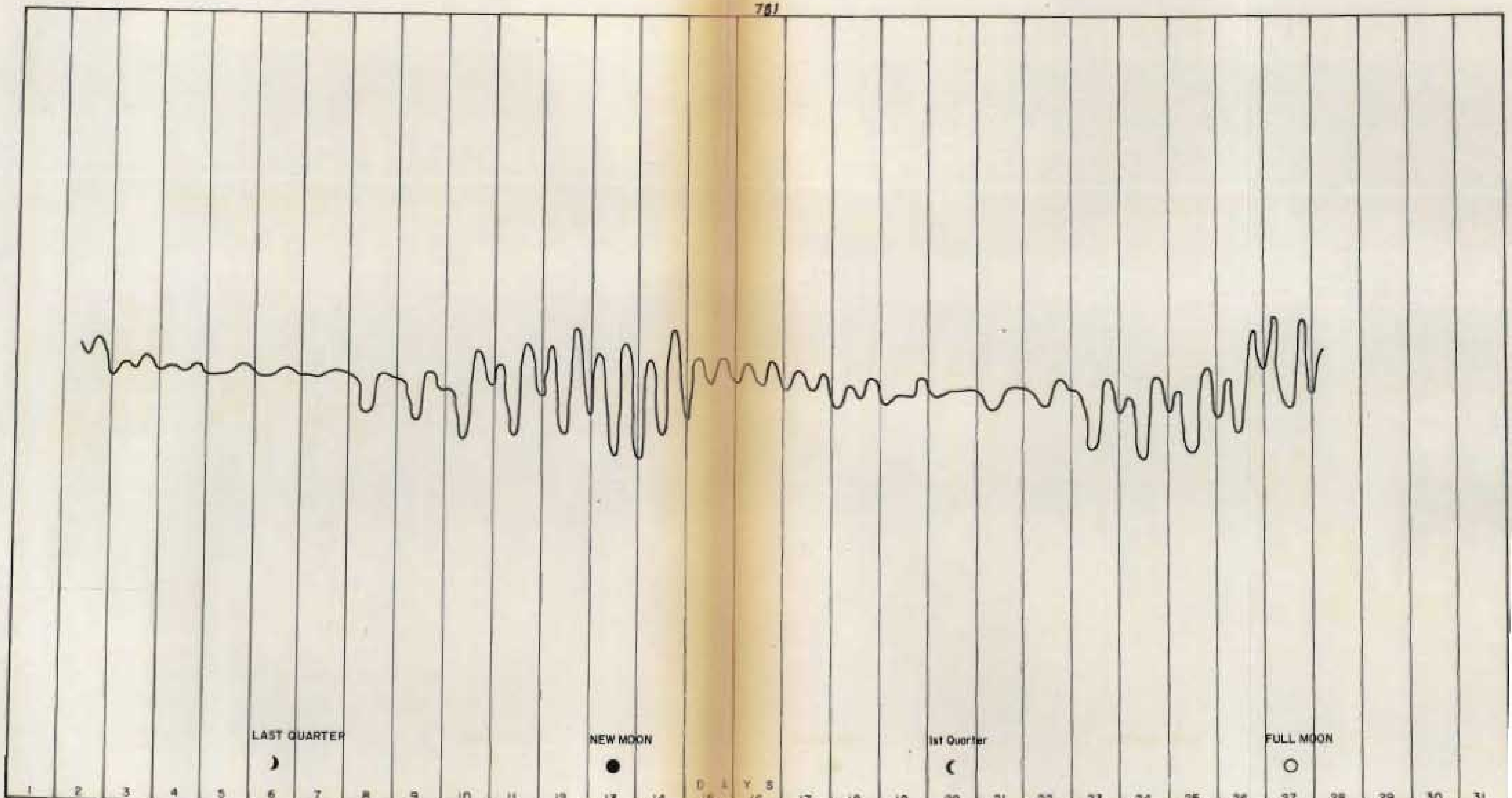


Fig. 19b HYDROGRAPH BH. 1463 - LOBATSE ESTATES NORTH BASIN
SHOWING TIDAL FLUCTUATIONS SUPERIMPOSED ON DIURNAL FLUCTUATIONS

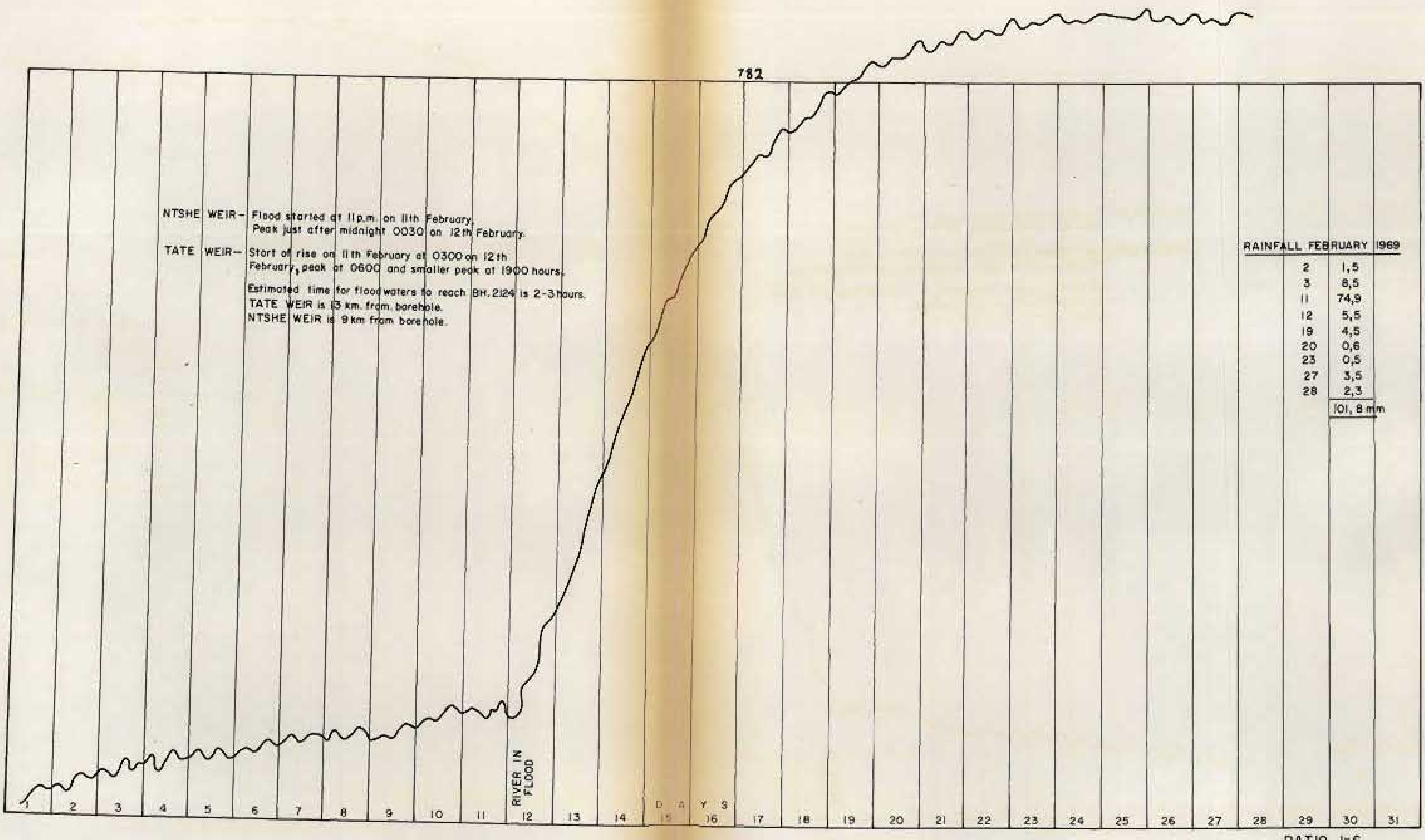


Fig. 197 HYDROGRAPH BH. 2124 - ON BANKS TATE RIVER - FRANCESTOWN
FEBRUARY 1969

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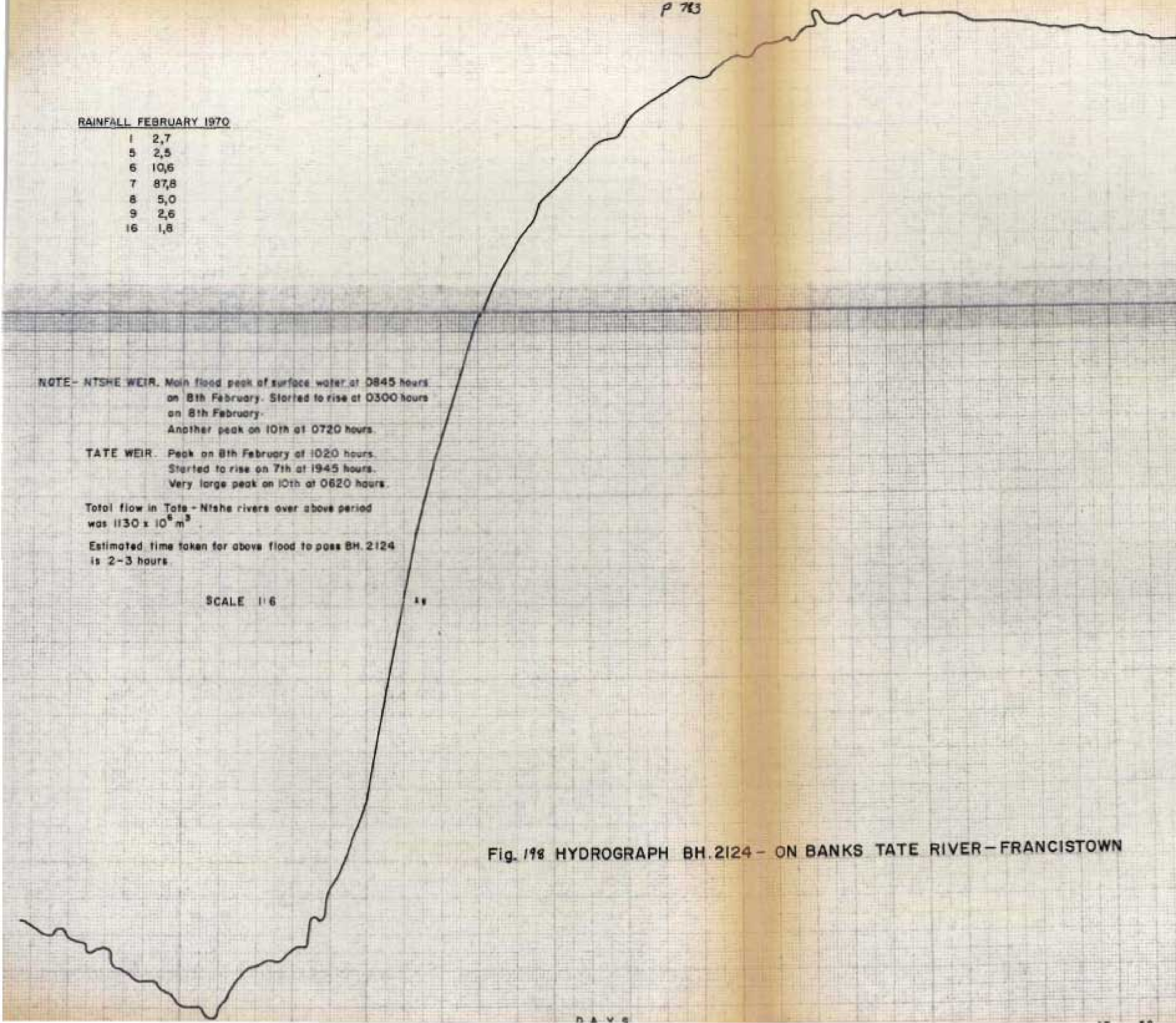
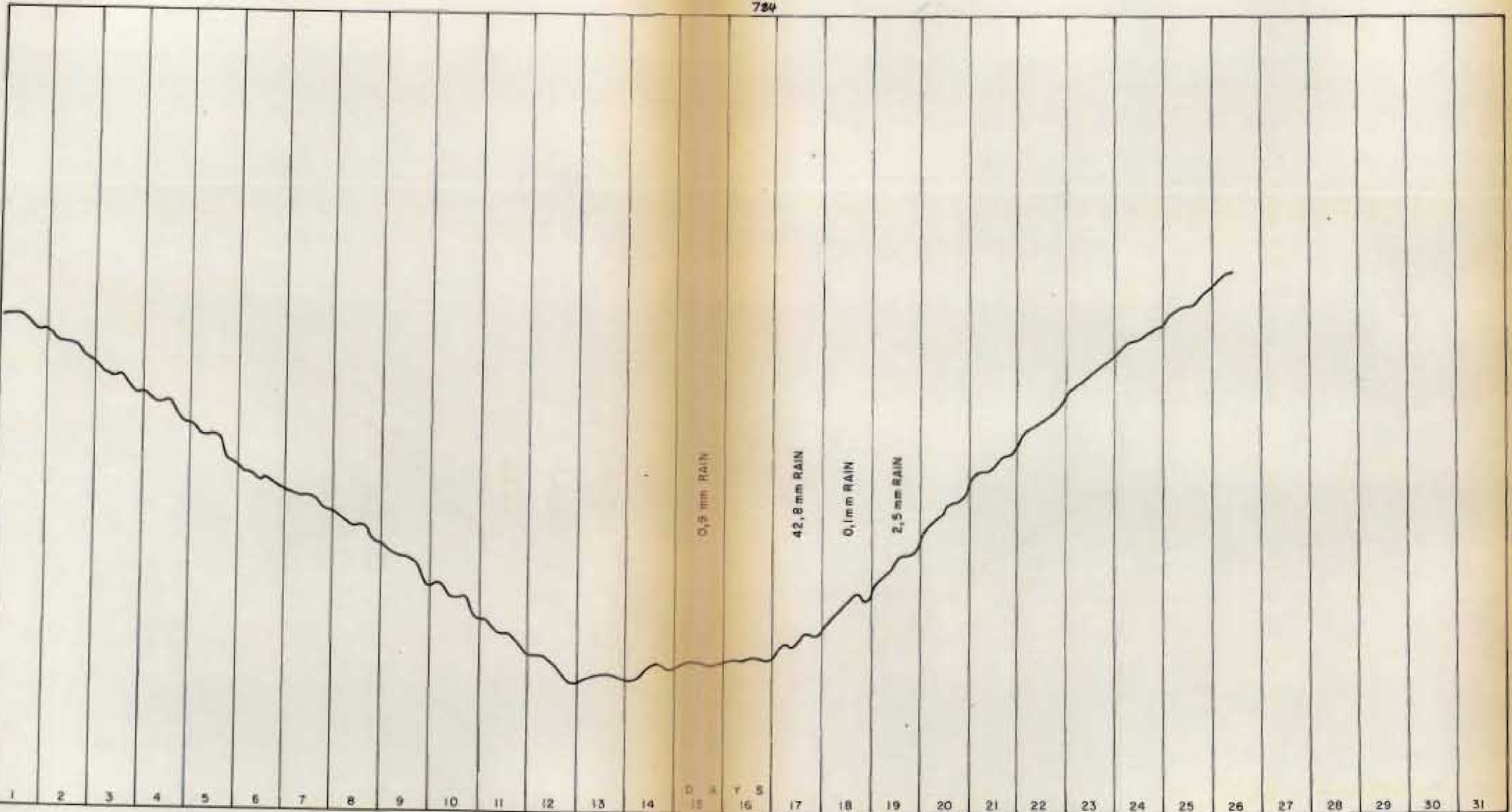


