BRITISH GEOLOGICAL SURVEY
Natural Environment Research Council

TECHNICAL REPORT WD/92/34

Hydrogeology Series

Technical Report WD/92/34

FINAL REPORT ON ODA/BGS R & D PROJECT 91/7: Development of Horizontal Drilling Rig for Alluvial Aquifers of High Permeability.

WORK ON SAND RIVERS IN BOTSWANA AND SUMMARY OF WORK IN MALAYSIA, ZIMBABWE AND UK

R Herbert

This report was prepared for the Overseas Development Administration

 Keyworth, Nottinghamshire British Geological Survey 1992

Cover Photograph: ***DRILLING ADITS AT BASE OF CHADIBE DUG WELL, BOTSWANA***

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available through the Sales Desks at Keyworth and at Murchison House, Edinburgh, and in the BGS London Information Office in the Natural History Museum Earth Galleries. The adjacent bookshop stocks the more popular books for sale over the counter. Most BGS books and reports are listed in HMSO's Sectional List 45, and can be bought from HMSO and through HMSO agents and retailers. Maps are listed in the BGS Map Catalogue, and can be bought from Ordnance Survey agents as well as from BGS.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Overseas Development Administration.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottingham NG12 5GG
☎ 0602-363100 Telex 378173 BGSKEY G
Fax 0602-363200

Murchison House, West Mains Road, Edinburgh EH9 3LA
☎ 031-667 1000 Telex 727343 SEISED G
Fax 031-668 2683

London Information Office at the Natural History Museum Earth Galleries, Exhibition Road, South Kensington, London SW7 2DE
☎ 071-589 4090 Fax 071-584 8270
☎ 071-938 9056/57

19 Grange Terrace, Edinburgh EH9 2LF
☎ 031-667 1000 Telex 727343 SEISED G

St Just, 30 Pennsylvania Road, Exeter EX4 6BX
☎ 0392-78312 Fax 0392-437505

Bryn Eithyn Hall, Llanfarian, Aberystwyth, Dyfed SY23 4BY
☎ 0970-611038 Fax 0970-624822

Windsor Court, Windsor Terrace, Newcastle upon Tyne NE2 4HB
☎ 091-281 7088 Fax 091-281 9016

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ 0232-666595 Fax 0232-662385

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 0491-38800 Telex 849365 HYDROL G
Fax (0491) 25338

Parent Body
Natural Environment Research Council
Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 0793-411500 Telex 444293 ENVRE G
Fax 0793-411501

Contents

<u>List of Figures</u>

<u>List of Tables</u>

EXECUTIVE SUMMARY

This is the final report of an ODA/BGS project which had the aim of developing a technique for the construction of collector wells which was appropriate for the developing world and suitable for thin, water-bearing, non-consolidated sediments.

A collector well consists of several 20 to 30 m long adits, or laterals, drilled out horizontally from within a small shaft, c. 2 m diameter, sunk into the water bearing formation. The report is in two parts: the first describes the most recent work done in Botswana and the second summarises work done in Malyasia, Zimbabwe and the UK.

The aim in Botswana was to construct collector wells at the side of the seasonally dry sand rivers. Two such wells were constructed satisfactorily and the Department of Water Affairs is presently exploring the possibility for constructing a further five at other villages in Botswana. The method was found to be cheap and gave a sustainable yield which was higher than that obtainable by boreholes in the surrounding basement.

The second part of the report summarises the work done with collector wells built in thin alluvial valleys or plains. It is shown that telescoped-jetting is the most appropriate drilling technique to emplace 2" diameter adits in coarse to medium sands whilst a much lighter moling rig can emplace 1½" diameter adits in silty to fine sands without throttling the maximum flow possible. Two collector wells were constructed in each of Malaysia and Zimbabwe (telescoped-jetting) and one in the UK (moling).

Further work is necessary to refine the telescoped jetting technique but this can be done during the process of development projects in the way that all drilling is experimental in nature.

Collector wells in thin alluvium have now become an established method of development of groundwater resources.

ACKNOWLEDGEMENTS

This project was funded by the Overseas Development Administration of the United Kingdom. It is carried out by the British Geological Survey and its overseas counterparts and is part of the programme of Research and Development in developing countries managed by the Engineering Advisers of the ODA. This R & D programme forms part of the British Governments Aid Programme.

The work reported in the first part of this report was carried out with, and jointly funded by, the Department of Water Affairs, Botswana. In addition the Geological Survey of Malaysia and the (then) Ministry of Energy, Water Resources and Development of Zimbabwe have both contributed significantly in terms of assistance with staff and equipment.

1. BACKGROUND

1.1 Project Description and Companion Reports

A project entitled 'Development of a Horizontal Drilling Rig for Alluvial Aquifers' has been underway since April 1989. The project's main aim was to develop a drilling rig, string and technique (a drilling system), which would be suitable for the construction of collector wells in alluvial valleys, plains or sand rivers. The system should be relatively cheap and suitable for developing countries. Two earlier reports summarise work which used telescoped-jetting as the drilling technique in alluvial valleys in Malaysia (Allen, 1988) and the alluvial plains of Zimbabwe (Herbert and Rastall, 1991). A third report, Morris et al. (1991) describes work done in the UK using a moling technique. This report, the last in the series, describes the construction of collector wells on the banks of sand rivers in Botswana. It also reviews the findings of the entire project and makes recommendations for the use of collector wells in alluviums. The unique problem posed by the work done in Botswana related to the fact that the shaft of the collector well was dug in weathered hard rock. The sand river cuts into the hard rock and the collector's adits have to be drilled laterally out through the hard rock, using air hammer and then through the non-cohesive sands of the sand river.

1.2 Project Organisation for Botswana Phase

The last phase of the project was carried out jointly by BGS and the Department of Water Affairs (DWA) Botswana. BGS provided the services of the driller and the drilling system. The DWA met the construction costs of the two wells, the site investigations made and in the later stages of the work, some of the drillers costs. The Ministry of Energy and Water Resources Development (MEWRD) Zimbabwe, provided storage facilities for the drilling equipment in Bulawayo and Harare.

2. SAND RIVERS IN BOTSWANA

Sand River is a term commonly used in Botswana to describe the particular type of ephemeral river channel (wadi) that occurs there. Sand rivers are filled with clean, relatively coarse sand and are typically 2-10 m thick. The sand is probably derived from the weathered hard rock which underlies it.

Wikner (1980) and Nord (1985) reported on the potential and development of the sand rivers of Botswana. Fig. 1 is taken from these reports. It shows the distribution of the main sand rivers and gives estimates of the total water reserves held in them.

2.1 The Sashe River at the Project Site

Collector wells were constructed at Borolong and Chadibe villages, which are adjacent to the stretch of the Sashe River shown on Fig. 1 as SHC27 to SHB87.

Fig. 2 gives the location of the villages in relation to Francistown. The site of Chadibe was determined using a GPS personal navigator; this was: S21°04.29', E27°21.61 Alt 3422 ± 81 ft.

Fig. 1 indicates there are 835 x 10^3 m^3 of total saturated reserves in this 55 km length.

In addition to the reserves of water it is assumed by Nord that much sand river water is lost direct to evaporation, bank storage and seepage to the bedrock. This water can be captured in the first few months of the dry season and will not affect the quantity of water in reserve.

A sand river of
South East Botswana

The collector well being constructed on the Sashe River at 30/11/91. (Note the caisson behind the trees).

With this in mind, Nord (1985) estimates that there are about 250 x 10^3 m^3 of exploitable reserves. The typical extreme dry period will last ca. 10 months and the safe yield of this stretch of the Sashe is about 20 m^3/day/km length of river.

Nord reports T and S values for the Sashe derived from pumping tests as follows:

	T (m^2/d)	S (-)
Sashe Sebina	600	0.15-0.2
Sashe Tonota	2700-4900	0.03-0.04

It is clear from Nord (1985) that there is much potential for the exploitation of groundwater from the sand rivers of Botswana. Collector wells are just one way of achieving this.

2.2 Earlier Site Investigation Work at Villages

Apart from the work described by Nord (1985), Geotechnical Consulting Services [PTY] Ltd. (1990) have written an inception report describing data collection and site investigation of the area around Borolong and Chadibe villages. The area is underlain by granitic gneisses. Post-Karoo system, dolerite dykes are ubiquitous. These have a predominant WNW trend and can be seen exposed crossing the Sashe river at frequent intervals. Fig. 3 is taken from Geotechnical Consulting Services [PTY] (1990), and shows the location of magnetic anomalies in the area and suggests a 4 to 6 km spacing between major dykes and faults in the area. In the reference above, the details are given of seven boreholes drilled into bedrock in the area. The water strike in these boreholes is between 20 and 36 m and the weathered zone is of variable thickness, ca. 25 m. Yields of the boreholes are also variable, having reported yields of nil to 9.6 m^3/hr, although it is not clear how these yields were established and whether they are permanent or not.

3. THE BOROLONG SITE RESULTS

This section describes work done as part of the BGS/ODA-DWA project.

3.1 Site Location

Two boreholes were drilled by the DWA near to the site finally chosen for the sand river collector well at Borolong village. There was some confusion in the records as to which borehole log was which, but site confirmatory work now suggests that the final location for the collector well was chosen to be 1 m distance from borehole 6876. Its borehole log is given below.

Borehole No. 6876

0.00 - 3.50	Dark brown sandy silt, mainly loose
3.50 - 4.00	Pinkish weathered granite (boulder?)
4.00 - 9.50	Light brown silty sand (weathered granite)
9.50 -	Fresh granite

3.2 Site Investigation

Fig. 4 shows the relative locations of the collector well, the site of the pumping test (36 m from the river bank), the two lines along which a profile of thickness of sand were determined and distances to the dyke outcrops upstream and downstream which were observed to be outcropping, in part, above the sand river bed. Figs 5 and 6 show the thicknesses of sand along the two lines of Fig. 4 as estimated using penetration tests.

The height of the dug well above sand level was found to be 6.7 m and so the dug well needed to be at least 9.5 m deep to allow room for horizontal drilling along bedrock.

3.3 Sieving Analysis

A large sample of sand was taken from the surface at the middle of the sand river opposite the dug well. Fig. 7 shows the grading curve obtained by sieving and Table 1 gives the sieving results in detail. One estimate of the permeability is given in the Table as 193 m/day. A second estimate can be obtained using Hazen's formula, $k = (100\text{-}150)*D_{10}^2$, where k is in cm/sec and D_{10} is the effective size in cm of the sieve which retains 10% of the sand sample. Using Hazen, a permeability of 50 to 120 m/day is predicted.

3.4 The Pumping Test

Three 2" diameter wells were installed to bedrock 36 m from the sand river's bank. The three wells were at 5 m spacing (see Fig. 4). One well was pumped for 90 mins at 0.132 cumeters/minute and the drawdowns in the two other wells, which were at 5 m and 10 m distance, were recorded. Table 2 gives the drawdowns observed in the two observation wells in metres.

The software described by Barker (1989) was used to analyse the results of Table 2. Very good fits were achieved. The best fit for Transmissivity was 1.164 m^2/min (1670 m^2/d) and had a 50% confidence of lying between 1.07 and 1.26. The Storage Coefficient was 0.16(-) and had a 50% confidence of lying between 0.13 and 0.20. The aquifer behaves like a simple unconfined, highly permeable aquifer. The difference between the permeabilities determined from the pumping test (ca. 1670 ÷ 3 m/d) and the grading curve results (ca. 190 m/d) probably indicates the superficial deposits of the sand river are much finer than those at depth. This is not unreasonable when the mode of deposition of the sand is considered.

3.5 Shaft Construction

The 2.2 m diameter shaft at Borolong was not ideally sited. There were locations both nearer to the river and with greater depths of weathering. Both these situations would have eased construction. Nevertheless a 9.5 m deep shaft was constructed successfully and the last 5 m had to be blasted out using explosives. Logistics, the availability of the right equipment and staff, posed the most difficulties. Assuming these are now overcome, a 2.2 m diameter shaft could easily be sunk within one month. 2.2 m diameter Armco lining is available in R.S.A. The costs of this work were met entirely by the DWA and are unknown to the writer.

3.6 Drilling of Collectors

Six laterals were drilled. Fig. 8 is a sketch showing the unscaled disposition of the laterals.

The first lateral (lateral 1) was air-hammered out (4") to 26 m. Nine metres of hard rock (river bank) were drilled through before reaching the river bed. Then the bit bounced along the river bed hitting hard rocks now and then and it was thought to be in non-producing clays. Screens were not installed.

Lateral 2 was air-hammered out to 9 m (4" hammer) until the river bed was met. Two inch diameter Terraline screens were then jetted in to 26 m through sand. This lateral produced ca. 4.5 l/sec but the internal jetting pipe was sand-locked against the exterior screen and was very difficult to extract.

Lateral 3 was air-hammered out 6 m until hitting the river bed. Two inch diameter Terraline screen was then jetted in a further 11 m before surfacing in the river bed.

The experience of Lateral 3 was repeated at Lateral 4.

In Lateral 5 there were 16 m of hard rock before hitting the river bed. The lateral was then jetted out to 25 m (a further 9 m) in sand. Once again the jetting pipe was sand-locked to the screen and the pipe was broken off in-situ when it was extracted.

Lateral 6 was drilled well after the others. Extra jetting holes were drilled in the jetting pipe about 10 m down from the jetting head to see if this would help prevent sand-locking. In the event there was 9 m of hard rock to be air-hammered through and the lateral was then jetted out to 16 m before hitting a boulder or bedrock. This produced only a little water, like Lateral 1. It is likely the sand was very clayey and was either weathered bedrock or clay. There was little problem with extracting the jetting pipe.

3.7 Pumping Tests on Completed Collector Well

Four pumping tests were carried out on the collector well. Two were before the sixth lateral had been drilled and two were after. The results of the very last test carried out on 16 July 1992 are presented in Table 3 and are plotted in Fig. 9. Analysis of the results using large diameter well techniques based on Papadopulos and Cooper was not successful. This could be because the length and geometry of the laterals which are in direct contact with the main aquifer are not known with any certainty. All that can be said is that if the well is pumped at ca. 45 m^3/day for 450 minutes the drawdown will be about 0.5 m but that a good 60% recovery will be achieved in another 160 minutes.

3.8 Water Quality

Two water samples taken from the pumped well and analysed by the DWA are given in Tables 4 and 5. Both samples are considered suitable for drinking purposes.

4. THE CHADIBE SITE RESULTS

4.1 Site Location

The collector well was constructed at Chadibe village adjacent to exploratory borehole no. 6798. The location was determined, using a GPS personal navigator, to be: S21°04.29', E27°21.61 Alt 3422 ± 81 ft.

4.2 Site Investigation

Fig. 10 shows a cross-section taken across the river at Chadibe which was determined using penetration tests.

4.3 Shaft Construction

As at Borolong a 2.2 m diameter shaft was sunk to below the bedrock level of the sand river. The shaft was lined with Armco galvanised lining. Explosives were not used.

4.4 Drilling of the Collectors

Three laterals were drilled. Fig. 11 is a sketch showing their relative positions.

The first lateral was drilled as far as possible in a line ca. 75° to the perpendicular with the line of the centre of the river. The hammer broke out of hard rock after 11 m. Jetting failed to penetrate further. This was indicative of cohesive but softer material. A 4" drag bit was then used to drill a further 12 m, there the bit broke out into sand. The hole was terminated at 23 m and 2" diameter Terraline screens were jetted in to complete the hole.

Lateral 2 was constructed entirely with a 4" drag bit which was drilled out to 25 m but only 16 m of 2" Terraline screen could be jetted-in.

Lateral 3 was also drilled with a drag bit through weathered granite. The hole would not stay open and a large rate of inflow of cuttings were flowing into the shaft. For convenience the drilling was stopped at 7 m and screen was jetted in to 6 m.

During drilling the laterals produced a total inflow of about 2 l/sec.

The drilling results were unexpected. It seems the laterals were drilled through highly-weathered bedrock and not sand. This shows that a highly versatile rig must be used to meet the wide variety of geological conditions possible.

4.5 Pumping Tests on the Completed Collector Well

Two pumping tests were carried out on the collector well at Chadibe. They both had the same characteristics. Table 6 and Fig. 12 show the results for the first of these tests.

For completeness an attempt was made to interpret the results using the Rushton-Singh digital modelling technique and these efforts are represented in the table and on Fig. 12. The technique did not reproduce the type of curve required. This is to be expected. In reality the three laterals are probably in a relatively low permeability stratum (weathered rock), which underlies the high permeability sands. If this is so a steady-state would be expected to be reached; the lower permeability strata being fed from above by a reservoir of, relatively, infinite capacity. There is strong evidence of this on Fig. 12 where the drawdowns become constant towards the end of the test.

There is insufficient data to allow accurate analysis of this test but it can be said that a yield of 45 m^3/day will produce a drawdown of about 0.28 m and recovery of well water-levels will be rapid.

4.6 Water Quality

Two water samples taken from the collector well and analysed by the DWA are given in Tables 7 and 8. Both samples are considered to be suitable for drinking purposes.

5. THE GROUNDWATER FLOW IN THE RIVER AND SAFE YIELD

Three hundred metres downstream of Chadibe, two piezometers were drilled into the river bed 200 m apart. The DWA determined the difference in water levels between them which was 3 mm. If the transmissivity of the sand is taken to be the same as that determined from the pumping test (1670 m^2/day) and the active river width to be about 50 m then 1.23 m^3/sec of groundwater flow could exist. There is of course uncertainty about all these measurements and how representative they are of the average conditions in the river bed. Nevertheless, it can safely be said that neither collector well can extract more than a small part of this flow and so their long-term yields will only be affected by drainage from the river bed to the hard rock aquifer beneath.

The true safe yield of the river will be best determined by monitoring piezometer levels in the river bed near the collectors throughout the dry season.

6. FURTHER EXPERIMENTAL WORK REQUIRED

Weathered rock that is sufficiently permeable can underlie the Sand Rivers of Botswana and might be the simplest stratum for inserting the laterals. They would be easy to drill and more permanent (being deeper). Accordingly, site investigation techniques should be developed to enable identification of such layers.

The jetting method used for river sands needs further development and testing. More work should be done to see if extra jetting holes along the length of the jetting pipe of the system described in this report will prevent sand-locking and ease drilling. Alternatively, techniques where the screen was carried within the jetting pipe could be devised.

The performance of the collector wells should be monitored and groundwater levels around them and in the river bed should be monitored for one or two years. This will allow predictions to be made of long-term performance and aid management decisions for different climatic conditions in the future.

7. PRECIS OF FINDINGS IN ALL FOUR COUNTRIES

7.1 Companion Reports

Morris et al (1991) describe the Moling Drilling System developed and tested in the UK. Allen (1988) and Herbert and Rastall (1991) describe the work done using the telescoped-jetting drilling system in Malaysia and Zimbabwe respectively.

Herbert (1990) describes an analytical technique for predicting when the 1½" diameter adits used by moling will throttle the flow into the collector well. The criteria so developed can be used to select which drilling system is appropriate for construction of collector wells.

The first part of this report is primarily concerned with the construction of collector wells on the sides of sand rivers, their shafts being constructed in the relatively low permeability material of the river banks.

7.2 Suitability of Collector Wells

Collector wells are only of use in shallow, thin aquifers or where fresh water lenses must be skimmed from above deeper saline water.

Moling cannot easily penetrate coarse sands and telescoped jetting cannot penetrate cobbly, coarse sands.

This report shows that sand rivers are occasionally underlain by weathered hard rock. In this case it is possible to air-hammer adits and their yield will depend on the type of weathered rock penetrated.

7.3 Types of Alluvium

<u>River Channel Sands:</u> Sand rivers or wadis, which are seasonally flooded river channel sands, are common in arid areas including Southern Africa. These channel deposits can yield a great deal of water and construction of dug wells in them will consequently need heavy dewatering pumping capacity and protection of works against seasonal flooding. A collector well's yield, constructed in the river bed, could be huge but construction works will be expensive.

There are places in Zimbabwe, the south and south-west borders (the Sashe and Limpopo rivers) and more so in Botswana, where the river channel deposits can be exploited cheaply by constructing collector wells sited above the river channels on the river banks, thus avoiding the dug well construction difficulties mentioned above. The first part of this report describes experiments to determine the difficulties of drilling adits through the low permeability banks of the sand rivers and out into the bottom of the sandy channel deposits.

Alluvial Plains: River terraces, extensive flood plains and colluvial deposits can all be amenable to development by collector wells. Their composition can be complex and will depend on their genesis. For example, coarse paleo-river channel deposits may be found at depth. In general there is a likelihood that coarse deposits do occur at depth. It should always be remembered that the horizontal adits of a collector well must penetrate the most permeable layers or they will have only a marginal effect on well yield. The work described by Herbert and Rastall (1991) was done on two such alluvial plains in Zimbabwe. In one plain a very coarse, thin, cobbly layer was found at its base, which could not be drilled by jetting, and the dug well's yield could not be enhanced by horizontal drilling. At the other site in NW Zimbabwe, a thin highly permeable layer was found at the base of the plain but the jetting tapped through this and a significant yield was obtained.

7.4 Selection of Drilling Technique

Fig. 13 was derived from the criteria developed in Herbert (1990) and from the experience gained during the project. Use of Fig. 13 will allow selection of the best means of development of groundwater.

The thickness of 2 m in the first decision-diamond is somewhat arbitrary. A widespread aquifer 1 m thick would be sufficient for drilling of laterals but if the bedrock is undulating there will be limits to the length of adit that can be drilled.

7.5 Drilling Costs

Moling Equipment: Morris et al. (1991) give the cost of a thrust-boring equipment package, excluding service vehicle and 38 mm ID well screen. This is repeated in the table below. Morris also estimates that, including mobilisation, the drilling of a collector well will take nine days.

Budget Estimate: Equipment Package

Thrust-boring equipment package to convert dug wells lined with concrete caisson-type rings into collector wells by screen-within-casing method. Excludes service vehicle (4WD utility/pickup).

Item	Approx. Cost £ (11/91)
Hydraulic thrust-borer c/w wellhead powerpack (e.g. PD-4 Powrmole and Power Stinger)	7,500
Boring tools (35 m sets of push-rods and HD temp. casing)	5,000
Other accessories (slings, tools, shuttering, etc)	1,000
Site construction equipment (drill, portable generator, travelling arm, winch, clean water pump)	2,500
Safety/amenity equipment (blower ventilator, gas sensor, harness, ladder, etc)	1,500
HD hydraulic dewatering pump c/w diesel powerpack (e.g. Flygt HB2102 3" diameter and STI unit)	5,000

Item		Approx. Cost £ (11/91)
2250 l water bowser c/w semi-rigid hose and fittings		2,000
HD double-axle 2 tonne trailer		2,000
	Sub-total	£26,500
Spares (at 15% for 1 years operations)		3,975
	TOTAL ca.	£30,500

Telescoped-Jetting: The latest quote for a drilling rig was received in March 1990 and is given below. Four such rigs have been constructed by the same manufacturer throughout the course of this project.

		£ (1990)
The rig		45,900
Drill string, bits and hammers		6,400
Dewatering pump system	ca.	5,000
Second-hand Bedford 4 x 4 truck (essential for rapid use of this relatively heavy rig)		7,000
	Sub-total	64,300
Spares for 1 years operation		9,645
	TOTAL	£73,945

The above costs are selected so as to be roughly comparable with the costs of the moling method but note that the costs derived are for different years. Moling can be seen to be much cheaper than jetting.

Screening: Neither set of costs include the screen left in the laterals. These would be best purchased locally and would need to have 7% open area of slotting of the appropriate slot width. For moling 1½" ID mesh-wrapped, cheap plastic pipe would be adequate. For telescoped-jetting 2" ID heavy-duty, unwrapped screen would be necessary.

Typically 90 m of screen would be required at an extensive alluvial plains site and one-half that at a sand river site.

Recurrent Drilling Costs: Spares for a rig will run at about 15% per annum and the life of the rig would be up to 10 years. In Zimbabwe, a senior driller with three local labourers were used for the duration of the horizontal drilling. The drilling is relatively dirty work compared to surface drilling and special rates of pay will need to be negotiated. In addition fuel for the compressor would need to be purchased.

Summary of Drilling Costs: Using the figures above (without allowing for inflation to present date) and assuming 20 wells can be drilled per year (allowing for breakdowns, holidays, etc) the following drilling costs per well are estimated:

	Moling £Cost/well	Telescoped Jetting £Cost/well
Offshore capital cost of equipment	132	321
P.V. of spares at 15% of capital/yr at interest rate of 5%	153	372
TOTAL	£285	£693

The local costs will vary from country to country and as stated above will include staff costs (1 driller + 3 local labourers), fuel (marginal) and more importantly ca. 90 m of screen for the adits.

7.6 Construction of Dug Wells with Costs

For this project 2 m ID diameter wells were required to allow horizontal drilling.

There are many ways and materials with which to construct such dug wells and not all have been used in this project.

The choice of construction method used depends primarily on the type of material dug through and this in turn affects the drilling method, moling or telescoped-jetting.

Consolidated Material: The dug wells constructed through weathered bedrock on the banks of the sand rivers in Botswana and those on the two alluvial plains in Zimbabwe were constructed by Open Hole Excavation. That is to say, the shaft was deepened by digging and the walls of the shaft at the base of the well temporarily needed no support. The lining used was lowered by gradually undercutting it as the shaft was lowered. That this could be done in the alluvium was a surprise. Presumably the high silt content of the alluvium gave some cohesion and the shaft walls were able to remain standing until at least the lining was lowered. Small slumps did occur but not often enough to affect progress despite the fact that there was a significant excess head of water in the material. A motorised winch or crane was required for rapid removal of spoil. In one well dug in the weathered hard rock in Botswana 5 m of hard bedrock had to be penetrated. Blasting was used successfully to achieve this.

Lining: Linings of reinforced brickwork and prefabricated concrete blocks were experimented with. These linings required skilled work and took a relatively long time to construct. The most convenient dug well lining was found to be corrugated galvanised 3 mm thick iron sheeting (ARMCO lining). A foreman using three casual labourers and a motorised winch can construct a 2 m diameter Armco-lined well to 15 m in 1½ months. A compressor is required to drive the dewatering pump and a hydraulic winch. The costing, given below, assumes the compressor is used continuously on dug well construction and is not hired-in.

Cost of Armco-lined Dug Well: The cost of a dug well at Makusia School, which was sited on a raised embankment next to the River Lundi in S. Zimbabwe is given below. The well was 16 m deep with a water table at 14 m. The well was dug in late 1989 and costs quoted relate to that date. At the time Z$3.11 was equivalent to £1 sterling.