Fig. 198 HYDROGRAPH BH. 2124 – ON BANKS TATE RIVER – FRANCISTOWN



RATIO 1:6

Fig. 199 HYDROGRAPH BH. 2124 – FRANCISTOWN – APRIL 1970

PEAK FLOOD AT NTSHE WEIR (9 Km upstream) AT 1430 HOURS ON 17TH. APRIL.
ESTIMATED TIME TO REACH POINT OPPOSITE BOREHOLE 2124 IS 2–3 HOURS.

but normally dry Tate River in Francistown. Peak flood times and water volume are also shown on the hydrographs for two gauging weirs situated about 10 km upstream (two to three hours flow time). One gauging weir is situated on the Tate and the other on its major tributary, the Ntshe River. The confluence of the two rivers is a few kilometres upstream from the observation borehole. The hydrographs therefore show clearly the mechanism (infiltration through the porous floor of the large sand rivers) whereby boreholes situated in proximity to sand rivers, are recharged. The rate of infiltration (less than one day), is also surprising. In the Lobatse area the response is not quite so rapid and evidence has been provided in the chapters on Isotopes and Lobatse that the water level response is probably due to a "piston-like" displacement of moisture in the unsaturated zone. (See also Fig. 200).

Conclusions

Data provided by the monitoring of ground-water levels has thus been able to give valuable hydrogeological information on the nature and frequency of recharge; semi-quantitative information has been obtained, from the size of peaks on the hydrographs, on the amount of recharge; observation of water levels over long periods, when coupled with abstraction figures, enabled safe and specific yield and storage calculations to be made. Knowing the thickness of the aquifer, predictions can then be made as to when ground-water supplies are likely to become depleted.
The observation that no semi-diurnal fluctuations in water levels occur in certain boreholes prior to major earthquake events could be of invaluable use in predicting future catastrophic earthquakes.

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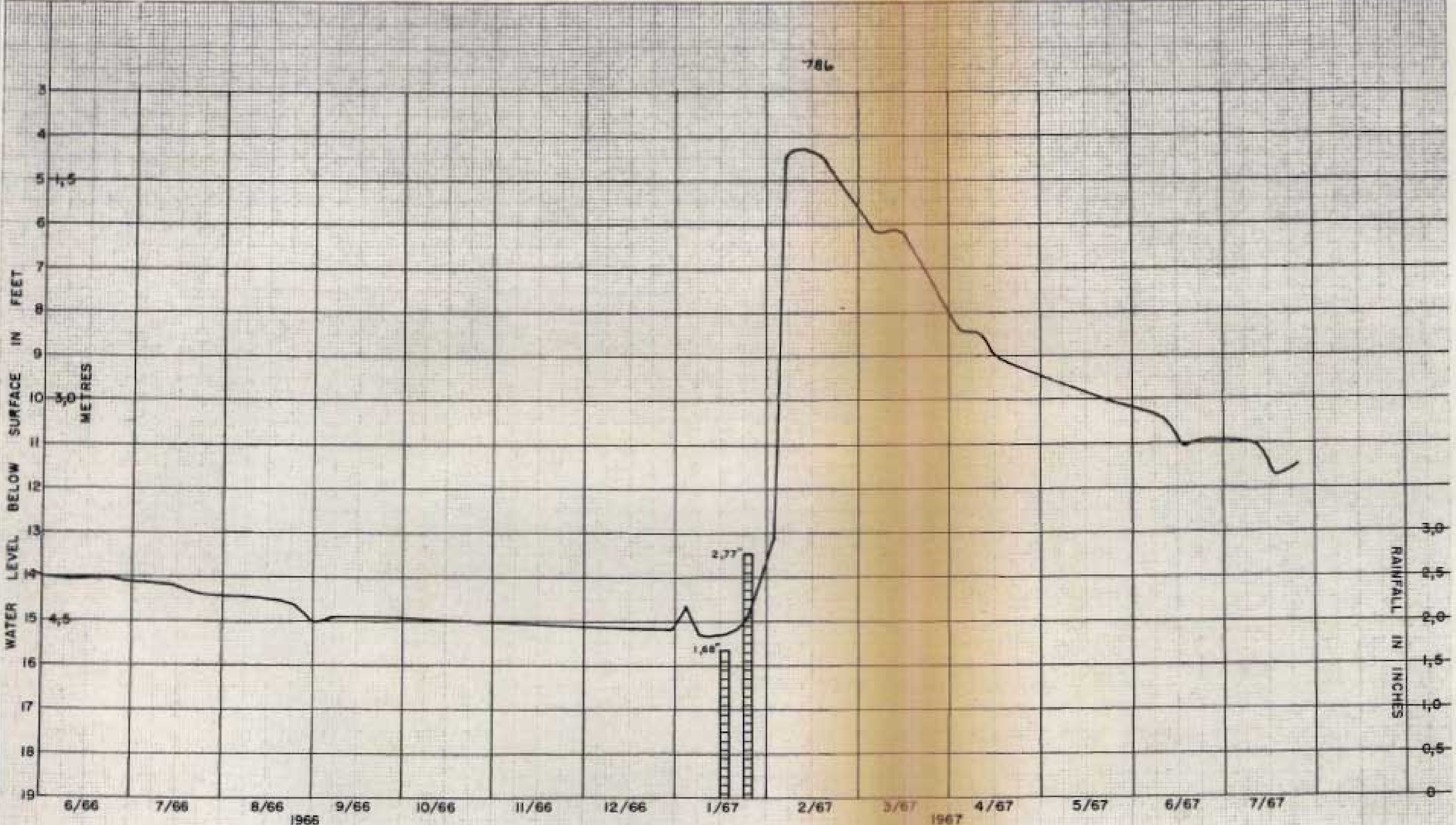


Fig. 2.00 HYDROGRAPH BH.L1 – E. NATA RANCH HOMESTEAD

Observation of water levels and their long and short term fluctuations thus forms one of the most important aspects of any hydrogeological research programme.

RECHARGE (REPLENISHMENT) AND SAFE YIELD

Replenishment of aquifers may occur as a result of infiltration from perennial or ephemeral streams and lakes; by direct infiltration of rainfall; or by infiltration following condensation of atmospheric moisture. Of these, infiltration from condensation of atmospheric moisture is likely to be insignificant in Botswana because of the depths to the water table and the generally high rates of evaporation and transpiration.

Replenishment by Infiltration of Rainfall

Martin (1961), van Straten (1955,1961), Boocock and van Straten (1962) have been widely quoted as stating their belief that no replenishment of present day rainfall takes place in certain Kalahari Bed covered areas. For example van Straten (1961) states "where, however, the solid formations are covered by Kalahari type sands to a depth of more than thirty feet (9m), with an extensive lateral persistence, infiltration of the available rainfall does not occur under present-day conditions". Martin (1961) stated that the areas devoid of ground water in the Kalahari desert in South West Africa are due to a thick, fine-grained aeolian sand cover in which the pore spaces are so small that gravity cannot draw the water down to the base of the sand. Under these conditions 6m of sand can easily accommodate 500mm of rain which is evapotranspirated during the long dry season. Martin thus maintains that the growth of vegetation is, in exact equilibrium, from year to year, with the available moisture content of the sand. No excess water, for replenishment of an aquifer, is left when the new rainy season starts.

However, evidence has been quoted, in the chapters on Isotopes, that recharge of shallow aquifers is taking place in the northern Kalahari, through thick Kalahari Beds (not necessarily all sand) cover west of Letlhakeng (G.5), and at isolated localities in the southern Kalahari. This has been confirmed by appreciable quantities of water being found in pits in the Kalahari at depths of up to 7 m. Other evidence of the ability of rain water to infiltrate to great depths was recently obtained by the writer in Kalahari sands in a 15m pit in Lower Zaire. This pit was excavated during a rainless period in typical fine-grained aeolian Kalahari sand and was sampled at 2m intervals and the moisture content of the sands measured for its tritium content. All samples were found to contain appreciable quantities of tritium and hence infiltration of rain water had taken place to a depth of at least 15 metres over the past twenty years. The mean annual rainfall for this area is 1243 mm. By analogy with similar sand-covered areas in Botswana but with a lower rainfall, it is possible that the occasional above average rainfall year could give rise to appreciable recharge. Another factor not possibly taken into account by earlier workers is the possibility that the true thickness of unconsolidated Kalahari sand is less than originally thought. For example, a number of borrow pits excavated along the main road to Ghanzi (D.2), show that the sand cover is surprisingly thin (Plate 76), and that this is underlain by a porous, nodular calcrete which could allow the rapid downward passage of water.

Despite the above evidence replenishment by direct infiltration in a semi-arid region such as Botswana, which has a summer rainfall, is considerably hampered because of the prevailing high

Pl.76 Nodular calcrete underlying Kalahari sand at depth of about 1 m in Central Kalahari.