The costs are of course peculiar to Zimbabwe in 1989 and care will need to be taken to translate them into modern costs at a different location. At that time the cost of the 2 m diameter dug well was £4387. Using the thinner lining option the cost would have been £3022.

Dug Well Costs, Makusia School (Lower Veld Alluvium)
(Zimbabwe Dollars, Z$)

	Salary**	Diesel	Compressor*	Misc.	Totals
August	1195	-	-	-	1195
September	932	504	-	100	1536
October	335	126	437	-	898
					3629
Additional Cost of Armco Lining*** 16 m @ Z$626/m					10016
∴ Total cost per dug well for a rolling project					13645

NB: * Compressor costs quoted are for assumed purchase then use over a 10-year period. Assuming spares at 5% per annum, construction of nine wells per annum and an interest rate of 5%, the compressor cost per well is Z$437.

** The above represents 44 days digging, 21 days preparing site, transporting equipment, holidays, etc.

*** 3 mm thick lining was used at a cost of £184/m (Z$626/m). The work has shown only 2 mm lining is necessary at a cost of £106/m (Z$330/m). These costs are inclusive of shipping.

Unconsolidated Material: Shafts cannot be sunk into clean saturated sands in open-hole as the walls will collapse. Construction is carried out by shaft sinking. In shaft sinking, material is removed from the base of the shaft whilst simultaneously the shaft sinks under its own weight. This process has been in use for many years. Cochran (1937) describes the construction of 300 such wells in Nigeria which used reinforced concrete lining for the shaft.

In the early stages of this project the Geological Survey of Malaysia let a contract for the construction of two dug wells. Their contractor used ready-made 1950 mm ID 6" thick reinforced concrete rings. The first well was 4.5 m deep and the second was 7 m. The work took only 18 days. No details of the construction techniques are available. The GSM were charged ca. £10,000 for this work. Whilst being convenient and rapid this was expensive and cheaper methods would have to be developed for regular use in the developing world.

The only other dug wells that were constructed in unconsolidated material for the project were at Efford, Hampshire and Carmer Wood, Lincolnshire UK. Although the details of construction differed, mechanical excavation within 130 mm thick reinforced concrete rings was employed at both sites. At Efford material was removed by an electrosubmersible sand and gravel pump (Photo Figure 14A and Morris, 1989); at Carmer Wood a hydraulic bucket excavator was used (Photo Figure 14B, C and Morris & Talbot, 1990).

At both sites the principal technical obstacle during construction of the well shafts themselves proved to be the provision of a safe, stable, impermeable floor which would allow the well shaft to be dewatered safely for thrust boring operation. A collector well in unconsolidated sands would differ from a traditional chamber-ring dug well in this important respect, and a floor installation design would be needed in a well construction programme for those shaft-only wells earmarked for subsequent conversion. Normally shaft-only dug wells are finished with a gravel floor, for reasons both of economy and to increase potential inflow area.

Even with this proviso, the trial well shafts sunk at these two sites differed markedly from those which were used with more traditional pipe-jacking methods to construct Ranney, Fehlmann or Preussag type collector wells. The latter need powerful jacks because they are designed to install arrays of collectors of relatively large diameter in heterogeneous, medium to coarse, alluvium. As a result, stringent design criteria are required for the main shaft to enable the well to be sunk safely to depths of 40 m or more, with static heads outside the shaft of several tens of metres. As jacking forces can approach 1000 kN/m^2 in these more traditional collector wells, design wall thicknesses of about 10% of the diameter are common.

Thrust-boring can be employed in concrete chamber-ring dug wells of much simpler design and cheaper construction because:

(a) saturated zone penetration is limited to less than 3 m, so static heads outside the shaft are low,

(b) resistance to penetration is much lower in loose uniform sands than in coarser mixed alluvium,

(c) the thrust-borers are much lighter, so maximum jacking forces can be controlled to not exceed 100 kN/m^2.

Suggestion for Future: It is possible that shaft sinking could be achieved using Armco lining combined with a sludge pump, as used at Efford, in high permeability mobile sands. If this type of construction were successful then material costs would be similar to those of dug wells in consolidated material, quoted earlier. Also, it could be that construction times would be significantly reduced. Excavation below the water table by sludge pumping in ideal conditions would be a matter of days.

7.7 Special Requirements of Lining for Moling

Moling imparts a thrust of up to 10 T. This force must be withstood. For all the work done in the UK the concrete rings used withstood the force successfully, the load being spread over a 90° sector of the reinforced concrete casing.

In consolidated material this requirement will pose no problem, the well walls being firm enough to withstand the force. In unconsolidated material care must be taken to ensure the lining is strong enough to take such a force.

The ultimate stress of mild steel is ca. 30 Tns/ins^2. If the thrust is spread over a 12" depth of arc within the well shaft the cross sectional area resisting the thrust can be conservatively estimated as 2 x 12 x (3/25.4) ins^2 or 2.8 ins^2. Thus 3 mm thick Armco lining will be more than adequate to meet the thrust requirements of moling.

REFERENCES

Allen, D J (1988) Construction and testing of two collector wells at Tampin, Malaysia, April-July 1988. BGS Technical Report WD/88/20, Wallingford, UK.

Barker, J A (1989) Programs to simulate and analyse pumping tests in large-diameter wells. BGS Technical Report WD/89/23, Wallingford, UK.

Cochran, H A (1937) The techniques of well sinking in Nigeria. Geological Survey of Nigeria, Bulletin No. 16.

Geotechnical Consulting Services [PTY] Ltd (1990) Borehole siting, supervision of drilling, construction and pumping test works in Dimaje, Lepokole, Mapoka, Chadibe, Borolong/Thalogang Villages. Draft Inception Report, CEP IV. Gaborone, Botswana.

Herbert, R (1990) Dug well vs. collector well performance: ODA R & D Project No. 90/11, development of horizontal drilling rig for alluvial aquifers of high permeability. BGS Technical Report WD/90/34, Wallingford, UK.

Herbert, R & Rastall, P (1991) Development of horizontal drilling for alluvial aquifers of high permeability. ODA/BGS R & D Project (91/7): Final Report on Work in Zimbabwe. BGS Technical Report WD/91/50, Wallingford, UK.

Morris, B L (1989) Radial wells in alluvium project - Preliminary trenchless moling trials at Efford Experimental Horticulture Station. BGS Technical Report WD/89/35R, Wallingford, UK.

Morris, B L & Talbot, J C (1990) Radial collector wells in alluvium project: progress report #1 on trenchless moling trials at Carmer Wood, Laughton, Lincolnshire. BGS Technical Report WD/90/32, Wallingford, UK.

Morris, B L, Talbot, J C & Macdonald, D M J (1991) Radial collector wells in alluvium project: Final Report (#3) on trenchless moling trials at Carmer Wood, Laughton, Lincolnshire. BGS Technical Report WD/91/69, Wallingford, UK.

Nord, M (1985) Sand Rivers of Botswana. Results from Phase 2 of the Sand Rivers Project sponsored by the Swedish International Development Authority (SIDA). [Report held by Department of Water Affairs, Botswana].

Wikner, T (1980) Sand Rivers of Botswana. Results from Phase 1 of the Sand Rivers Project sponsored by the Swedish International Development Authority (SIDA). [Report held by Department of Water Affairs, Botswana].

1 SAMPLE NUMBER SHASHI DEPTH

SUB-SAMPLE > 16MM DRY WEIGHT = 0.0

SUB-SAMPLE < 16MM WET WEIGHT = 604.6

MOISTURE CONTROL SAMPLE WET	=	0.1
ANALYSIS SAMPLE WET	=	604.5
PIPETTE SAMPLE WET	=	0.0
RESIDUAL SAMPLE WET	=	0.0
MOISTURE CONTROL SAMPLE DRY	=	0.1
SAND ANALYSIS SAMPLE DRY	=	574.9
FINE GRAVEL ANALYSIS SAMPLE DRY	=	29.6
RIFFLED SAND ANALYSIS SAMPLE DRY	=	574.9

SIEVING ERRORS : SAND 0.400%
FINE GRAVEL 0.000%
COARSE GRAVEL 0.000%
OVERALL 0.381%

MEAN	0.15
STANDARD DEVIATION	1.25
SKEWNESS	-0.3276
KURTOSIS	0.8122

MEASURES OF SKEWNESS (GAMMA 1) AND KURTOSIS (GAMMA 2) ARE AS DEFINED BY KENDALL AND STEWART - THE ADVANCED THEORY OF STATISTICS, VOLUME 1 (FOURTH EDITION) - PAGE 88

SPECIFIC SURFACE U = 16.057
PERMEABILITY ESTIMATE K = 50000/(U*U) = 193.93 M/DAY

1 SAMPLE NUMBER SHASHI DEPTH

PARTICLE DIAMETERS (PHI)	(MM)	WEIGHT IN SIEVE	ANALYSIS SAMPLE	WHOLE SAMPLE	% BY WEIGHT	CUM % PASSING	CUM % RETAINED
PHI < -6.0	OVER 63.0	0.00	0.00	0.00	0.00	100.00	0.00
-6.0 TO -5.5	63.0 TO 45.0	0.00	0.00	0.00	0.00	100.00	0.00
-5.5 TO -5.0	45.0 TO 31.5	0.00	0.00	0.00	0.00	100.00	0.00
-5.0 TO -4.5	31.5 TO 22.4	0.00	0.00	0.00	0.00	100.00	0.00
-4.5 TO -4.0	22.4 TO 16.0	0.00	0.00	0.00	0.00	100.00	0.00
-4.0 TO -3.5	16.0 TO 11.2	7.40	7.40	7.40	1.22	98.78	1.22
-3.5 TO -3.0	11.2 TO 8.0	3.00	3.00	3.00	0.50	98.28	1.72
-3.0 TO -2.5	8.0 TO 5.6	7.10	7.10	7.10	1.17	97.11	2.89
-2.5 TO -2.0	5.6 TO 4.0	12.10	12.10	12.10	2.00	95.10	4.90
-2.0 TO -1.5	4.0 TO 2.8	22.50	22.50	22.50	3.72	91.38	8.62
-1.5 TO -1.0	2.8 TO 2.0	43.10	43.10	43.11	7.13	84.25	15.75
-1.0 TO -0.5	2.0 TO 1.4	67.60	67.60	67.61	11.18	73.07	26.93
-0.5 TO 0.0	1.4 TO 1.0	93.70	93.70	93.72	15.50	57.57	42.43
0.0 TO +0.5	1.0 TO .71	107.20	107.20	107.22	17.73	39.83	60.17
+0.5 TO +1.0	.71 TO .5	98.00	98.00	98.02	16.21	23.62	76.38
+1.0 TO +1.5	.5 TO .355	68.20	68.20	68.21	11.28	12.34	87.66
+1.5 TO +2.0	.355 TO .25	43.60	43.60	43.61	7.21	5.13	94.87
+2.0 TO +2.5	.25 TO .18	19.10	19.10	19.10	3.16	1.97	98.03
+2.5 TO +3.0	.18 TO .125	7.20	7.20	7.20	1.19	0.78	99.22
+3.0 TO +3.5	.125 TO .09	1.70	1.70	1.70	0.28	0.50	99.50
+3.5 TO +4.0	.09 TO .063	0.40	0.40	0.40	0.07	0.43	99.57
+4.0 < PHI	UNDER .063	0.30		(BY DIFF.) 2.60	0.43	0.00	100.00
				TOT DRY WT: 604.60			

COBBLES AND BOULDERS	0.00
COARSE GRAVEL	0.00
MEDIUM GRAVEL	2.70
FINE GRAVEL	13.05
COARSE SAND	52.91
MEDIUM SAND	28.47
FINE SAND	2.44
MUD	0.43

Table 1. Sieving Results and Analysis of Surface Sand Sample at Borolong.

Time (mins)	Radius (m)	Drawdown (m)
1	5	0
1	10	0
2	5	0
2	10	0
3	5	0.01
3	10	0.005
5	5	0.015
5	10	0.01
10	5	0.02
10	10	0.01
20	5	0.025
20	10	0.01
40	5	0.03
40	10	0.015
60	5	0.035
60	10	0.02
90	5	0.04
90	10	0.025

Table 2. Time-Drawdown Observations during Pumping Test.

Project : Botswana
Organization : B.G.S.

Test : Borolong - 16/07/92

Constant Pumping Rate = 45.3 [m3/day]
Distance from Pumping Well = 1.00 [m]
Type of Aquifer = UNCONFINED
Initial Saturated Thickness = 2.52 [m]
Type of Input Data = DRAWDOWN
Well Type = DUG
Well Radius to Face of Aquifer = 1.00 [m]
Well Radius of Storage Portion = 1.00 [m]
Pumping Duration = 450. [min]
Test Duration = 610. [min]

No	Time [min]	Drawdown [m]	No	Time [min]	Drawdown [m]	No	Time [min]	Drawdown [m]
1	0.	0.01	31	50.	0.10	61	456.	0.51
2	1.	0.01	32	60.	0.11	62	457.	0.51
3	1.	0.02	33	70.	0.14	63	458.	0.50
4	2.	0.02	34	80.	0.16	64	459.	0.50
5	2.	0.02	35	90.	0.17	65	460.	0.49
6	3.	0.02	36	100.	0.18	66	462.	0.49
7	3.	0.03	37	120.	0.20	67	464.	0.47
8	3.	0.03	38	140.	0.22	68	466.	0.46
9	4.	0.03	39	160.	0.24	69	468.	0.45
10	4.	0.03	40	180.	0.26	70	470.	0.44
11	5.	0.03	41	200.	0.28	71	472.	0.43
12	6.	0.03	42	220.	0.30	72	474.	0.42
13	7.	0.03	43	240.	0.31	73	476.	0.46
14	8.	0.03	44	260.	0.33	74	478.	0.41
15	9.	0.03	45	280.	0.35	75	480.	0.40
16	10.	0.03	46	300.	0.37	76	482.	0.39
17	12.	0.03	47	320.	0.39	77	485.	0.38
18	14.	0.04	48	350.	0.43	78	490.	0.36
19	16.	0.04	49	400.	0.47	79	495.	0.34
20	18.	0.04	50	450.	0.53	80	500.	0.32
21	20.	0.05	51	450.	0.54	81	510.	0.31
22	22.	0.05	52	451.	0.54	82	520.	0.27
23	24.	0.06	53	451.	0.54	83	530.	0.24
24	26.	0.06	54	452.	0.53	84	540.	0.22
25	28.	0.07	55	452.	0.53	85	550.	0.21
26	30.	0.07	56	453.	0.53	86	570.	0.18
27	32.	0.07	57	453.	0.53	87	590.	0.14
28	35.	0.08	58	454.	0.52	88	610.	0.14
29	40.	0.09	59	454.	0.52			
30	45.	0.10	60	455.	0.52			

Table 3. Borolong Collector Well Pumping Test Data.

MINISTRY OF MINERAL RESOURCES
AND WATER AFFAIRS
REPORT ON THE EXAMINATION
OF WATER

Village: BOROLONG
Location:
District: CENTRAL

Medical Region No 12

Date Sampled: 27/07/92
Date Received: 30/07/92
Date of Report: 13/08/92

Analyst: KMK

Sample Identification
Incoming No: CEN/92/431
Borehole No: **Depth(m):** -9.00 **Hours:** -9.00
Source Code: PW

CO_3 : 5	Br : -9.00	PO_4 : -9.00	
HCO_3 : 85	NO_2 : -9.00	NH_4 : -9.00	
Cl : 5.4			
SO_4 : 16.0	Field Temp : -9.0	Field DO : -9.0	
NO_3 : 0.0	Field EC : -9	Field pH : -9.00	
F : 0.16			
	Lab EC : 211	Lab pH : 8.10	
Na : 7.0	TDS : 121	Susp. Solid: -9	
K : 6.6	SiO_2 : -9	NTU : -9	
Ca : 22.0			
Mg : 6.2	**CALCULATED PARAMETERS**		
Fe : 0.32			
Mn : 0.00	Hardness (mg/l $CaCO_3$) : 81		
	Alkalinity (mg/l $CaCO_3$) : 78		
Ionic Balance %: -0.948	Saturation Index ($CaCO_3$): -0.13		

Missing data = -9

COMMENTS: Corrosivity Classification 2

Ion concentrations are satisfactory for drinking water. Moderately soft.

SIGNATURE:

Table 4. Chemical Analysis of Water Sample at Borolong.

MINISTRY OF MINERAL RESOURCES AND WATER AFFAIRS
REPORT ON THE EXAMINATION OF WATER

Village: BOROLONG
Location: SHASHE RIVER
District: CENTRAL

Medical Region No 12

Date Sampled: 27/07/92
Date Received: 30/07/92
Date of Report: 13/08/92

Analyst: KMK

Sample Identification
Incoming No: CEN/92/433
Borehole No:
Depth(m): -9.00
Hours: -9.00
Source Code: RIV

CO_3 : 0	Br : -9.00	PO_4 : -9.00	
HCO_3 : 141	NO_2 : -9.00	NH_4 : -9.00	
Cl : 4.4			
SO_4 : 4.5	Field Temp : -9.0	Field DO : -9.0	
NO_3 : 0.0	Field EC : -9	Field pH : -9.00	
F : 0.13			
	Lab EC : 228	Lab pH : 7.30	
Na : 5.0	TDS : 115	Susp. Solid: -9	
K : 3.8	SiO_2 : -9	NTU : -9	
Ca : 33.6			
Mg : 7.4	CALCULATED PARAMETERS		
Fe : 0.64			
Mn : 0.00	Hardness (mg/l $CaCO_3$) : 116		
	Alkalinity (mg/l $CaCO_3$) : 116		
Ionic Balance %: -1.704	Saturation Index ($CaCO_3$): 0.54		

Missing data = -9

COMMENTS: Corrosivity Classification 3

Ion concentrations are satisfactory for drinking water. Slightly hard.

SIGNATURE:

Table 5. Second Chemical Analysis of Water Sample at Borolong.

Project : Botswana
Organization : B.G.S.

Test : Chidibie - 17/07/92

Constant Pumping Rate = 45.3 [m3/day]
Distance from Pumping Well = 1.00 [m]
Type of Aquifer = UNCONFINED
Initial Saturated Thickness = 3.44 [m]
Type of Input Data = DRAWDOWN
Well Type = DUG
Well Radius to Face of Aquifer = 1.00 [m]
Well Radius of Storage Portion = 1.00 [m]
Pumping Duration = 500. [min]
Test Duration = 640. [min]

Transmissivity = 139.00000 [m2/day]
Storage Coefficient = 0.40E-02
Standard Deviation = 0.0148 [m]

Number of Points = 87 of 87

No	Time [min]	Drawdown [m]	Computed Drawdown	Diffe- rence
1	0.	0.04	0.01	0.03
2	1.	0.04	0.02	0.02
3	1.	0.04	0.02	0.02
4	2.	0.05	0.02	0.03
5	2.	0.05	0.02	0.02
6	3.	0.05	0.03	0.02
7	3.	0.05	0.03	0.02
8	4.	0.06	0.03	0.03
9	4.	0.06	0.04	0.02
10	5.	0.06	0.04	0.02
11	6.	0.07	0.04	0.03
12	7.	0.07	0.05	0.02
13	8.	0.07	0.05	0.01
14	9.	0.08	0.06	0.02
15	10.	0.08	0.07	0.01
16	12.	0.09	0.08	0.01
17	14.	0.10	0.09	0.01
18	16.	0.11	0.09	0.01
19	18.	0.11	0.10	0.01
20	20.	0.12	0.11	0.01
21	22.	0.13	0.12	0.01
22	24.	0.13	0.12	0.00
23	26.	0.14	0.13	0.01
24	28.	0.15	0.14	0.01
25	30.	0.15	0.14	0.00
26	32.	0.16	0.15	0.01
27	35.	0.17	0.15	0.01
28	40.	0.17	0.16	0.00

Table 6. Chadibe Collector Well Pumping Test Data and Attempt at Analytical Analysis.

No	Time [min]	Drawdown [m]	Computed Drawdown	Diffe- rence
29	45.	0.18	0.17	0.01
30	50.	0.18	0.18	0.00
31	60.	0.20	0.20	0.01
32	70.	0.21	0.21	0.01
33	80.	0.22	0.21	0.01
34	90.	0.23	0.22	0.01
35	100.	0.24	0.23	0.01
36	120.	0.25	0.24	0.01
37	140.	0.26	0.24	0.02
38	160.	0.26	0.25	0.01
39	180.	0.27	0.25	0.02
40	200.	0.27	0.26	0.01
41	220.	0.27	0.26	0.01
42	240.	0.28	0.26	0.01
43	260.	0.28	0.27	0.01
44	280.	0.28	0.27	0.01
45	300.	0.28	0.27	0.01
46	320.	0.28	0.27	0.00
47	350.	0.28	0.28	0.00
48	400.	0.28	0.28	0.00
49	450.	0.28	0.28	-0.01
50	500.	0.28	0.29	-0.01
51	500.	0.28	0.29	-0.01
52	501.	0.28	0.29	-0.01
53	501.	0.28	0.29	-0.01
54	502.	0.28	0.29	-0.01
55	502.	0.27	0.29	-0.02
56	503.	0.27	0.29	-0.02
57	503.	0.27	0.29	-0.02
58	504.	0.26	0.29	-0.03
59	504.	0.26	0.29	-0.03
60	505.	0.26	0.28	-0.02
61	506.	0.25	0.27	-0.02
62	507.	0.25	0.27	-0.02
63	508.	0.24	0.26	-0.02
64	509.	0.23	0.25	-0.02
65	510.	0.23	0.24	-0.01
66	512.	0.22	0.23	-0.01
67	514.	0.21	0.22	-0.01
68	516.	0.21	0.21	0.00
69	518.	0.20	0.20	0.01
70	520.	0.18	0.19	-0.01
71	522.	0.18	0.18	0.00
72	524.	0.18	0.17	0.01
73	526.	0.18	0.17	0.01
74	528.	0.18	0.16	0.02
75	530.	0.17	0.15	0.01
76	532.	0.17	0.15	0.02
77	535.	0.16	0.14	0.02
78	540.	0.15	0.13	0.02

Table 6 (Cont'd)

No	Time [min]	Drawdown [m]	Computed Drawdown	Diffe-rence
79	545.	0.14	0.12	0.02
80	550.	0.13	0.11	0.02
81	560.	0.11	0.09	0.01
82	570.	0.10	0.08	0.01
83	580.	0.09	0.08	0.01
84	590.	0.08	0.07	0.01
85	600.	0.07	0.06	0.00
86	620.	0.06	0.06	0.00
87	640.	0.05	0.05	0.00

Table 6 (Cont'd)

MINISTRY OF MINERAL RESOURCES AND WATER AFFAIRS
REPORT ON THE EXAMINATION OF WATER

Village: CHADIBE
Location: SHASHE RIVER
District: CENTRAL

Medical Region No 12

Date Sampled: 27/07/92
Date Received: 30/07/92
Date of Report: 13/08/92

Analyst: KMK

Sample Identification
Incoming No: CEN/92/430
Borehole No: **Depth(m):** -9.00 **Hours:** -9.00
Source Code: RIV

CO_3 : 0	Br : -9.00	PO_4 : -9.00	
HCO_3 : 100	NO_2 : -9.00	NH_4 : -9.00	
Cl : 3.0			
SO_4 : 3.7	Field Temp : -9.0	Field DO : -9.0	
NO_3 : 1.1	Field EC : -9	Field pH : -9.00	
F : 0.16			
	Lab EC : 169	Lab pH : 7.04	
Na : 4.8	TDS : 94	Susp. Solid: -9	
K : 3.2	SiO_2 : -9	NTU : -9	
Ca : 22.6			
Mg : 5.6	CALCULATED PARAMETERS		
Fe : 0.16			
Mn : 0.00	Hardness (mg/l $CaCO_3$) : 80		
	Alkalinity (mg/l $CaCO_3$) : 82		
Ionic Balance %: -1.573	Saturation Index ($CaCO_3$): -1.10		

Missing data = -9

COMMENTS: Corrosivity Classification 4

Ion concentrations are satisfactory for drinking water. Moderately soft water.

SIGNATURE:

Table 7. Chemical Analysis of Water Sample at Chadibe.

MINISTRY OF MINERAL RESOURCES AND WATER AFFAIRS
REPORT ON THE EXAMINATION OF WATER

Village: CHADIBE
Location:
District: CENTRAL

Medical Region No 12

Date Sampled: 27/07/92
Date Received: 30/07/92
Date of Report: 13/08/92

Analyst: KMK

Sample Identification
Incoming No: CEN/92/432
Borehole No: Depth(m): -9.00 Hours: -9.00
Source Code: PW

CO_3	0	Br	-9.00	PO_4	-9.00
HCO_3	109	NO_2	-9.00	NH_4	-9.00
Cl	3.4				
SO_4	3.3	Field Temp	-9.0	Field DO	-9.0
NO_3	1.0	Field EC	-9	Field pH	-9.00
F	0.16				
		Lab EC	184	Lab pH	6.96
Na	4.6	TDS	113	Susp. Solid	-9
K	3.7	SiO_2	-9	NTU	-9
Ca	24.2				
Mg	5.1	CALCULATED PARAMETERS			
Fe	0.30				
Mn	0.00	Hardness (mg/l $CaCO_3$)	82		
		Alkalinity (mg/l $CaCO_3$)	89		
Ionic Balance %:	1.092	Saturation Index ($CaCO_3$)	-1.12		