Pl.77 Nuane River (north of Lobatse) in flood.

temperatures and consequent high evaporation and transpiration losses. This is however offset to a certain extent by the high permeabilities of the coarse sandy soils overlying much of the Basement Complex area and also by the occasional high intensity rain storms.

Replenishment Along River Courses

All rivers and streams in Botswana (both ephemeral and perennial) are influent with respect to ground water i.e. they are losing streams and contribute water to the zone of saturation. Examples have been given in the chapter on Water Levels of the rapid response of ground water levels to recharge by flood waters flowing along large, normally dry rivers (e.g. Tate River) and smaller streams (Lobatse Estates southern basin, see chapter on Lobatse) (Plates 31, 32, 36, 55, 77, 78).

Replenishment by Annual Flooding of Okavango Swamps

Although no quantitative evidence is available it is probable that large quantities of water infiltrate annually to the large phreatic aquifer present beneath the Okavango Swamps. As no significant abstraction of ground water from this aquifer takes place it is probable that a balance is maintained between the amount infiltrated and the amount transpired by the dense vegetation growing in the swamps.

SAFE YIELD (SUSTAINED YIELD)

"Safe yield" has been defined by Conkling (1946) as "the annual extraction from the ground-water unit which will not, or does

Pl.78 Notwane River in flood at Mochudi (G.7).

Pl.79 Boscia tree at Bh. 1028, Phuduhudu. Probably responsible for roots found at depth > 68 m.

not:-

(1) exceed the annual average recharge;

(2) so lower the water-table that the permissible cost of pumping is exceeded; or

(3) so lower the water-table as to permit intrusion of water of undesirable quality".

Todd (1959) introduced a simplification of the above definition - "Safe yield of a ground-water basin is the amount of water which can be withdrawn from it annually without producing an undesired result".

In Southern Africa Enslin (1956) has given a definition of "Safe yield" while Vegter (1961) in considering the Colesberg catchment went so far as to regard the concept of safe yield as "highly questionable". Enslin(1961) however felt that if the concept were well-defined then it should be possible to establish a safe yield, whether a single value, or a variable as a function of other variable factors, which could be useful if not essential for the planning of future development.

In both Conkling's (1946) and Todd's (1959) definitions above a time unit of one year has been used which is all very well for humid climates with regular rainfall. In semi-arid or arid climates however "safe yield" or "sustained yield" should be related to the overall abstraction from ground-water basin, its storage capacity and the calculated frequency and amount of major periods of ground-water replenishment. Should these not be taken into account both under-or over-abstraction could take place.

By studying hydrographs for boreholes in Botswana and using the synthetic record proposed by Lund and Bylsma (1972) from which it is deduced that major recharge of aquifers in eastern Botswana is likely to occur once in every five years, it can be seen that there is therefore a strong argument in favour of keeping the storage capacity to as low a volume as possible towards the end of any five year drought period. This is the maximum period for which no recharge has been known to occur over the past 60 years though it should be pointed out that during the drought lasting from 1925/1926 to 1932/1933 only 24mm (0,96in) went to the recharge component in April 1930 (Fig. 32). By so doing spare capacity would be created to cater for the occasional abnormal year when run-off and replenishment are considerably greater than normal. These conditions for a modified definition of "safe yield" would naturally only hold good where the storage capacity of the aquifer is known and is several times larger than the average annual recharge. Ideally this would only be practicable where an alternate source of supply (either a dam or another groundwater basin) is available.

The study of hydrographs has shown that recharge takes place in virtually all areas for which hydrogeological data are available. (See chapters on Lobatse, Orapa, Serowe and Water Levels). In the Lobatse and Serowe areas a safe yield (mean annual recharge) has been calculated.

A POSSIBLE WATER BUDGET FOR BOTSWANA

Detailed hydrogeological studies at Lobatse have indicated a mean recharge of 4 per cent of the annual rainfall. Assuming that this value is too high for the whole of Botswana, and that only one per cent of the rainfall infiltrates to the ground-water table, then for the whole of Botswana (570 000 km^2), which has a mean annual rainfall of 380mm, the annual replenishment would be:

$$\frac{1}{100} \cdot \frac{380}{103} \cdot \underline{570\ 000} \cdot 10^6 m^3$$

$$= 2,16 \cdot 10^9 m^3 = 2160 \cdot 10^6 m^3$$

The following calculation is considered to be more accurate than the above calculation. The following assumptions are made:

1. Recharge over eastern and northwestern Botswana amounts to 4 per cent of the rainfall - area 111 200 km^2
2. Recharge over the Ghanzi outcrop area amounts to 4 per cent of the rainfall - area 20 000 km^2
3. Recharge from the Okavango amounts to 7 per cent of the annual inflow i.e. $\frac{7}{100} \cdot 11\ 800 \cdot 10^6 m^3 = 826 \cdot 10^6 m^3$
4. Recharge over the remainder of the area amounts to one per cent of the rainfall - area 419 200 km^2
5. Mean annual rainfall for all calculations is assumed to be 380mm.

The safe yield would then be

$$\left\{\frac{4}{100} \cdot \frac{380}{10^3}\ 131\ 200 \cdot 10^6\right\} + \left\{826 \cdot 10^6\right\} +$$

$$\left\{\frac{1}{100} \cdot \frac{380}{10^3} \cdot 419\ 200 \cdot 10^6\right\} m^3$$

$$= (1994 \cdot 10^6) + (826 \cdot 10^6) + (1593 \cdot 10^6)$$

$$= 4413 \cdot 10^6 m^3$$

The above calculations thus indicate that an annual amount of between 2 000 and 4 000 million cubic metres per annum should be available for long term ground water use in Botswana.

PHREATOPHYTES

Introduction

Meinzer (1927) proposed the term phreatophytes, which is derived from the Greek roots meaning "well plants", for plants that habitually obtain their water supply from the saturated zone or it's capillary fringe. These plants form a distinct ecologic group in desert climates. They have an arid climate for their transpiration organs but a humid environment for their roots. Because of the depth to which their roots penetrate, these plants have a highly specialised pumping ability to bring the moisture to the surface.

Smitter (1955) recognised the value of plants as indicators of ground water in southern Africa, though water diviners have long recognised the value of "aars" and certain specific trees for indicating ground water. These "aars" consist of linear belts of trees and shrubs which invariably grow long dykes, joints and fault planes and hence indicate favourable loci for ground water.

Martin (1961) noted that in the eastern parts of South West Africa (near the Botswana border), "hidden channels", with coarser sediments - and more ground water - are often marked by distinct rows of Camelthorn trees (acacia giraffae) penetrating into areas where Camelthorn trees are often scarce or lacking. Such lines of Camelthorn trees tend to peter out where the water table drops to about 60 m.

In southern Africa indirect evidence of the vast quantities of water transpired by phreatophytes, has been afforded by Van Wyk (1963) who quotes a rise in the water table near False Bay (Republic of South Africa) of nearly 12 m following

/the

the clearing of all vegetation for pineapple farming. Dixey (1960) quotes the water used by cottonwood or saltcedar trees covering 640 acres (1 square mile) as being sufficient, during the growing season, to supply the needs of a city of about 25 000 inhabitants for a year.

Depths to which Tree Roots can Penetrate

Meinzer (1942) records that mesquite sends it's roots to more than 15 m, while van Wyk (1963) records that tree roots were found "in a great number of boreholes at depths of up to 80 feet (24 m) below surface".

During an underground inspection of the old Bushmen Mine in 1957 numbers of fine rootlets in fissured rock on the 30 metre level were noted, while similar rootlets were observed on the 45 metre level of an exploration drive at the Matsitama copper prospect. Both localities are east of the Makgadikgadi pans. (C.7).

In 1958 the writer retrieved living rootlets from an unused borehole (No. 1028) at Phuduhudu in the central Kalahari while carrying out an electrical resistivity log of the borehole. These rootlets were brought up on the heavy weight on the end of the cable and must have come from a depth exceeding 68 metres as the borehole was cased with unperforated casing from surface to this depth. The borehole is uncased beyond this depth and it is possible that the roots were utilising the easy passage made by the borehole to obtain water from the water table at 141 m (436 feet) below the surface. The only fair sized tree in the vicinity of the borehole was a "motlopi" (boscia albitrunca) and this was almost certainly the phreatophyte responsible for sending it's roots to this incredible depth. (Plate 79). This is, to the best of the writer's knowledge, the greatest known depth (68m and possible 141m) to which tree roots have been known to penetrate. The boscia belongs to the Capparidaceae family of which the pickled flower buds of several European species are the capers of commerce. The tree is one of the few evergreen trees found in Botswana and hence the tremendous root system serves to supply water to the tree during the dry winter months. The writer has also recovered tree roots from a borehole at Eersterus (No. 1197), near Werda in the Southern Kalahari (H.4) from a borehole which has unperforated, eight inch solid steel casing, to a depth of 30 metres and a further 48m of perforated six inch casing. The roots must thus have penetrated to at least 30m and could have penetrated to 78,6m. The water level in this particular borehole was 97,5m below surface.

In the Nata Ranches area north of the Makgadikgadi Pan the dense vegetation probably results in enormous losses of ground water through transpiration losses and drops of several metres have been noted in boreholes with rest levels from 4 to 9m below surface (Fig. 189). Lamoreaux (1970) quoted the saving of 1 billion gallons per year (10^9 U.S. gallons) by removing phreatophytes from 1 700 acres in the Gila River Valley, Tuscon, U.S.A.

Examination of the banks of the larger ephemeral sand rivers in Botswana shows that the dense vegetation fringing these rivers often sends a dense matte of roots into the

...../saturated

saturated sands (Plate 65) and the considerable losses noted in the storage in these aquifers may be partly the result of transpiration losses.

The dense riverine vegetation, growing along the margins of the Okavango Swamp, the Thamalakane (Plate 80), the Nghabe and Boteti Rivers consists largely of phreatophytes.

Trees as Indicators of Ground Water in Botswana

The dense riverine vegetation along the semi-perennial rivers fringing the Okavango are certain indicators of shallow, fresh ground water. The combretum imberbe ("motswere" or "hardekool") appears to be an indicator in the Ghanzi district and south of the Boteti River south-east of Makalamabedi. (C.5).

In the country west of Tsienyane (D.5), large acacia giraffae trees appear to grow in areas with saline ground water, while R.J. Hastings (personal communication) commented, while doing a resistivity survey in the Nata Ranches area, that the presence of the palm tree (hyphaene) invariably indicates saline ground water.

In the Serowe area the writer often noted the presence of wild olive trees (olea africana) in proximity to drainage lines with shallow ground water.

In the southeastern part of Botswana, particularly in areas underlain by acid lavas (Ventersdorp Supergroup and Kanye Volcanic Formation), literally hundreds of blank boreholes have been sited by water diviners on their favourite "aar" features. These prominent linear vegetation features are generally formed by diabase dykes which weather to greater depths than the surrounding acid

Pl.80 Dense riverine vegetation near Okavango Swamps

Pl.81 Measuring water level in an observation borehole near Thamalakane River, Maun.

rocks and hence develop a clayey soil in an otherwise hard, rocky terrain. Unfortunately the dykes are not sufficiently weathered for ground water to accumulate along these features, but nevertheless, because of their greater overlying soil cover, support a denser and more luxuriant vegetation cover. The writer has also sited boreholes on linear vegetational features (undoubtedly joint planes) in terrain underlain by Stormberg lavas at Serowe and Orapa without obtaining materially greater yields than in unjointed basalt elsewhere. (Probably because the aquifer is the contact with the underlying sandstone and not in the basalt).

Vegetational changes, associated with changes in the underlying geology may, however, give indirect evidence resulting in the obtaining of good ground water supplies e.g. marked vegetation changes occur over the "greenschist belts" in Botswana which invariably yield greater quantities of ground water than in the surrounding gneissic rocks.

COSTS OF IRRIGATION USING GROUND WATER

INTRODUCTION

Because of the low and unreliable rainfall in Botswana and a consequent lack of perennial supplies of surface water, irrigation is rarely practised amongst the African farmers of Botswana. In general, water is scarce and humans have first priority to water supplies and livestock second. The only area with a regular water supply is in Ngamiland around the Okavango swamps. Here crops are grown behind the receding flood waters of the swamps but the amount of crops produced are relatively unimportant on a national scale.

As virtually no irrigation is carried out from boreholes and, as a statistical survey of borehole yields had indicated that 17% of all government boreholes drilled (many of whose yields are underutilised) produced yields high enough to justify limited irrigation (79 000 l/hour or 150 l/min), a research project was commenced in which an unused borehole (for Lobatse Township supply) was used to irrigate a 4 hectare (10 acre) plot. This scheme was jointly supervised by the writer and the Agricultural Department. The writer is indebted to Mr. G. S. Jackson of the Department of Agriculature for assistance in this project.

LOBATSE IRRIGATION UNIT PROJECT

This project using borehole No. 665 (Depth 60m, water struck 36-47m, water level 34m, and tested yield 228 l/min.), was commenced in Lobatse in 1968 and was prematurely concluded after a full year because of the drying up of the Nuane Dam and the need to include borehole 665 within the emergency township water supply system. The results obtained therefore relate to one season only and must remain rather tentative although certain conclusions may be drawn with a fair degree of confidence.

Unit smallholdings, comparable to the peasant dry land farming units operated elsewhere in Botswana, were set up to study the economics of irrigation using a borehole as source of supply. A 15m diameter reservoir was built by the Geological Survey and two systems of irrigation, sprinkler and furrow, were established so that they could be compared with each other. Field work commenced in April 1968 with the planting of a part of the acreage to winter crops - wheat and vegetables.

Objectives

Local conditions for irrigation farming are, on the whole, not too favourable: water supplies are usually scarce and costly; irrigation requirements were thought to be very high; markets for produce in Botswana are small and easily glutted and a very disciplined attitude to field work is needed. This could be overcome or circumvented to gain for a small-holder a stable, less risk-affected and satisfactory income.

The various objectives of the project were:-

1. The gathering of input/output data i.e. costs of farm inputs, yields, prices, markets, revenues and analysis of returns to the three chief resources - land, labour and water.
2. Gaining a clearer idea of crop water requirements by relating irrigation applications to potential evapotranspiration.
3. Planning improved cropping programmes on the basis of the above data and assessing the economic feasibility of irrigation schemes utilising different sources of water.
4. Comparing sprinkler and furrow irrigation systems with regard to capital requirements, water and labour requirements, revenue earning potentials and net profitability.
5. Obtaining long term hydrogeological data on any changes in water level, and water quantity and on the general behaviour of the dolomite aquifer under intensive pumping conditions.

Results

1. Input/Output Results

These results are summarised in Table 105

2. Irrigation Requirements (See Table 106)

Good results, particularly of summer crops, were achieved with due economy in the use of irrigation water. Total quantities applied to each crop were possibly below the technical maxima. This was caused by an unusually hot and dry period in midsummer, which placed the borehole supplies under strain and intervals between irrigation cycles had to be widened. In the case of sprinkler grown maize for example, the ratio of actual water available to the crop to its potential evapotranspiration, the Et/Eo ratio was ,6 compared with an accepted ratio of 0,8. To have irrigated the crop to achieve this latter ratio would have required a further 207 mm (8 ins):

$$\frac{\text{(Pan evaporation cumulative total)}}{\text{Irrigation efficiency)}}\frac{637}{75\%} \times 0{,}80 \text{ (Et/Eo ratio)}$$

$$= 679{,}50 \text{ mm}$$

During this period rainfall contributed 138,94 mm and 332,99 mm was actually applied, leaving a net deficit of 679,50 - 571,94

= 207,56 mm (See Table 107)

<u>LOBATSE IRRIGATION UNITS : CROPPING RESULTS ANALYSIS TABLE</u> 105

CROP	PER ACRE								
	Yield (lbs)	Gross Output	Variable Costs	Gross Margin	Labour Input (Man-Days)	Irrigation Input (Inches)	G.M. per Man-Day R	G.M. per inch irrig.	Estimated least Incremental return to Irrigate (per inch)
tton-Sprinkler Block	2,716	154.20	34.53	119.67	107	20.4"	R1-12	5.87	R4 - R5
tton-Furrow Bloc	2,212	125.60	25.36	100.34	125	24.7"	RO-80	4.06	R2 - R3
een Maize-Sprinkler Bloc	7,250 (cobs)	143.60	26.60	117.00	45	13.1"	R2.60	8.92	R8 - R9
een Maize-Furrow Bloc	6,640 (cobs)	151.80	24.07	127.73	55	11.95"	2.32	10.70	R9 - R11
oundnuts-Sprinkler Bloc	2,172	66.67) 8.33) 75.00	33.25	41.75	144	13.5"	0.29	3.10	R2 - R3
oundnuts-Furrow Bloc	2,110	64.56	28.47	36.09	184	13.3"	0.20	2.72	R2 - R3
nter Wheat-Sprinkler Bloc	1,638	60.66	26.91	33.75	77	10.1"	0.44	3.34	R3 - R4
een and Dried Peas-Spr.Bloc	(1,030)	17.85) 17.82) 35.67	21.33	14.34	75	10.1"	0.19	1.42	n.a.
een Peas - Furrow Bloc	(3,560)	183.50	32.20	151.30	191	15"(est)	0.79	10.09	n.a.
ied Peas - Furrow Bloc	571	17.13	19.09	1.96	75	15"(est)	0.026	-	n.a.
ons - Furrow Bloc	5,050	112.70	38.18	74.52	180	15"(est)	0.42	4.97	n.a.
bage - Sprinkler Bloc	316 heads	4.78	19.33	14.55	42	10.1"	0.35	-	n.a.
bage - Furrow Bloc	1,825 heads	31.55	22.73	8.82	53	15"(est)	0.17	0.59	n.a.
<u>rall Summer & Winter Crops:</u>									
inkler Bloc (7.32 acres)	R 104		R 29	R 75	86	14.2"	RO.87	R5.29	n.a.
row Bloc (5.28 acres)	R 108		R 25	R 83	106	18.6"	RO.78	R4.46	n.a.

LOBATSE IRRIGATION UNITS : OVERALL CROPPING RESULTS 1968/69 TABLE 106

CROP	SPRINKLER BLOC					FURROW BLOC					BOTH BLOCS GRAND TO			
	Acre-age	Total Gross Output	Total Vari-able Costs	Total Gross Marg.	Total Man-Days Labour	Acre-age	Total Gross Output	Total Vari-able Costs	Total Gross Marg.	Total Man-Days Labour	Acre-age	Total Gross Output	Total Gross Marg.	T L
COTTON	2.37	365.34	81.85	283.49	253	2.38	298.97	60.10	238.87	297				
AIZE	1.27	182.34	33.77	148.57	57	1.11	168.55	26.72	141.83	61				
ROUNDNUTS	0.60	45.01	19.95	25.06	87	0.34	22.02	9.68	12.34	63				
OTAL SUMMER CROPS	4.24	592.69	135.57	457.12	397	3.83	489.54	96.50	393.04	421	8.07	1082.23	850.16	
HEAT	2.43	147.46	65.38	82.08	188	-								
NIONS	-					0.13	14.65	4.96	9.69	23				
REEN PEAS	{0.56	19.97	11.95	8.02	42	0.22	40.37	7.08	33.29	42				
RIED PEAS						0.73	12.51	13.94	1.43	55				
ABBAGE	0.09	0.43	1.74	1.31	4	0.37	11.68	8.41	3.27	20				
OTAL WINTER CROPS	3.08	167.86	79.07	88.79	234	1.45	79.21	34.39	44.82	140	4.53	247.07	133.61	
RAND TOTAL :	7.32	760.55	214.64	545.91	631	5.28	568.75	130.89	437.86	561	12.60	1329.30	983.77	
		R 104	R 29	R 75	86		R108	R 25	R 83	106				

Et/Eo RATIOS FOR MAIZE GROWN ON SPRINKLER BLOC 1968/69 TABLE 107

BETWEEN IRRIGATIONS

WEEK OF SEASON	IRRIGATION DATE	INVERVAL IN DAYS	QU	CUMULATIVE RAINFALL	GROSS WATER E_g	PAN EVAPORATION Eo	DAILY EV.	PAN FACT i.e. Eg/Eo
(Planted Nov.20 after soaking rains)		16					.19"	
1. 24 - 30 Nov.								
2.	Dec. 6		.90" (Av.)	2.32"	3.22"	3.01"		1.07
3.								
4.		18					.31"	
5.	Dec.24		1.87"	1.28"	3.15"	5.58"		.56
6.		13					.35"	
7.	Jan. 6		1.95"	0	1.95"	4.60"		.42
8.		15					.35"	
9.	Jan. 21		2.77"	.79"	3.56"	5.29"		.67
		10					.30"	
10.	Jan. 31		2.92"	.27"	3.19"	2.99"		1.07
11.		13					.28"	
12.	Feb.13		2.70"	.81"	3.51"	3.61"		.97
		15					.18"	
13. 14. Picking to 28th Feb.			0	2.10"	2.10"	2.74"		.77
Subtotal to last irrigation Feb13			13.11"	5.47"	18.58"	25.08"		.74
Full total to Feb. 28			13.11"	7.57"	20.68"	27.82"		.74

Despite this, an excellent crop was obtained and only a series of carefully controlled irrigation experiments would be able to establish the added yield and revenue that this additional irrigation would have produced. It is possible that returns to additional irrigation would be so marginal that it would be preferable to apply irrigation at sub-optimum levels.

Cropping Possibilities and Programme

Experience from the one year experiment indicated that, except where the farmer has special horticultural skills and is well placed for marketing his produce, the growing of crops such as fresh vegetables, as well as the growing of winter crops, should be avoided. This need not necessarily lead to a long slack winter period as the start of the summer cropping and the completion of harvesting may leave less than a few weeks' break.

It was considered that a simple system of maize and cotton be considered. On a small holding of five acres, three might be devoted to maize with several staggered plantings and harvestings and two to cotton. A labour profile drawn up from results under sprinkler irrigation shows that the annual labour requirements of 358 man-days would be readily within the ability of a peasant family unit which could be expected to provide 500 man-days between them. On this basis, an enterprising farmer, given sufficient water, might be able to handle a plot of 3,68 ha (7,68 acres).

At a gross margin per acre of both crops of around R120 the total gross margin for a 7,68 acre plot would be R922, from which fixed costs would have to be deducted.

Furrow and Sprinkler Systems and Economic Feasibilities

It was found that furrow irrigation required higher inputs of labour per acre and accordingly returns to labour and irrigation water were rather better under the sprinkler system and more than offset the higher fixed costs accruing to the sprinkler system.

The final assessment of the economic viability of irrigated small holdings rests with the level of fixed costs which must be deducted to arrive at the final net farm income. These fixed costs were calculated on three assumptions as to the availability and source of irrigation water. The first assumption under which net farm income was derived is that in which water is freely available for distribution by sprinkler from a dam or canal layout.

The second assumption made was that in which water is obtained from a borehole drilled and equipped to be wholly and specifically used for irrigation.

The third assumption is that an existing, but under-utilised, borehole is brought into full use to provide irrigation water. It is thought that 800 to 1000 such boreholes exist in Botswana.

<u>Assumption 1</u> (Water freely available from surface supply)

Total capital costs for sprinkler pump etc. (1968)	=	R1200	(R1050 fixed equipment and R150 working capital)
Depreciation on above	=	R100	
Labour 500 man-days at 50c/day	=	R250	
Gross margin on 7,68 acre plot	=	R922	
∴ Balance management & investment income	=	R922 - (R250 + R100)	
	=	R572	
Interest on capital at 8% per annum	=	R96	
∴ Return on capital	=	$\frac{572}{1200}$ - 96% = $\frac{476}{1200}$	
	=	39,66%	

<u>Assumption 2</u> (Borehole drilled specifically for irrigation)

Borehole capital costs - drilling and casing to 60m	R850
6 h.p. Lister engine and mono pump	R1000
TOTAL:	R1850

Annual depreciation

Drilling and casing costs depreciated over 20 years	R42
Total life estimated at 720 000 hours or 10 years minimum at 2000 hours/year	R100

Annual maintenance

Say 2 major overhauls during 10 year life of engine and pump at R300 each = R600, or average/year	=	R60
Interest Charges per Annum		
8% on initial investment of R1 850	=	R148
∴ Total depreciation + interest + maintenance per annum	=	R350

Sprinkler and borehole operating costs work out at 43 cents and 60 cents per acre inch respectively.