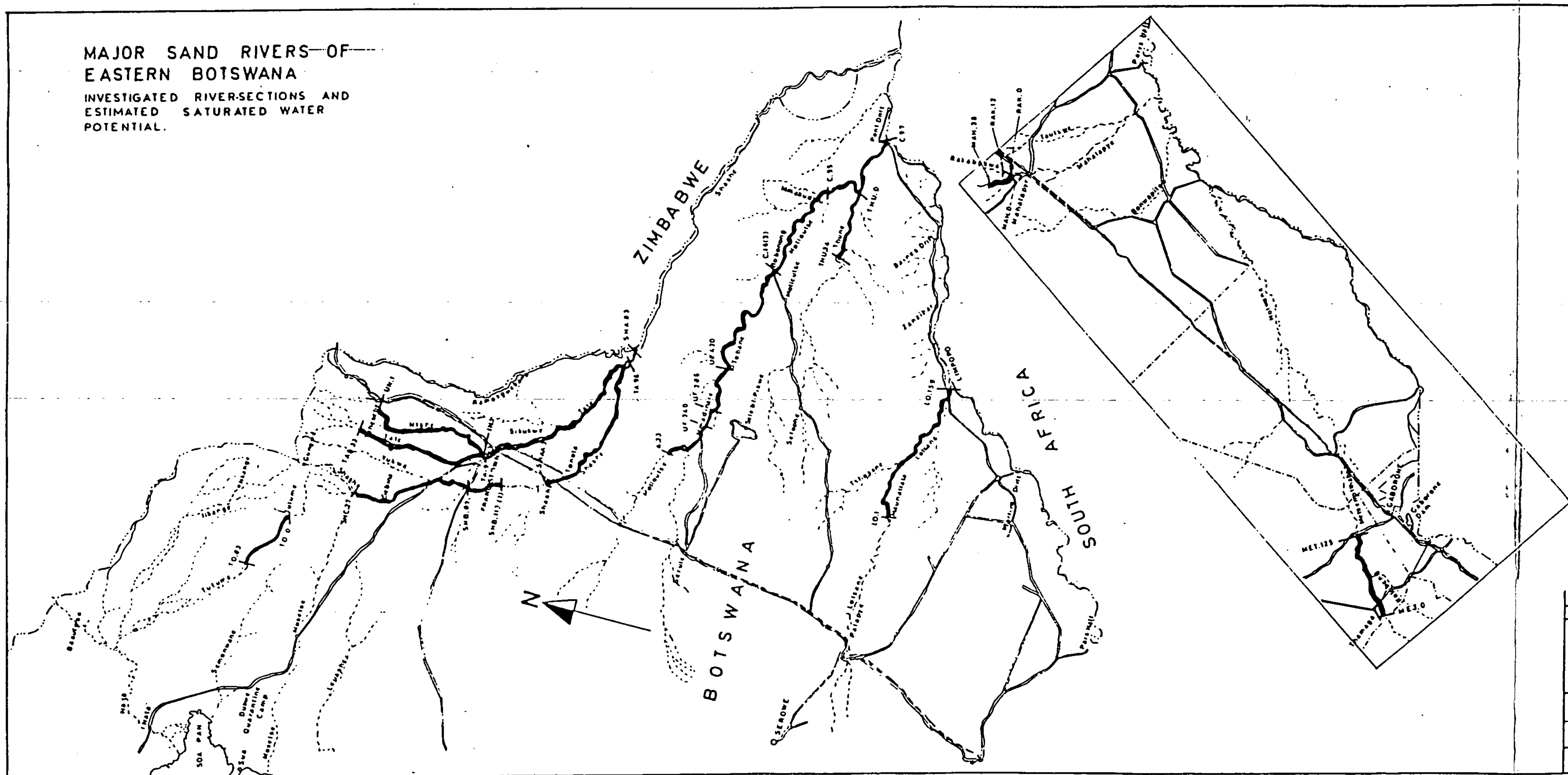
Missing data = -9

COMMENTS: Corrosivity Classification 4

Ion concentrations are satisfactory for drinking water. Moderately soft water.

SIGNATURE:

Table 8. Second Chemical Analysis of Water Sample at Chadibe,



INVESTIGATED SAND RIVERS AND ESTIMATED SATURATED WATER POTENTIAL

River	Section	Length (Km)	Tot.res. $(10^3 m^3)$	Sat.res.per Km $(10^3 m^3)$
Tutume	TO 0 - TO 83	29,5	580	19,7
Ntshe	IN 1 - UI 1	65	1100	17
Tati, u.str F'town	TA 9 - TAB 53	74	840	11,4
Tati, d.str F'town	TA 9 - TA 96	87	2100	24
Shashe	SHC 27 - SHB 87	54,9	835	15
	SHB 87 - SHB 113(1)	12,9	360	28
d.str Tonota	SHAA 3 - SHA 83	76,5	4490	58,7
Motloutse	A 23 - UF 224	23,7	870	36,7
	UF 240 - UF 286	7,5	150	20
	UF 286 - UF 430	21,7	650	30
	UF 430 - C 16 (3)	81	4300	53
	C 16(3) - C 97	78,9	3400	43
	(C55 - C97)	40	2570	64
Thune	THU 0 - THU 34	33,1	610	18
Lotsane	LO 1 - LO 159	78,9	500	6
Mahalapye	MAH 0 - MAH 38	13,7	290	21
Bakabesva	RAK 0 - RAK 12	6	93	15,5
Metse-motlhaba	MET 0 - MET 125	42,9	680	16

DATE	REV.	NO.	CONCERNING	SIGN

DEPARTMENT OF WATER AFFAIRS GABORONE
PRIVATE BAG 0029, PHONE 52341
TELEGRAM: WATER

SAND RIVERS PROJECT

LOCATION PLAN

Surveyed	Drawn	SCALE 1:1000,000	Fig. 1
Plotted	Traced	DRG. NR.	REV
Approved T. Wilkner	Date 800310	WSRP 80/1	

Figure 1. Survey of sand rivers and their potential reserves in Botswana (copied from Wilkner, 1980)