∴ For 40 inch annual irrigation, costs for 7,68 plot per annum	=	R316
∴ Total costs	=	R350 + 316
	=	R666
Capital costs for sprinkler pump etc.	=	R1200
Depreciation on above (10 year life)	=	R100
Interest charges on R1200 @ 8% pa	=	R96
Capital cost of storage reservoir and pipe line = R550 for 10 acre plot or R422 for 7,68 acre unit		
∴ Depreciation on reservoir over 20 years	=	R21
Interest on R422 @ 8% per annum	=	R34
Labour costs - 500 man-days @ 50c	=	R250
∴ Total depreciation, interest maintenance costs	=	R666 + 196 + 5 5 + 250
	=	R919 + 250 = 1169
∴ Net annual loss per 7,68 acre unit	=	R247

Assumption 3 (Existing underutilised borehole with its own reservoir for irrigation)

Cost of sprinkler equipment	=	R1200
Depreciation on above	=	R100
Interest on above at 8% per annum	=	R96
Maintenance costs for sprinkler pump per annum, say	=	R60
Running costs at 43c/acre inch for 40 in or 307,2 acre inches	=	R132
Labour costs - 500 man-days at 50c	=	R350
∴ Net income	=	R922 (R100 + 96 + 60 + 13 +250)
	=	R284
∴ Return on capital	=	$\frac{284}{1200}$ %
	=	23,66%

COSTS OF PUMPING WATER FROM A BOREHOLE

At Lobatse it was found that 3 gallons of fuel (13,5 l) was sufficient to run the engine for 12 hours at a pumping rate of 2500 gallons per hour.

∴ Hourly costs = $\frac{3}{12}$

= 0,25 gals/hour @ 25c

= 6,25c/hour

plus oil (2 gallons) changed every 500 hours @ R1.00 per gallon.

= $\frac{2,00}{500}$ cents/hour

= 0,40 cents/hour

∴ Total running costs = 6,55 cents/hour

Costs per unit volume of water

$$\frac{6,65 \text{ cents/hour}}{2500 \text{ gallons/hour}} = 2,7 \text{ cents per 1000 gallons}$$

OR

$$\frac{2,7 \times 22645}{1000} = 60 \text{ cents per acre inch}$$

Upton (1969) has supplied costs for the pumping of a high yielding shallow borehole on the farm Gesond in the Tuli Block :-

"1. Capital Cost

		R
Drilling and casing		500
Equipping		5000
	TOTAL	5500

2. Annual Costs

Assuming economic life of 10 years at 8%		
Annual sinking fund annuity		820
Operating costs, fuel oil and maintenance		1000
	TOTAL	1820

A yield of 45000 gallons per hour, 10 hours per day should water 69,6 acres (27,8 ha).

∴ Capital cost per acre = R79

Annual cost per acre = R26

∴ Cost per 1000 gallons = 1,5 cents

5. Hydrogeological Data

Borehole Number 665 was drilled in 1956 in colluvial soil and decomposed dolomite (Dolomite Group, Transvaal Supergroup) to a depth of 60 m. This borehole is situated in the Lobatse Western Dolomite Basin. Water was encountered between 36 and 47 m with a static rest level of 34m and a tested yield of 228 l per minute (3000 gallons per hour). A detailed aquifer evaluation test on borehole 665 using borehole 2135 (12 feet away) as an observation borehole gave values for T of 21082 gallons per day per foot for borehole 665 and of 12 741 gpd/ft for borehole 2135 and a value for S of 0,0557 using the Time-Drawdown graph; a value of 11 982 gpd/ft using the distance drawdown graph; and values of 22298 gpd/ft and 22 735 gpd/ft for boreholes 665 and 2135 respectively using the residual drawdown graph (See chapter on aquifer tests).

Water level fluctuations

During the period April till December 1968 a total of 11 736 m^3 (2 582 000 gallons) of water were pumped from borehole 665 (See Table 108). During the period 1st January 1969 till the end of the trial period, a further 9072 m^3 (1995 732 gallons) were pumped to give a total of 20 808 m^3

TABLE 108

BH.665 - WATER PUMPED FOR LOBATSE IRRIGATION UNIT, 1968

Month	Water pumped gallons	m^3	Rainfall in	mm	Water level observation Bh 952m.
April/May	67 000	304,5	5,37	136,4	25,37
June	215 000	972,3	0,06	1,5	25,31
July	290 000	1318,2	-	-	25,2
August	346 000	1572,7	0,04	1	25,13
September	337 000	1122,7	-	-	25,11
October	334 000	1518,2	0,02	0,5	25,00
November	326 000	1481,8	2,62	66,5	25,08
December	657 000	2986,4	3,44	87,4	25,19

(4577 732 gallons). Despite this considerable amount of water pumped, a study of the observation borehole (952)hydrograph shows that no significant drop in water level occurred and hence the above amount of water may be regarded as being comfortably within the safe yield of the aquifer. It is thus obvious that, in the consideration of a borehole for irrigation, cogniscance should be taken of the amount to be pumped in relation to the storage capacity, the frequency of recharge and thus the long term safe yield of the borehole. The statement by Upton (1969, page 25) "that there is concern over the possible depletion of underground aquifers in general and the use of boreholes for irrigation will be discouraged" (by the Department of Agriculature) can be most misleading and, in fact, could lead to under-usage of boreholes with a consequent loss to the national economy. It is felt that the relative merits of each individual borehole should be considered and that there should not be a blanket discouragement of limited irrigation using boreholes.

CONCLUSIONS

The determining factor in the economic viability of irrigating smallholdings is the cost of water. Where this is relatively expensive as for example in fairly deep boreholes (with yields of 228 l/minute or less)drilled specifically for irrigation purposes, it appears that such schemes are likely to run at a loss.

Where, however, the water from boreholes is less expensive because of shallow depth and considerably greater yield (as in the north-eastern Tuli Block) or where the costs are borne by the cattle enterprise (i.e. an existing underutilised borehole is used) then the use of boreholes can provide an excellent opportunity for the peasant smallholder to provide himself with a sound and stable income.

High yielding boreholes should not automatically be disregarded for irrigation purposes but should be considered in relation to the overall extraction rate and safe yield of the particular ground-water basin in which it is situated. Where the storage capacity of a particular basin is exceptionally high, the possibility of "mining" the ground-water resource might even be contemplated.

LEGAL ASPECTS OF GROUND WATER IN BOTSWANA

INTRODUCTION

Botswana is extremely fortunate that legislation was introduced at an early stage ensuring that the invaluable information relating to all boreholes sunk in the territory be submitted to the Geological Survey, together with samples of strata penetrated by the bore. This has proved to be of tremendous use, not only for the siting of further boreholes and for hydrogeological research purposes, but also as a valuable aid to geological mapping.

BOWSWANA BOREHOLE PROCLAMATION NUMBER 62 OF 1956

In terms of the Botswana Borehole Proclamation (No. 62 of 1956) all Drillers and Drilling Contractors, who operate in the territory, are required to submit the following to the Director of Geological Survey at Lobatse:-

(a) Notice in writing of the intention to sink a borehole.

(b) A record of the progress of the work which includes measurements of strata passed through, levels at which water is encountered, and the level at which the water finally rests.

(c) The results of a pumping test.

(d) Adequately labelled samples of the superficial deposits and strata passed through taken at every change of formation or in uniform formation at every ten feet.

The Director of Geological Survey supplies, on application, books of completion forms whereupon the information mentioned in 1 (b) and 1 (c) above is to be entered. The Director of Geological Survey also supplies,on application, sample containers, copies of a standard form of notice of intention to sink or deepen a borehole and copies of a standard form to be included with all sludge samples sent to the Geological Survey office at Lobatse.

Sample Storage

Samples are generally washed by the driller prior to placing them together with a tag indicating the depth of the sample in a small tobacco bag. The tobacco bags are then placed in a canvas sample bag which is sent post-free to the Geological Survey in Lobatse. Here all samples are sorted, assigned a borehole number and placed in labelled glass containers which are stored on boards in which holes slightly larger than the bottles have been drilled. These boards are then, in turn, labelled and stored and can be referred to whenever necessary. All samples submitted to the Survey are logged by a geologist and the log filed on an index card in the water record office.

THE WATER ACT OF 1967

The Water Act, 1967, came into force on 9th February 1968 and applies to the whole of Botswana. The purpose of the Act is to control the use of public water, that is water flowing over the surface of the ground in rivers, streams, springs, lakes or pans, or under river beds or underground. The Act was introduced to ensure that Botswana's scanty water resources be used to the best advantage of the country. It was also considered necessary to protect the interests of persons who have acquired or been granted rights to use water as well as to maintain a record of rights to the use of water.

Holders of existing rights were given a year from 9th February 1968 to notify the Water Apportionment Board. After investigating an existing right to satisfy themselves that the right existed, it was recorded and a certificate issued by the Board.

Except under an existing right, the Act prohibits the diversion, damming, storing, obstructing, polluting, or constructing of any water works on public water unless under a right granted in accordance with the Water Act. A person may, however, take water for the immediate purpose of watering stock or drinking, washing and cooking or use in a vehicle from any public water without a water right.

The owner or occupier of any land may, without a water right, sink or deepen a well or borehole on his land and abstract or use water from it for domestic purposes up to a limited quantity a day to be prescribed by the Minister, but a borehole may not be sunk or deepened within 250 yards of any other borehole. He may also construct works on his land to conserve public water and may use it for domestic purposes, but he may not construct such works in a public stream unless the whole of the Catchment Area of the stream is not more than 2½miles from the works.

The powers of the Water Apportionment Board, which administers the Water Act, includes the power to lay down conditions on which water rights are granted, and to cancel or reduce or vary water rights in certain circumstances. It may create servitudes in favour of holders of water rights where such servitudes are necessary to enable holders to enjoy their water rights and where servitudes cannot be obtained by agreement.

Pollution of public water is punishable under the Act and penalties are laid down for such infringements.

GROUND WATER TEMPERATURES

Introduction

Van Wyk (1963) gave details of results of the measurement of temperatures of water in about 180 boreholes in Northern Natal and Zululand and found that the temperature of water was everywhere from 1 to 3,5° C higher than the mean annual air temperature and closely approached the mean summer air temperature. This accords well with findings in the United States of America where temperatures of ground water at a depth of 9 to 18m generally exceeded the mean annual air temperature by 2 to 3° F (Todd, 1959). Tate, Robertson and Gray (1970) have given a valuable account of the use of temperature measurements in an investigation of fissure-flow in boreholes.

Temperature Measurements in Botswana

The systematic measurement of ground-water temperatures was commenced in Botswana in 1966. Temperatures were measured with carefully calibrated mercury thermometers graduated in degrees Fahrenheit. Temperatures were always taken as long as possible after the commencement of pumping so that the rising main could have no warming or cooling effect (depending on whether measurements were taken in summer or winter) on the water temperature. Ground water temperatures in Botswana in general compare closely with the mean annual air temperature and become progressively warmer towards the north.

In-situ Water Temperature Measurements

In addition to the measurement of pumped water temperatures a number of in-situ water temperature measurements were made in boreholes using a thermistor as sensor. This temperature logger was designed and built by the Geological Survey of Botswana. This instrument was later replaced by a less cumbersome commercially produced temperature logger made by the Tamron Instrument Company of Israel. This instrument has not yet been widely used but initial temperature logging of boreholes has indicated a steady increase in temperature with depth corresponding to the normal geothermal gradient. Small fluctuations in the overall temperature gradient are ascribed to points of entry or water into the borehole (Figs. 89 and 90).

GROUND-WATER CHEMISTRY

Water comes closest, of all naturally occurring substances, to being the universal solvent and is, in fact, such a good solvent that perfectly pure water does not occur in nature. As water condenses and descends in the form of rain atmospheric gases such as oxygen, carbon dioxide and nitrogen, as well as ammonia and ammonium nitrate are dissolved while it soon attacks and dissolves varying amounts of organic and inorganic substances immediately it reaches the earth. The study of the chemical quality of water and its temperature is extremely important as regards the use of water and also in determining the physical features of the aquifers from which the water was derived. In its journey underground, the percolating water loses most of its organic matter and dissolves more mineral compounds, mainly of calcium, magnesium and sodium, as well as carbon dioxide etc. As water under pressure is a powerful solvent, the greater the depth to which water percolates the greater the amount of solid matter it can dissolve. When water contains an unusual amount of some particular constituant in solution which gives it some particular property, or a particular taste, it is termed a mineral water as opposed to "fresh water" which does not contain much dissolved matter.

The first chemical analyses of ground waters in Botswana were commenced by the Geological Survey Department in 1952 while systematic sampling of ground water from all government boreholes drilled was commenced in 1961. Results of this work were published briefly by van Straten (1953, 1954, 1956 and 1958) while Boocock and van Straten (1961) described the development of potable water supplies at depth at Boritse Pan in the Central Kalahari and the same authors (1962) described certain aspects of the ground water chemistry of samples derived from the Central Kalahari region. Van Straten (1961) proposed a classification of ground water types in Botswana using fifty analyses, while Jennings (1969, 1970, 1971) made brief mention of various points relating to ground water geochemistry. No comprehensive study of the chemistry of groundwaters in Botswana has been made date.

In 1968 the commencement of detailed sampling in selected ground water areas in Botswana for tritium analysis was accompanied by the collection of water samples at varying depths in selected unused boreholes. This systematic sampling at selected depth intervals and in various pumped boreholes has been repeated at regular intervals up to the present time. The sampling method used for depth sampling has been fully described in the section on radio isotope dating.

Units used in reporting of water analyses

All water analyses are reported in parts per million (ppm) and N/1000. This latter may be equated with equivalents per million (epm) which expresses the concentration of substances in solution in terms of their chemical equivalence. The equivalent or combining weight of an ion equals its atomic weight divided by its ionic charge (valence). The concentration in epm is obtained by dividing the concentration in ppm by the combining weight of the substance. In practice epm is obtained by multiplying ppm by the reciprocal of the combining weight.

Total Dissolved Solids

Is obtained by evaporating an aliquot to dryness on a steam bath and weighing the residue after the dish has been heated in an oven for an hour at 120°C.

Sum Total (Computed or "Sum")

Is obtained by adding the concentrations separately determined for all anions and cations in the water. This computed value is possibly a more useful indication of t.d.s. for certain types of water than the residue on evaporation provided a rather complete analysis is done.

The disadvantages of using t.d.s. data from a water evaporated to dryness are that the solid material deposited does not coincide completely with the material that was originally in solution - dissolved gases are driven off; bicarbonate is converted to carbonate with the loss of carbon dioxide and water; while some solid salts deposited may be volatalized at the drying temperature - this is especially important in waters high in magnesium; chloride and nitrate; some waters may deposit residues which contain water of crystallization not driven off at the drying temperature, (e.g. highly mineralised waters, especially those from which gypsum crystals are deposited) (Hem (1959)).

Both "Sum Total" and "T.D.S." are quoted in all analyses in order to provide a rough check on the accuracy and completeness of the analysis. It should be noted that, because of the limitations, quoted above, of the residue-on-evaporation (T.D.S. at 120°C) determinations such a comparison can only be approximate.

Theoretical T.D.S.

This is a calculation made in order to take into account losses of water and carbon dioxide driven off from the bicarbonate content of the water. The theoretical total dissolved solids figure will therefore invariably be higher than the Total Dissolved Solids figure quoted in water analyses.

Range in Concentration

Ground waters in Botswana range from exceptionally pure waters with 42 ppm of dissolved solids (Bh 1482) to brines with 76 712 ppm.

Carbon Dioxide

Free carbon dioxide is the chief cause of acidity in ground waters. It is readily soluble in water and forms carbonic acid: $CO_2 + H_2O = H_2CO_3$. The carbonic acid then dissociates producing H - ions which lower the pH value. The pH value is generally controlled by the amount of carbon dioxide present as well as amounts of the dissolved carbonates and bicarbonates. These latter may, together with carbonic acid formed by dissolved CO_2, form a buffered solution and, where this occurs, little change in pH takes place. The low pH values recorded in boreholes from the Kanye area are probably a result of a high dissolved CO_2 content and resultant large change in pH due to the virtual absence of dissolved carbonates and bicarbonates and hence the absence of a buffered solution. See section on pH.

Iron

No routine analyses are carried out in Botswana for the presence of iron. Only one instance of suspended iron (red water) has been recorded in Botswana and was the result of acid ground waters corroding the borehole casing, pump and mains resulting in bad staining of laundry. See section on pH.

Hydrogen Ion Concentration (pH)

The relative hydrogen ion concentration in water indicates whether it will act as a weak acid or an alkaline solution, depending on whether the pH is less than or greater than 7 respectively.

All pH determinations were carried out in the laboratory of the Geological Survey using an electrical pH meter. As most ground water in Botswana is present under confined or semi-confined conditions, it should be borne in mind that pH data can be misleading as the pH is determined in the laboratory at varying times after the sampling and hence loss of carbon dioxide from the water, either while it is being brought to surface by pumping, or during transit to the laboratory or whilst in storage prior to analysis, could take place. This could lead to a disturbance of the carbon dioxide - bicarbonate equilibrium and buffer system with a resultant change in pH and precipitation of calcium carbonate or other compounds. As a precaution against loss of carbon dioxide, bottles are tightly stoppered but the type of plastic bottle used has, on occasions, been known to leak.

Range of pH values

pH Values in Botswana ground waters range from 2,95 to 9,9.

The most acid water (pH 2,95) recorded in Botswana is from ground water encountered in drives and winzes at Phikwe Mine in the Central District. This water contains free mineral acid (sulphuric) derived from the oxidation of massive (predominantly pyrrhotite) sulphide ore present. This prospect is currently being brought into production for its nickel and copper content. T.d.s. of this water is 14036 ppm and its conductivity k = 11000.

In Kanye, water from several boreholes supplying the Seventh Day Adventist Mission hospital and tapping an aquifer in Waterberg Formation sandstone were found to contain considerable amounts of red ferric oxide in suspension, which caused discolouration and staining of clothing during laundering. At first it was presumed that the ferric oxide was derived from the highly ferruginous sandstones, but on analysing the water, it was found to have a low pH and thus,being acid, it attacked the galvanised iron pipes and released iron oxide which was causing the staining. The corrosion was considerably reduced by adding 10 ppm sodium silicate or sodium hexametaphosphate in a small tank just after it left the borehole and prior to pumping to the hospital. An analysis of one the three boreholes is given below:-

Bh	1482
Date	6.6.65
pH	5,3
HCO_3^-	14
Cl^-	11
SO_4^-	6
F^-	1
K^+	1
Na^+	3
Ca^{++}	2
Mg^{++}	4
SUM TOTAL:	42
Theoretical t.d.s.	35

This borehole is thus one of the purest waters encountered in Botswana. It was found to vary in pH quite markedly with time:-

Date	pH
8-4-63	4,9
5-6-65	5,3
17-1-67	4,5
29-3-72	6,10

The maximum pH recorded in Botswana was 9,9 for brine underlying the Makgadikgadi depression.

Upper Limits of Tolerance of Game and Cattle to Mineralised Water

Quality of water and its use by wildlife

Child, Parris and Le Riche (1971) carried out a detailed study in the Kalahari Gemsbok National Park of South Africa and the adjacent Game Reserve in South Western Botswana in an attempt to determine whether mineralised water was used in significant amounts by antelope and also to determine whether the chemical composition of the water influenced the acceptability of water by the most common species. This survey was carried out in collaboration with the Geological Survey, which carried out all the water analyses. These authors found that game species drank regularly and deeply from boreholes situated along the Nossob River with surprisingly high dissolved solid contents. Examples of these were:-

Jans Draai	(42579 ppm tds), springbok, gemsbok and black-backed jackal.
Kransbrak	(38942 ppm tds), wildebeest, steenbok and secretary bird.
Kyky	(26637 ppm tds), ostrich.
Grootbrak	(16403 ppm tds), hartebeest.
Kaspersdraai	(11611 ppm tds), lion, brown hyaena and spotted hyaena.
Langklass	(9 175 ppm tds) Cape fox.

These authors stress that the results should be used to provide a measure of magnitude rather than as precise values partly because the relative activity of the four most common antelope near the boreholes was based on the frequency of defecations, some of which were several months old and the concentration of salts in the drinking water may have changed since the animals visited it. In addition, there were also often large differences in composition between the effluent water from the borehole, the drinking trough and the overflow water (See Table 109) and also differences in the same borehole when sampled at different times (Table 110).

Chemical data from fifteen boreholes along the Nossob River (Table 111) was subjected to multivariance analysis on an I.B.M. computer "No significant correlation emerged between the number of springbok, hartebeest and wildebeest defecations and the contrations of dissolved ions, either separately or as total dissolved salts."

T A B L E 109

COMPARISON OF CONCENTRATIONS OF DISSOLVED SALTS IN BOREHOLE, TROUGH AND TROUGH OVERFLOW WATER (AFTER CHILD ET AL, 1971)

LOCATION	SITE: BOREHOLE	SITE: TROUGH	SITE: OVERFLOW	DISSOLVED IONS: CO_3^-	HCO_3^-	Cl^-	SO_4^-	F^-	K^+	Na^+	Ca^{++}	Mg^{++}	THEOR. T.D.S.
Kasper's Draai	X			69	718	3 735	3 200	4	38	4 100	39	61	11 611
		X		139	887	3 525	2 875	4	76	3 900	30	64	11 064
			X	596	563	6 274	4 575	4	69	6 700	26	86	18 617
Montrose	X			42	535	353	257	3	5	575	6	1	1 493
			X	263	1 444	899	128	16	17	1 375	9	5	3 422
Kyky	X			124	841	11 030	4 975	4	100	9 800	65	112	26 637
		X		96	729	8 665	5 375	4	70	8 300	43	78	23 001
			X	623	606	18 325	7 075	8	142	15 600	35	135	42 251

T A B L E 110

COMPARISON OF RESULTS OF DIFFERENT ANALYSES OF WATER FROM SELECTED BOREHOLES (AFTER CHILD ET AL, 1971)

LOCATION		DATE SAMPLED	DISSOLVED IONS CO_3^-	HCO_3^-	Cl^-	SO_4^-	F^-	K^+	Na^+	Ca^{++}	Mg^{++}	THEOR. T.D.S.	SUM TOTAL
Unions End	(1)	May,1956	6	512	107	58	1	?	290	0	0		690
	(2)	Oct.,1968	48	448	106	76	3	3	295	4	5	760	988
Grootkolk	(1)	May,1956	0	226	745	1 441	1	?	649	317	134		3 484
	(2)	Oct.,1968	0	239	864	1 750	1	28	950	277	110	4 098	4 219
Kaspers Draai	(1)	May,1956	0	842	2 698	1 729	1	?	2 760	50	43		11 700
	(2)		123	998	3 300	1 872	5		3 350	33	66		9 747
	(2)	Oct.,1968	69	718	3 735	3 200	4	38	4 100	39	61	11 611	11 964
Dikbaards Kolk	(2)		184	811	4 296	2 016	6		4 135	16	27		11 491
	(2)	Oct.,1968	152	956	11 193	5 158	8	78	10 125	15	14	27 214	27 701
	(2)	do.,(4)	166	775	11 193	5 250	10	78	10 000	56	45	27 179	27 573
Kameelsloep	(1)	May, 1956	36	921	5 609	2 882	5	?	5 371	Tr.	Tr.		12 288
	(2)		123	1 123	10 652	4 608	7		9 595	0	24		26 132
	(2)	Oct.,1968	97	577	5 054	2 395	7	60	3 625	171	117	10 810	11 103
	(2)	- do -	111	796	6 258	3 647	8	53	6 125	13	12	16 618	17 023
Jans Draai	(2)		215	998	14 599	7 008	10		13 344	0	16		36 190
	(2)	Oct.,1968	180	887	16 834	9 256	18	78	15 750	15	12	42 579	43 030
Kyky	(1)	May,1956	36	811	4 970	2 594	2	?	4 763	40	49		10 968
	(2)		123	811	4 428	2 064	4		4 175	27	31		11 663
	(2)	Oct.,1968	124	841	11 030	4 975	4	100	9 800	65	112	26 637	27 051
	(2)*	- do -	78	870	9 519	5 250	8	118	8 750	74	92	24 317	24 759
	(2)*	- do -	78	870	9 519	5 250	8	118	8 750	74	92	24 317	24 759

* = Sub-divisions of same sample.