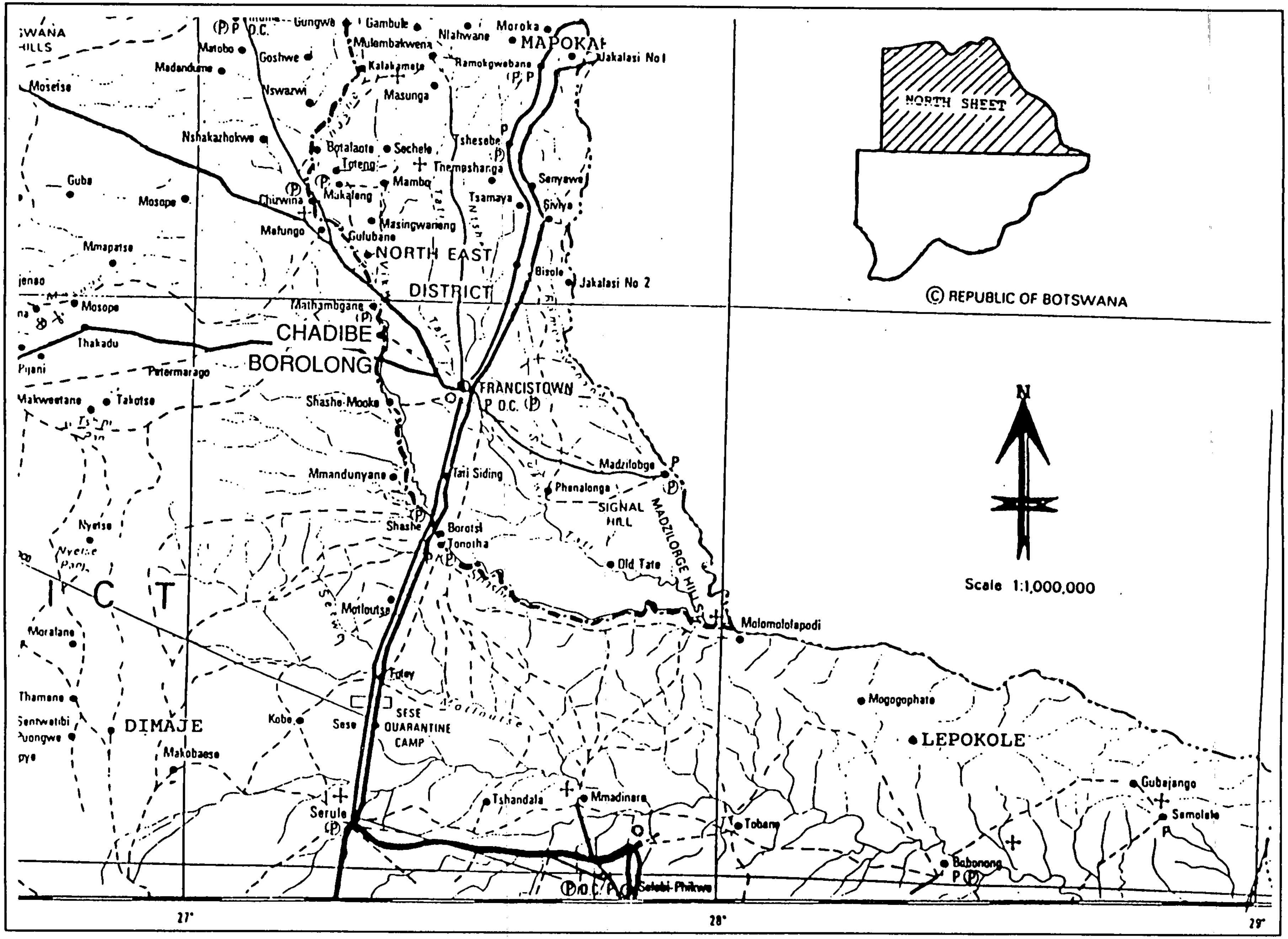


Figure 2. The locations of Chadibe and Borolong villages

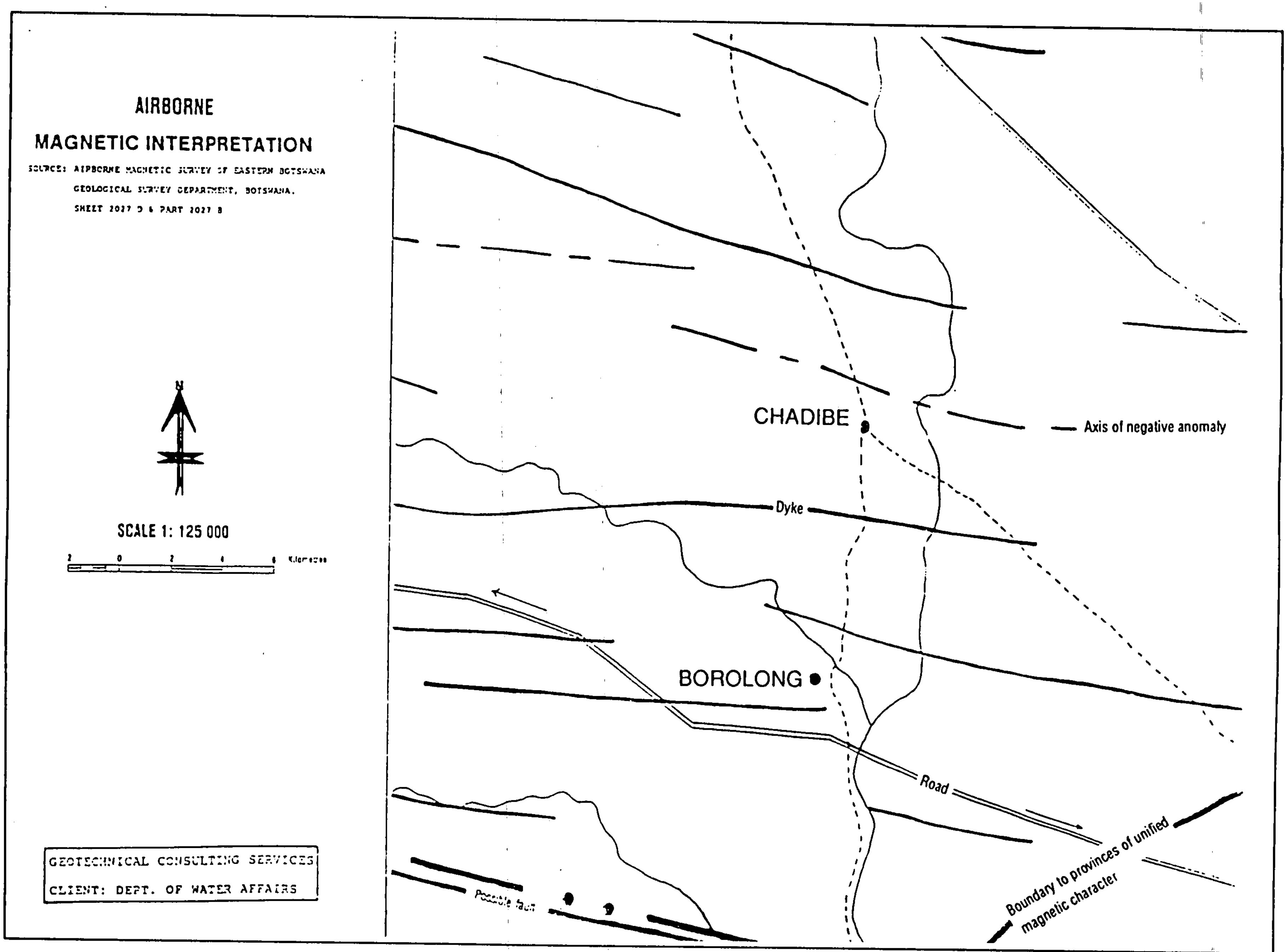


Figure 3. Major magnetic anomalies in the region of Borolong village

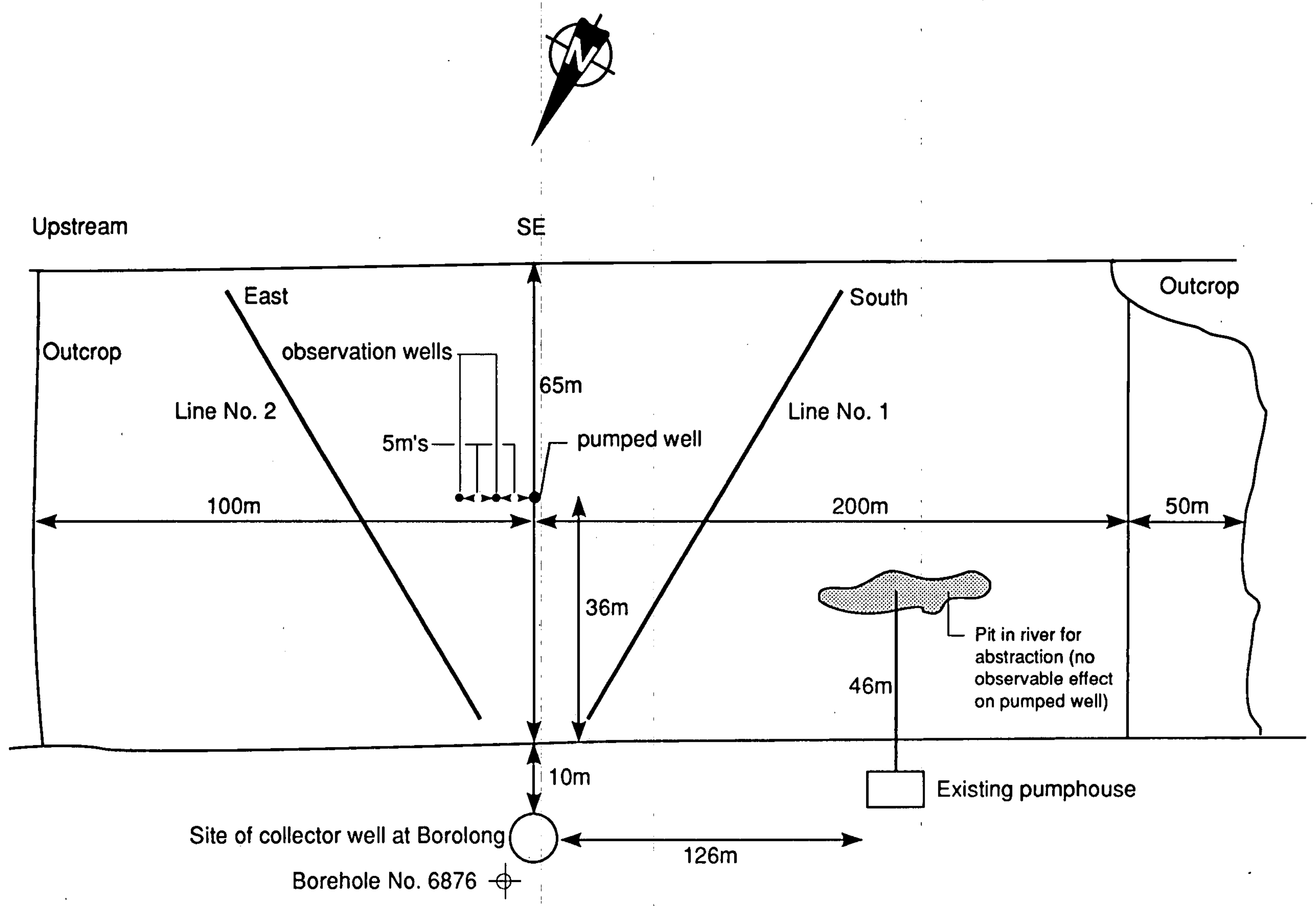


Figure 4. Sketch map of collector well site and works at Borolong

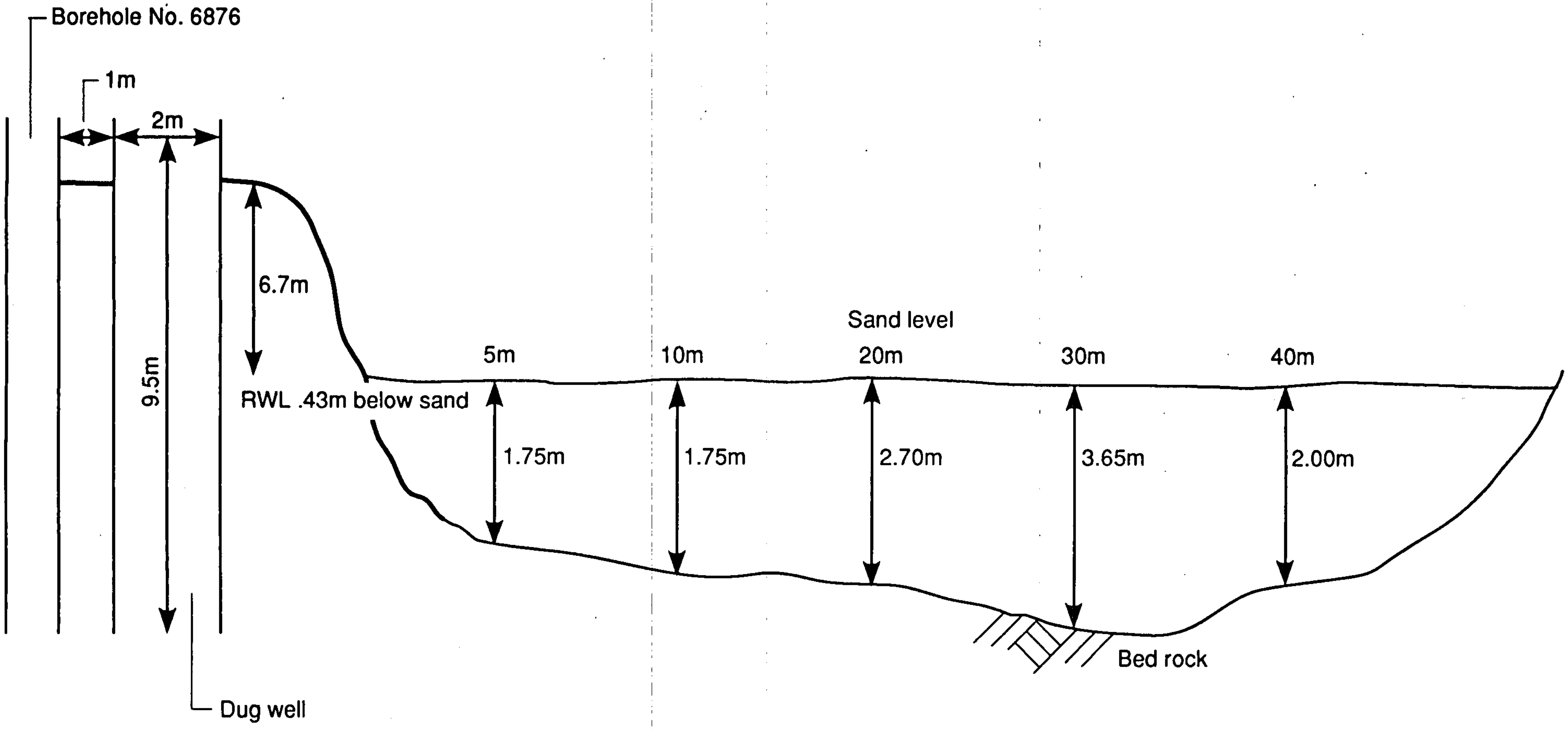


Figure 5. Sand depths along Line No. 1 of Figure 4

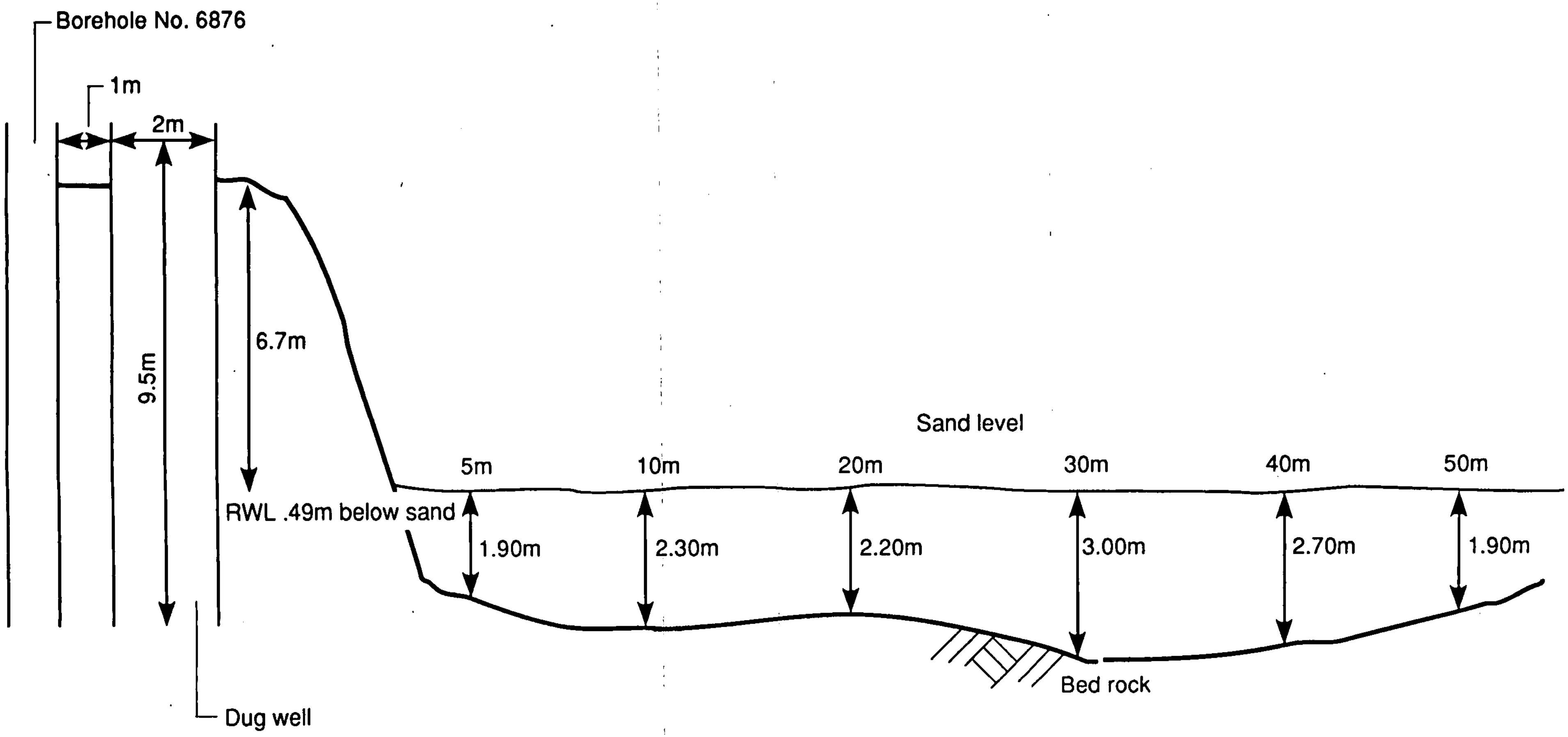
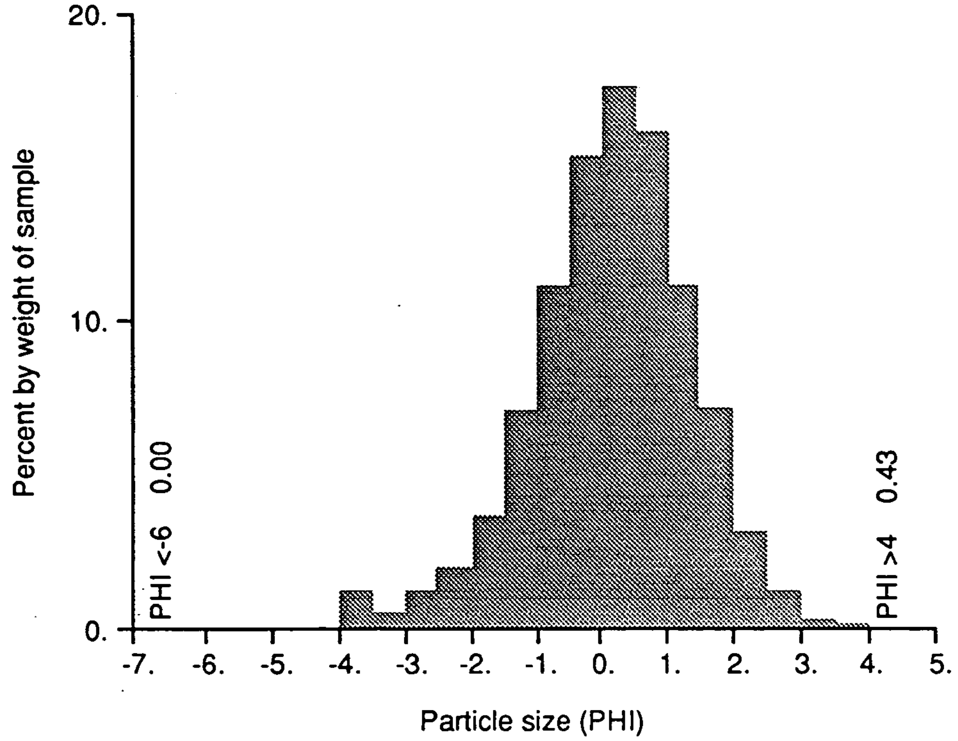


Figure 6. Sand depths along Line No. 2 of Figure 4

Sample number Shashi depth



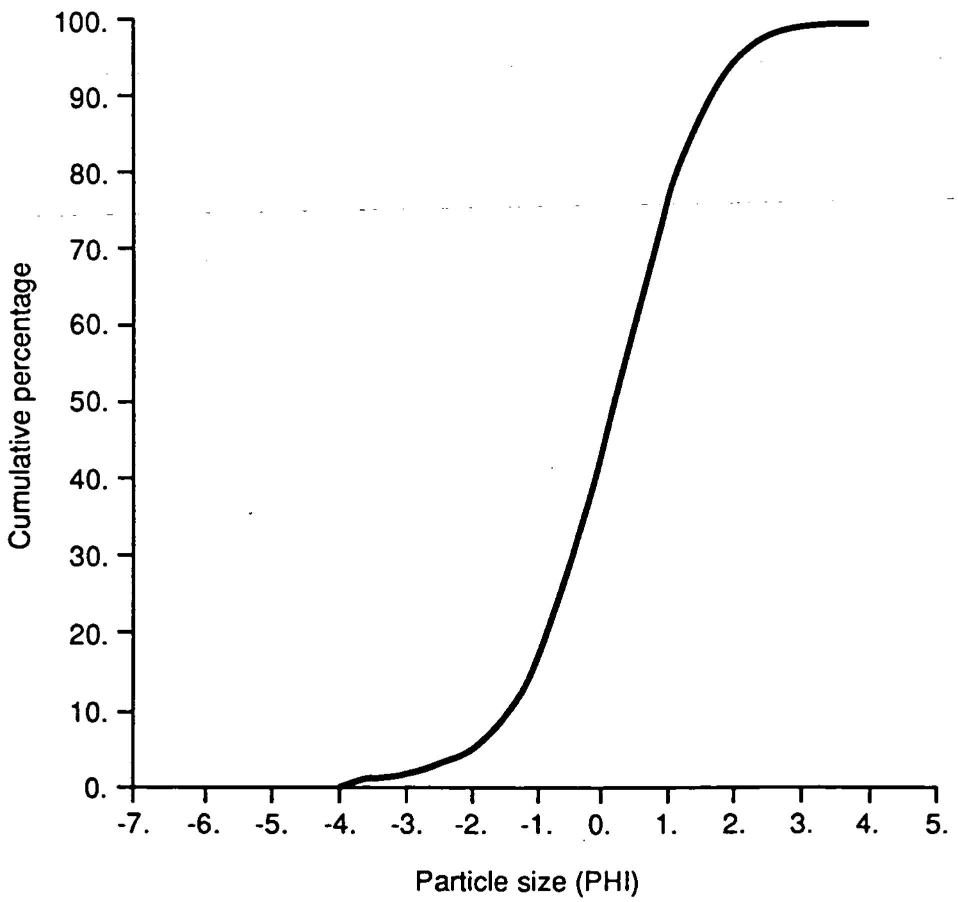
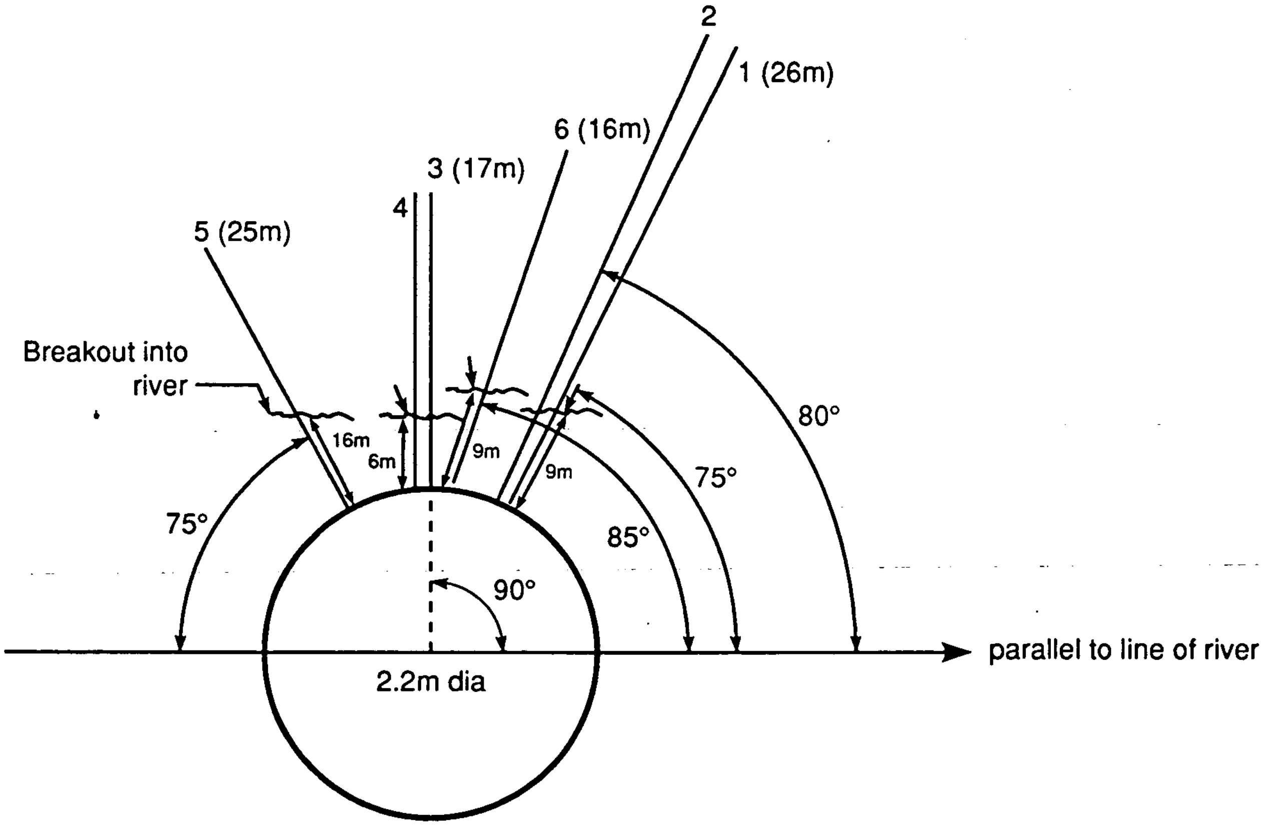


Figure 7. Sieving analysis of sample dug from surface of Sashe River



N.B. Laterals 1 and 6 were about 25cm lower than all the others

Figure 8. Laterals drilled at Borolong

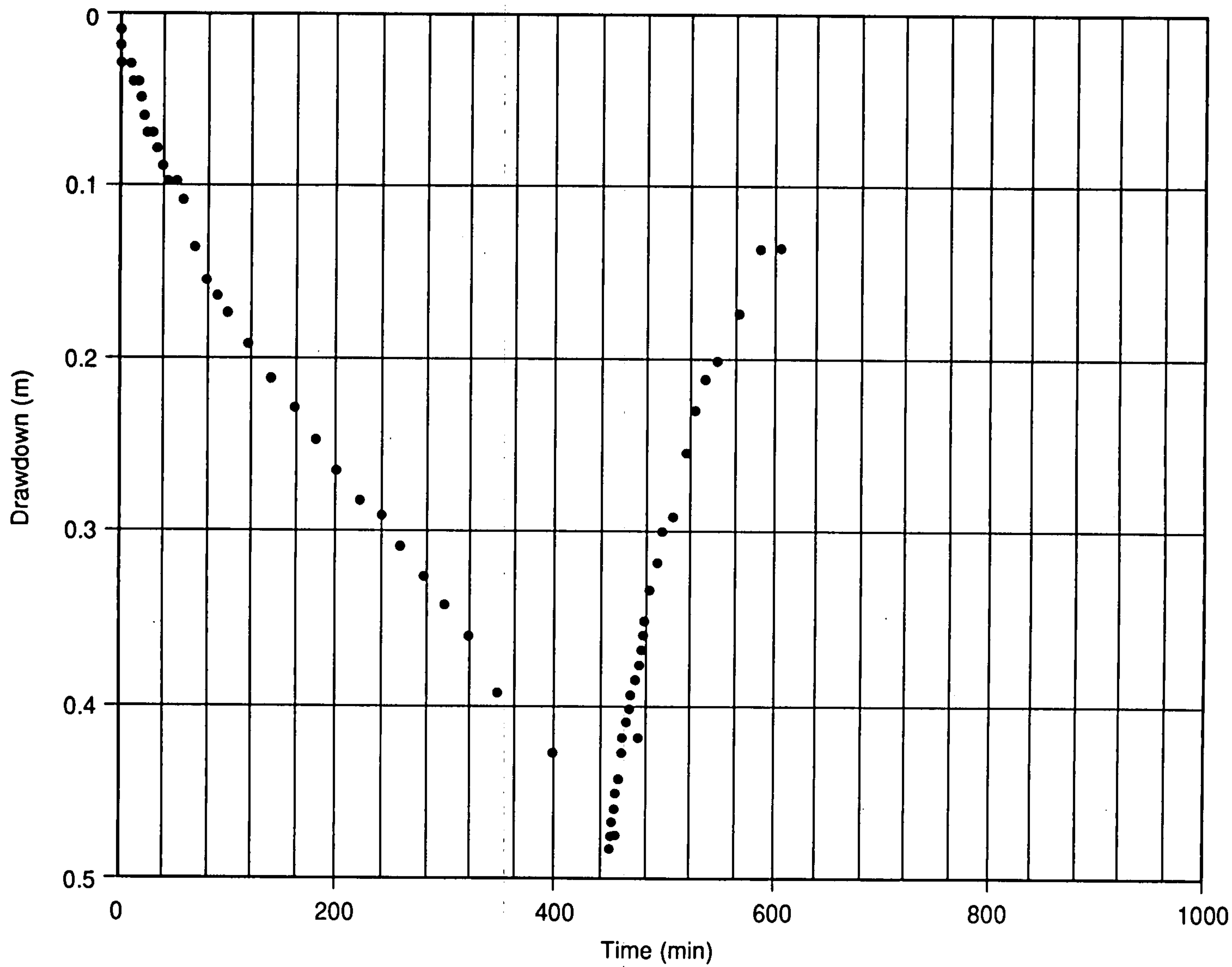
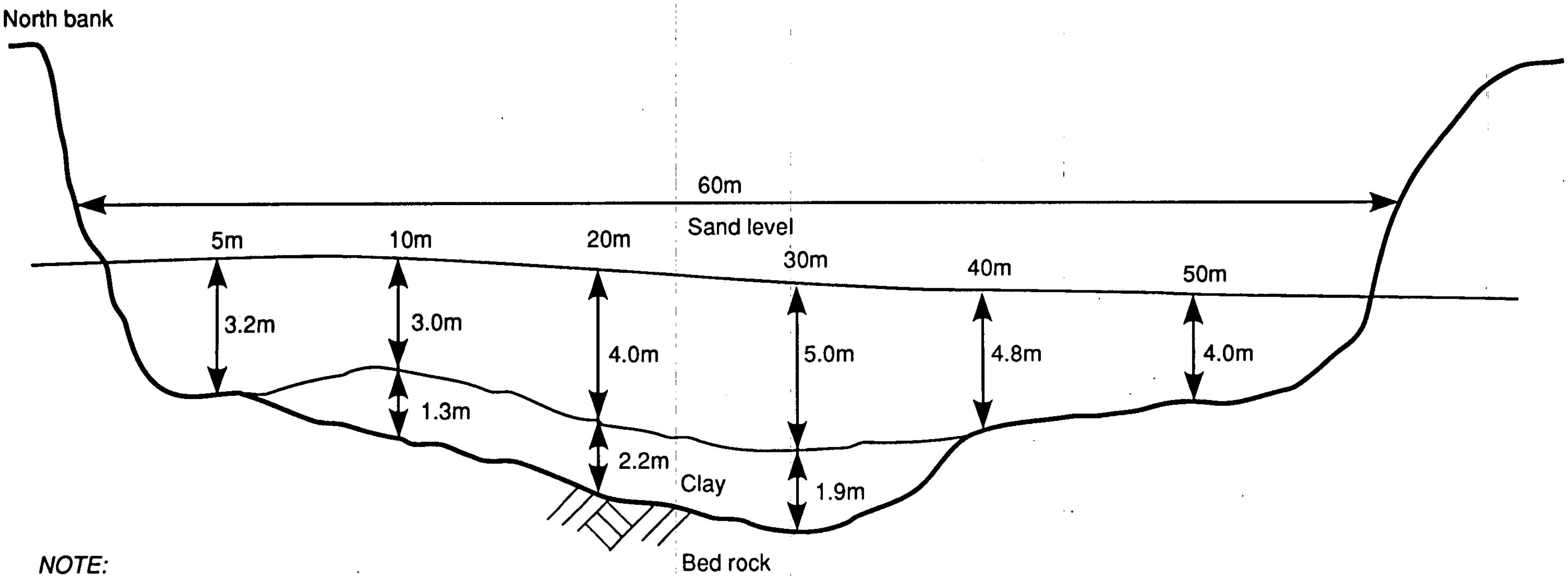


Figure 9. Pumping test at Borolong (16/07/92) - water level changes in collector well



NOTE:

RWL 0.36 BSL
Borehole No. 6798

Figure 10. Sand depths opposite the Chadibe collector well

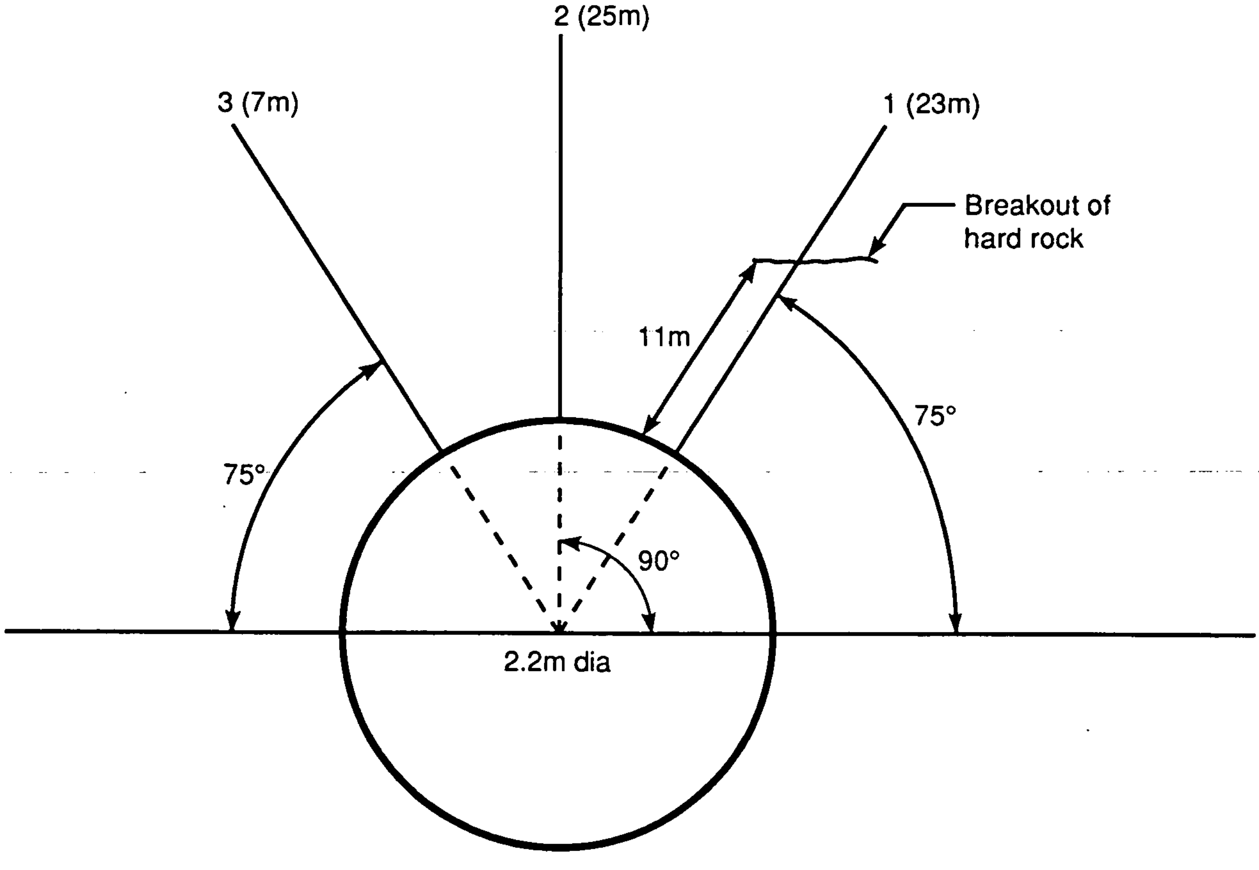


Figure 11. Laterals drilled at Chadibe

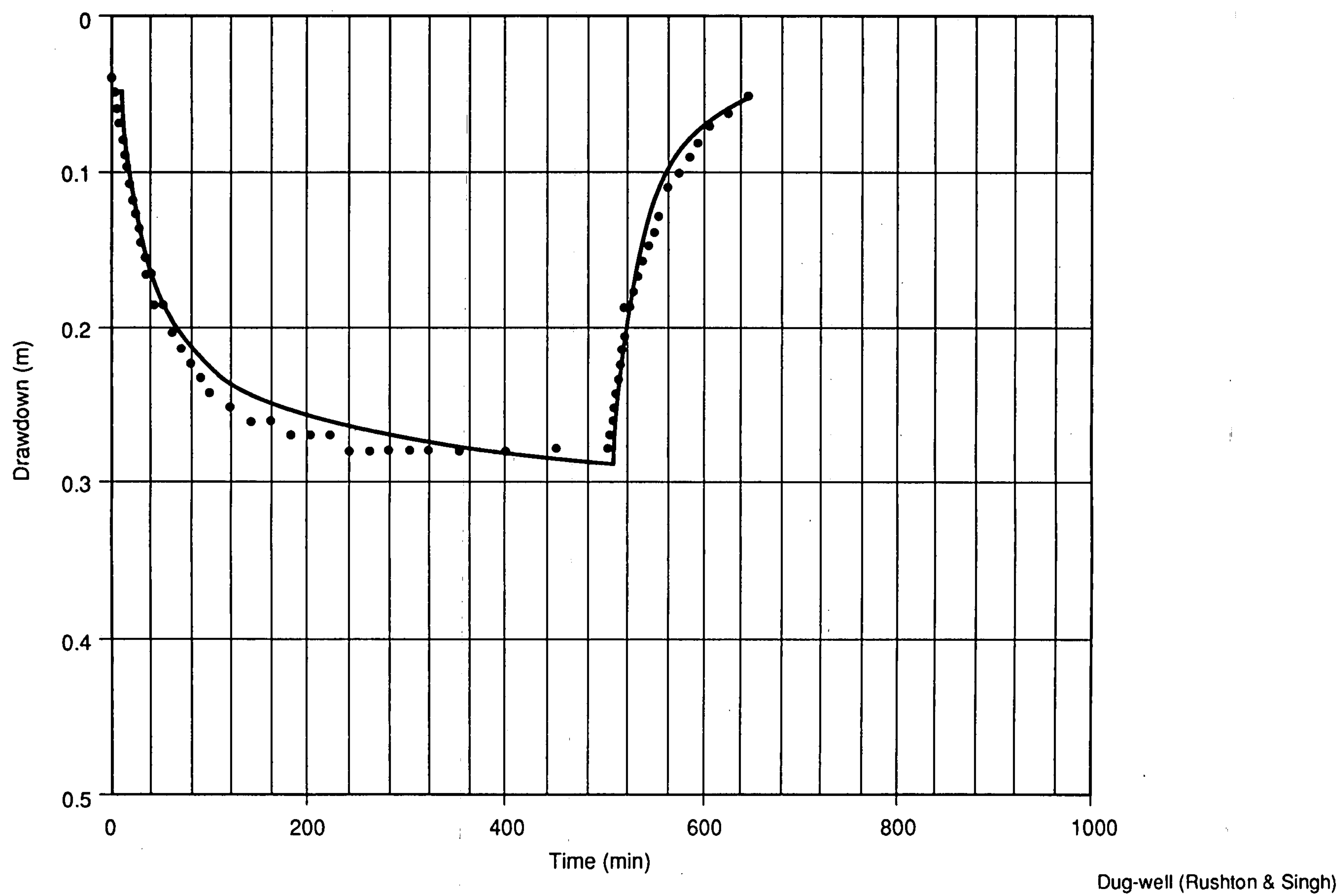


Figure 12. Pumping test at Chadibe (17/07/92) - water level change with time

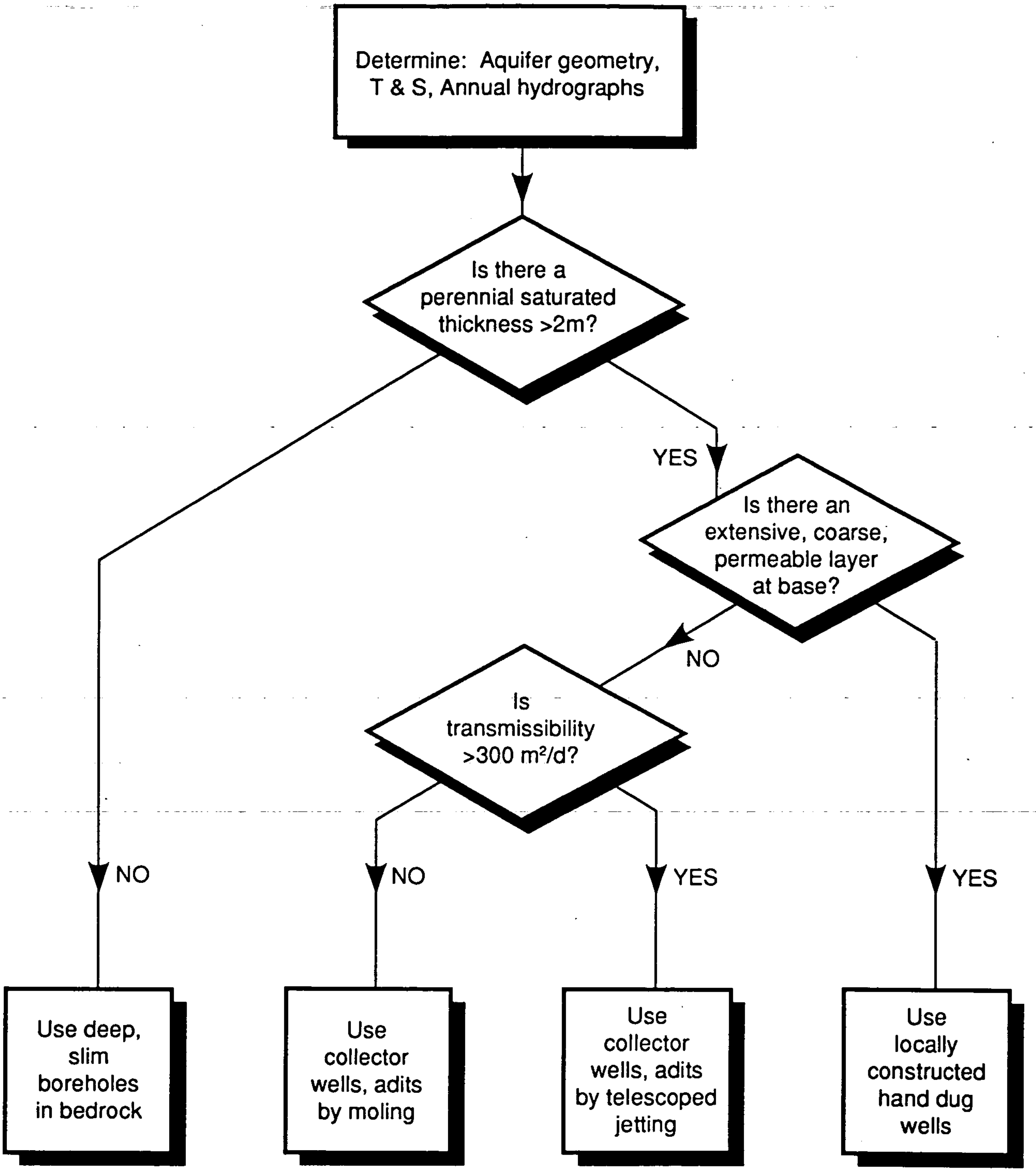


Figure 13. Selecting the optimum development technique for alluvial aquifers

Figure 14A.

Efford; excavation of material with gravel pump @ 50 l/s.

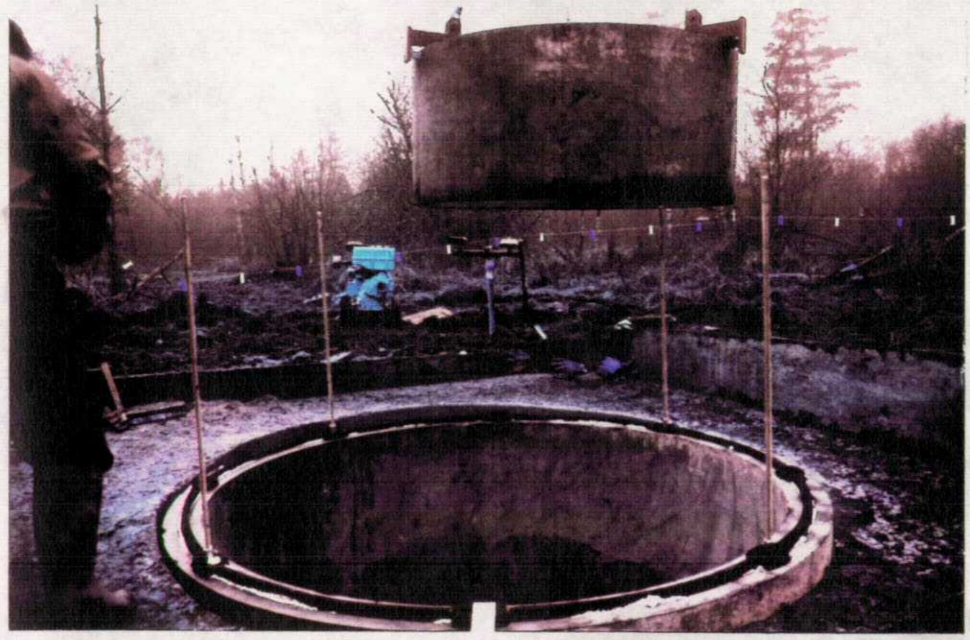


Figure 14B.

Carmer Wood; tie-rods prevent lateral displacement of rings during excavation.

Figure 14C.

Carmer Wood; mechanical excavation below water table.