(1) S.A. Geol. Survey Dept. Report
(2) Analyses by Botswana Geological Survey.

TABLE 111

DISTRIBUTION OF ANTELOPE IN RELATION TO THE QUALITY OF BOREHOLE WATER ALONG THE NOSSOB RIVER (AFTER CHILD ET AL, 1971)

BOREHOLE	NUMBER OF DEFECATIONS							DISSOLVED IONS PPM									
	SPRINGBOK	HARTEBEEST	WILDEBEEST	GEMSBOK	SPP?	GEMSBOK+SPP?	TOTAL	CO_3^-	HCO_3^-	Cl^-	SO_4^-	F^-	K^+	Na^+	Ca^{++}	Mg^{++}	THEOR. T.D.S.
UNION'S END	54	3	1	10	12	22	81	48	448	106	76	3	3	295	4	5	760
GROOTKOLK	61	23	1	3	5	8	93	0	239	864	1,750	1	28	950	277	110	4,098
LIJERSDRAAI	76	16	3	4	6	10	105	0	462	414	760	1	43	575	74	62	2 156
GROOT BRAK	50	22	1	5	21	26	99	63	852	5 465	4 421	10	80	5 875	19	51	16 403
LANG KLAAS	51	32	13	8	25	33	129	48	841	2 687	2 661	6	80	3 205	26	48	9 175
KWANG	92	14	9	4	35	39	154	110	1 331	2 404	2 851	10	68	3 450	11	10	9 569
DIEP BOORGAT	35	6	2	5	4	9	52	0	48	10 527	2 496	1	25	6 625	1 188	17	20 903
KASPERSDRAAI	13	0	0	10	2	12	25	69	718	3 735	3 200	4	38	4 100	39	61	11 611
DIKBAARDS KOLK	29	9	2	31	3	34	74	116	775	11 193	5 250	10	78	10 000	56	45	10 179
KAMEELSLEEP	56	5	3	23	6	29	93	97	577	4 054	2 395	7	60	3 625	171	117	10 810
JANS DRAAI	58	14	2	34	8	42	116	180	887	16 834	9 256	18	78	15 750	15	12	42 579
KRANS BRAK	118	1	0	47	6	53	172	290	1 063	16 575	6 825	8	290	14 300	52	62	38 942
KYKY	242	0	0	31	8	39	281	124	841	11 030	4 975	4	100	9 800	65	112	26 637
ST. JOHN'S DAM	100	4	8	29	7	36	148	41	574	1 802	1 371	3	25	2 000	30	13	5 567
ROOIPUTS	80	4	13	44	5	49	146	95	795	464	333	6	7	813	4	1	2 114

"There may, however, be some interesting association between some salts and gemsbok, especially as Leistner (1967) notes that their diet consists largely of plants that are notably deficient in minerals. There was a positive correlation between gemsbok, plus unidentified pellets, and the carbonate, bicarbonate, fluorine and potassium ions. There may also have been some relationship with sodium and calcium as these were significant at the 10 per cent level." (Child, Parris and Le Riche, 1971).

Discussion on chemical differences between water from pumped borehole, trough and overflow

Analyses of water from southwestern Botswana (Table 109) show small differences in quality between pumped water and trough water and large differences in quality between that of the trough and that of overflow water in the neighbourhood of the trough. The small but definite improvement in quality between the pumped water and that of the trough is rather unexpected in that normally water in the trough would be expected to evaporate and become more concentrated. However, apparently this improvement in quality, mainly a reduction in Na^{+} Cl^{-} and, in one case, SO_4^{-}, could have been caused either by precipitation of these salts due to a change in temperature and pressure or more likely may be due to pumping from different levels of a stratified aquifer depending on the pumping rate caused by varying wind velocities.

The large differences in quality between the trough and the overflow (collected from pools in the floor of the dry river bed) is undoubtedly due to a combination of concentration of salts by evaporation, pollution by urine from the game animals and from solution of the alkaline salts present in the dry river bed.

Limits of tolerance in humans to mineralised ground water

The World Health Organisation (1963) published international standards for drinking water, although it emphasised that rigid standards cannot be set. The following are the maximum allowable limits as set out by the W.H.O. :-

Substance	Maximum Allowable Concentration ppm
Total dissolved solids	1500
Iron	1
Manganese	0,5
Copper	1,5
Zinc	15
Arsenic	0,05
Lead	0,05
Calcium	200
Magnesium	150
Sulphate	400
Chloride	600
Magnesium + Sodium sulphate	1000
Nitrate	45
Fluoride	1,5
Cyanide	0,2

In practice the acceptability of water for drinking depends largely on what the individual is prepared to tolerate in regard to suspended matter, odour, colour and soluble salts while in many cases in Botswana, the total lack of any more suitable alternative source of water often results in waters, normally unacceptable by W.H.O. standards, being consumed. It is not surprising therefore that a random sample of 1200 ground water analyses from Botswana showed that 17 per cent would be classified as unpotable by World Health Organisation standards.

In South Africa, Bond (1946) gave a detailed treatise on ground water geochemistry, while in South West Africa, van Wyk and Hamman (1969) and Hellwig (1969) have given details of ground water chemistry. Van Wyk and Hamman (1969) quote maximum allowable chemical contents in water for humans of 1500 to 3000 ppm depending on whether used in towns with populations exceeding 10 000 or for farm use. Details of maximum allowable dissolved solid contents for South West Africa where conditions are very similar to Botswana are given in Table 112.

TABLE 112

Maximum permissable dissolved solid contents
(After van Wyk and Hamman 1969)

Specification for	A	B	C	D
pH	7,0-8,5	7,0-8,5	6,5-9,2	5,6-9,2
Total dissolved salts	1500	2000	3000	5000
Sodium	-	-	-	2000
Calcium (as $CaCO_3$)	-	-	-	2500
Magnesium (as $MgCO_3$)	200	600	-	2050
Nitrate (as N)	20	20	20	90
Chloride	-	-	-	3000
Fluoride	1,5	2,0	2,0	6,0
Sulphate	250	500	500	1000

A Towns with populations over 10 000

B Villages, tourist camps and small state water schemes.

C Limited water use such as farms

D Livestock (standards laid down by Department of Agriculture and Technical Services, South Africa.)

In Botswana water from the following boreholes or wells is used regularly by humans as no alternative supplies are available:-

Sekhuma Pan Wells	T.D.S.	7328
Sir R. Englands borehole (windmill) Lobatse	"	4416
Morwamosu	"	3856
Nata Ranch house (BhP.201)	"	2428
Bh.2941 Molopo Farms (C. Coetzee)	"	2048

(See Table 113).

Quality of water used by livestock

In Botswana an arbitrary maximum limit of 10 000 p.p.m. total dissolved solids has long been adopted with the sole proviso that the water has a predominantly sodium and chloride ionic composition. (Table 113)

Comparitively little work has been done on the quality of drinking water tolerated by domestic stock apart from sheep (Pierce, 1957, 1959, 1960, 1961, 1963 and 1965) and Anon. (1967) Table 113 taken from this report indicates the upper limits recommended for livestock by State Authorities in Australia. Van Wyk and Hamman (1969) mention that an experimental farm had been set up in South West Africa to establish experimentally limits of tolerance of livestock to saline waters.

TABLE 113

Water analysis bh Z 431 Farm 31-JM (D. Blaaw)
Water consumed regularly by cattle with no ill effects.
Bh 858 MorwamosuWater used regularly by humans with no ill effects.

Date:	6.9.66	28.5.80
pH:	8,15	8,40
CO_3:	-	13
HCO_3:	659	569
Cl:	4166	1684
SO_4:	1894	343
F:	1	1
Total anions:	6720	2610
K^+:	132	107
Na:	3240	1230
Ca:	119	55
Mg:	210	68
Total cations	3701	1460
Sum total	10421	4070
k	13300	5700

TABLE 114

UPPER LIMITS USED BY AUSTRALIAN AUTHORITIES FOR TOTAL SALTS IN WATER FOR LIVESTOCK (FROM ANON, 1967)

CLASS OF LIVESTOCK	QUEENS-LAND	NEW SOUTH WALES	NORTHERN TERRITORY	SOUTH AUST.	WESTERN AUST.	VICTORIA
	p.p.m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.
Poultry	3,500	4,000		3,000a	3,000	3,500
Pigs	5,500	4,000		3,000a	4,500	4,500
Horses	5,500b	7,000	6,000	7,000	6,500	6,000
Cattle Dairy	5,500b	10,000	6,000	7,000	7,000	6,000
Beef	8,500c	10,000	10,000	10,000	10,000	7,000
Sheep						
Lambs, Weaners					10,000	4,500
Ewes in Milk					10,000	6,000
Adult, on dry Feed	14,500	14,000	12,000	13,000	13,000	7,000e to 15,000
Adult, on green grass	18,500		15,000	18,000	18,500d	

NOTATIONS WITHIN TABLE:

a. 4,000 p.p.m. if on salt-free rations, 1,500 p.p.m. if on high salt diet.

b. 7,000 p.p.m. if on green feed.

c. 10,000 p.p.m. if on green feed.

d. For short periods.

e. If unaccustomed to saline water; if accustomed, up to 15,000 p.p.m.

Fluoride in ground water

Fluoride in ground water is probably derived mainly from silicate rocks containing fluorite, flourapatite, micas (biotite and muscovite), amphiboles, topaz and tourmaline. Analyses are now widely made for this element as an excess may lead to the pathological condition recognised in man and animals known as endemic cumulative fluorosis which results in skeletal damage in both children and adults.

Although much has been written about endemic fluorosis elsewhere in the world, it was only relatively recently found by Steyn (1938) and Ockerse (1940, 1941) that widespread dental fluorosis was present in Southern Africa and that systematic fluoride poisoning was probably occurring in these districts where dental fluorosis was evident. Generally where fluorides are present in drinking water in excess of 1.0 to 1.5 mg of fluorine per litre, they may give rise to dental fluorosis in some children, though concentrations of 1.0 to 1.5 ppm were beneficial in that dental decay was inhibited with no significant mottling. Where the drinking water of a community contains less than 0.5 mg/l of fluoride, a high incidence of dental caries is likely to occur in children and consequently numerous communal water supplies are fluoridated to bring the fluorine content to 1.0 mg/litre.

When assessing the safety of a water-supply with regard to fluoride content, it is necessary to take into account a number of factors, such as the presence of fluorides in certain foods and also the total intake per day of water e.g. in hotter climates the water intake is likely to be much higher and hence more deleterious effects are likely to take place than in a colder climate.

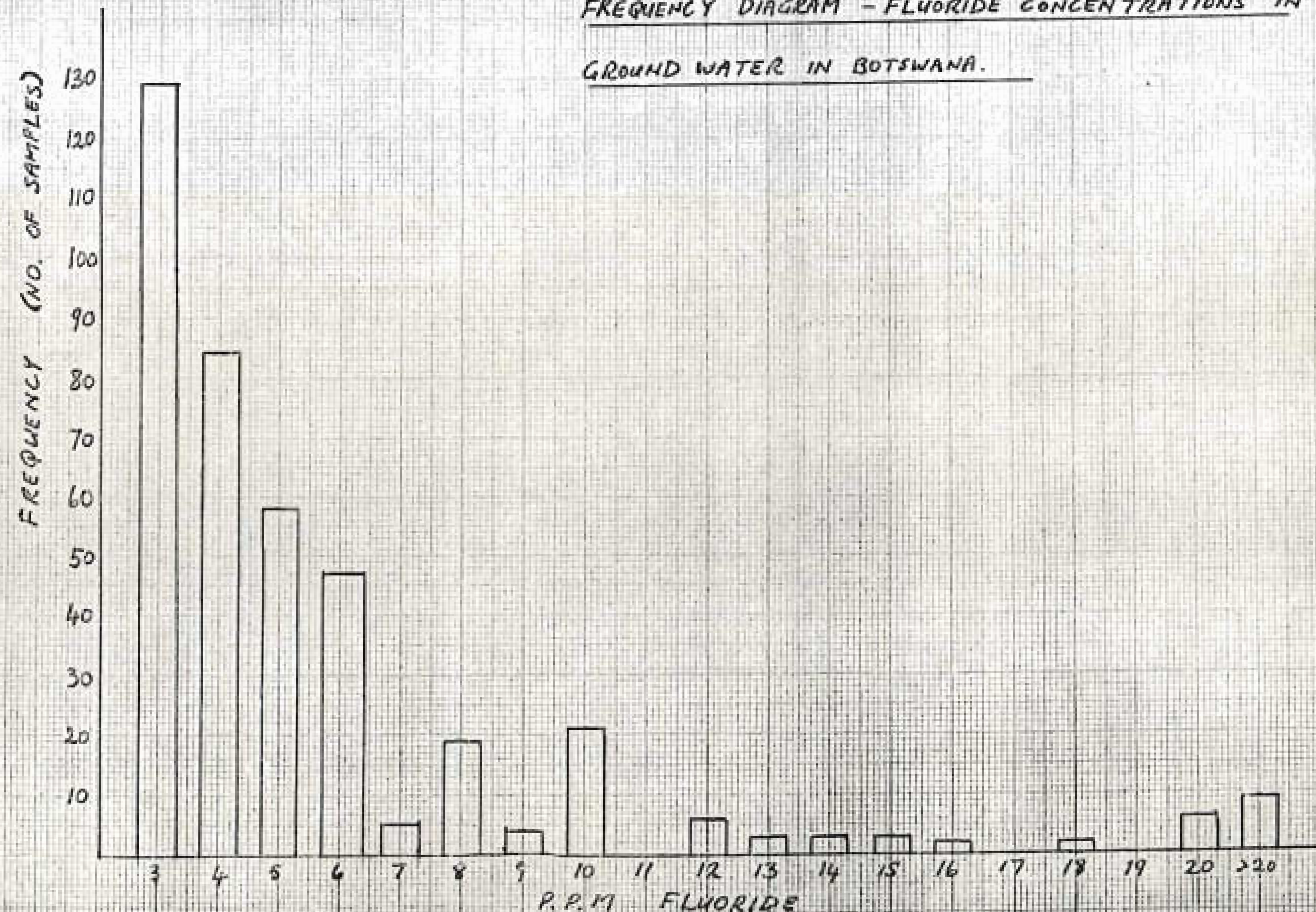
Out of several thousand boreholes and wells in Botswana on which chemical analyses have been carried out, no fewer than 403 contain fluoride concentrations of three or more parts per million. Fig. 201 shows a bar graph giving the distribution of supplies with varying fluoride concentrations. Concentrations in ground water range from nil to 60 ppm.

It can be seen therefore that fluoride concentrations occur frequently at levels above the maximum allowable limit as set out by the World Health Organisation (1963) (i.e. 1.5 mg/l) and because of chronic water shortages, supplies which elsewhere in the world would normally be abandoned, have to be used often to the detriment of man and beast. There is thus an urgent need for an effective method of defluoridation of high-fluoride bearing waters. Fluoride may be removed from water by ion-exchange or by absorption on various flocculent precipitates.

Cillie (1955a,b) investigated the efficiencies of various defluoridising agents based on defluoridising capacity; lowest residual fluoride concentration obtained;

Fig. 201

FREQUENCY DIAGRAM - FLUORIDE CONCENTRATIONS IN GROUND WATER IN BOTSWANA.



and potentiality for regeneration. Of 55 materials tested, those which depended for their defluoridising activity upon the formation of an apatite in which fluoride and hydroxide ions are exchanged were most efficient - illustration by the following equation:-

$$Ca\ OH\ Ca_4\ (PO_4)_3 + F^- \rightleftharpoons CaF\ Ca_4\ (PO_4)_3 + OH^-$$

Flocculent precipitates were found to be unsuitable as they were inefficient and regeneration was impossible. The most useful defluoridant appeared to consist of superphosphate of lime treated with excess dilute sodium hydroxide solution (activated superphosphate). The ion exchange properties are critically controlled by changes in pH value with optimum pH values between 6 and 8. Regeneration of the defluoridant saturated with fluoride ions was possible with a 1% solution of sodium hydroxide.

DISTRIBUTION OF HIGH FLUORIDE WATERS

A glance at Fig. 202 shows that far and away the greatest concentrations of waters containing high fluoride ion contents occur west of the railway line. The main areas with high concentrations are Lobatse, Thamaga-Mogobane, Ramotswa, Mochudi, Dibete, N.E. of Mahalapye, Lerala-Selika area, Tati African area, Matsitamma, Bushman Mine-Dukwe area, Makoba area, Orapa area, Nata Ranch area, Odiakwe, Kanyu, Bushman Pits, Shorobe, Chobe National Park, Sehitwa, Tsau, Ghanzi, the whole Kalahari area along the road to Ghanzi, Bokspits, Kalahari Gemsbok Game Reserve and the Molopo Farms area.


Fig 202.
BOTSWANA
Showing Locations with high F⁻ Content (> 3ppm)
CAPRIVI STRIP
SOUTH WEST AFRICA
RHODESIA
NORTHERN STATE LANDS
K A L A H A R I
SOUTHERN STATE LANDS
REPUBLIC OF SOUTH AFRICA

In general the areas which receive regular recharge, i.e. the eastern non sand covered regions contain the lowest fluoride ion concentrations. Elsewhere the presence of fluoride constitutes a major health hazard over large areas. This is particularly worrying as these latter areas seldom have alternative supplies of better quality water. The general poorer quality of cattle from the Botswana, N. State Lands, Ghanzi and W. Kalahari areas could possibly be partly due to high fluoride concentrations and research on this aspect should be carried out by the Animal Husbandry section of the Ministry of Agriculture.

Potassium in Ground Water

More than seventy boreholes and wells in Botswana contain more than 50 ppm of potassium ion concentration. A number of waters containing more than 300 ppm were noted in only four diserete areas; these being at Gooi Pan (south of Rakops) with 1750 ppm or 0.1750% K^+, at P.106, Nata (670 ppm) Bh No. 9, Nata (625 ppm) Bh on JM 31 Molopo (360 ppm) Oikhe Pan well, Kalahari (334 ppm), Bh on JM 30 Molopo (peg 31, 300 ppm), JM 32 Molopo (220 ppm).

The exploitation of potassium from these areas should be considered in the future.

Common sources of potassium are the potash rich rocks such as orthoclase, microcline , biotite, leucite and nepheline in igneous and metamorphic rocks. Water percolating through evaporite deposits often contain large quantities of potassium derived from solution of sylvite (KCl) and nitre (KNO_3). All the above-mentioned localities probably contain evaporite deposits.

Waters in Botswana generally contain relatively low concentrations of potassium in most potable waters.

General Remarks Concerning Water Analyses in Botswana

Remarks concerning water quality in general and variations in water quality with depth; with change in geological formation and with time have been given in the chapters on the Central Kalahari, Lobatse, Orapa and Serowe.

The systematic analysis of ground waters has given valuable information on different types of ground water and its relationship to different geological formations; has assisted in determining time of recharge of boreholes while the conjunctive use of chemistry and isotopes as a tracer has enabled a picture of recharge mechanisms to be built up (e.g. Serowe Bhs 670 and 1970).

SUMMARY

Botswana covers an area of 570 000 km^2 and has a population of about 600 000. It is estimated that three-quarters of the human and livestock populations are dependent on ground water, with an estimated 26 x $10^6 m^3$ of water from this source being used annually. Details of the physiography, climate, denudational and depositional surfaces and geology are given:-

Ground water occurs in both primary and secondary aquifers under both water-table and artesian conditions at varying depths from less than 1m to over 300m. The water-bearing properties of the various aquifers are described with the basalt/Cave sandstone contact providing the greatest number of successful boreholes and the sedimentary rocks of the Pretoria Group providing the highest yields (208,45 litres/minute). The shallowest water is found in the Kalahari Beds and the deepest in the Ecca Group.

Detailed descriptions are given of the hydrogeology of the Central Kalahari, Lobatse, Orapa and Serowe. In the Lobatse area, estimates of the average monthly recharge rate have been made as well as estimates of the total storage capacity of the various ground-water basins. The percentage of annual rainfall contributing to ground water has also been calculated. An annual recharge rate has also been calculated for Serowe while the total amount of water in storage in the important Cave sandstone aquifer has been estimated. Hydrogeological details of the Kalahari Beds, basalt/Cave sandstone aquifer and Middle Ecca aquifers are given following core drilling programmes.

ERTS photography was used to assist in obtaining a figure of 56 x $10^6 m^3$ of extractable water present in storage in the "sand rivers" of eastern Botswana.

Detailed aquifer tests on a variety of aquifers are described and show that the secondary aquifers present often behave in a similar fashion to primary aquifers.

Approximately 5 000 boreholes are presumed to be present in Botswana. It is estimated that 17% of the successful boreholes have yields in excess of 150 l/min. The siting of boreholes using geological/geophysical aids has resulted in an increase in the success rate of nearly 25%. New geophysical techniques for the location of ground water have been investigated and ground geophysical methods used include electrical resistivity, inductive and conductive electromagnetic, Afmag, self-potential and seismic reflection and refraction methods. The well-tried resistivity method remains the most successful technique but self-potential, Afmag and seismic methods have given encouraging results.

Extremely detailed studies using environmental isotopes are described. These have enabled quantitative estimates of ground-water storage and turnover times to be made; have given ground-water flow rates; have outlined areas of recharge; have enabled permeabilities to be calculated; have enabled a clearer picture of recharge mechanisms through the unsaturated zone to be built-up; and have provided important evidence of areas in which recent recharge has contributed to ground-water supplies. The studies have shown that measurable amounts of tritium are present over far wider areas than originally anticipated and thus more recharge is taking place than thought earlier from laboratory tests and hydrogeological considerations. In Lobatse a water balance model is proposed and calculations based on this model indicate that some leakage, hitherto unsuspected, between several of the ground-water basins, take place. The carbon-14 method has, in addition, helped outline areas of recharge (Central Basin, Lobatse) which tritium had failed to do and has shown by using combined ^{3}H and ^{14}C data that mixing of young and old waters takes place. In the Kalahari, radiocarbon has been used to calculate ground-water flow rates, permeability and transmissivity. The oldest ground water in Botswana has an age of 33 700 years.

Isotopic studies in the unsaturated zone have shown that water moves given rates downward at a rate of between 31 and 41 cm per year.

Studies of water levels in boreholes have shown that nearly all boreholes show responses which can be directly correlated with seasonal recharge and hence the nature and frequency of recharge can be estimated. In addition, storage capacity and safe yield have been estimated using long term water level changes and knowing the amount abstracted from the basin. The rapid responses shown in some boreholes indicates surprisingly rapid recharge. Two boreholes in Botswana showed effects of the Tulbagh earthquake on 29th September 1969. The disturbance of semi-diurnal fluctuations in boreholes could possibly be used as an early warning device to predict catastrophic earthquakes.

A preliminary annual safe yield for ground-water supplies in Botswana is estimated to be $4 \times 10^{9} m^{3}$ per annum.

Tree roots have been found in boreholes at depths greater than 68m. This emphasises the role vegetation can have in causing transpirational losses from ground-water supplies.

Irrigation from boreholes is unlikely to be profitable unless exceptionally large supplies are obtained or water be present at very shallow depth. Underutilised boreholes, e.g. boreholes drilled specifically for cattle ranching, could also be profitably used for irrigation.

Details of ground-water chemistry and examples of fresh water overlying saline, saline water overlying fresh, chemical stratification with depth and changes in quality with time are given. The distribution of fluoride rich waters in Botswana is also given.

This thesis has therefore attempted to outline the current status of hydrogeological research in Botswana and it is hoped that this will lay the foundation for later, more detailed and quantitative, studies. These will become even more vital than at present, as it is estimated that all readily available surface water resources in eastern Botswana will be fully utilised by the late 1980's and the country will rely even more heavily on ground water than at present.

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