INVESTIGATIONS TO DETERMINE THE LONG-TERM SUSTAINABLE YIELD OF THE KAROO AQUIFER AND THE SUSTAINED AVAILABILITY OF GROUNDWATER FOR SMALL-SCALE IRRIGATION PROJECTS, IN DENDERA AREA, KWEKWE DISTRICT - ZIMBABWE

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ABSTRACT

In this thesis the long-term sustainable yield of the Karoo sediment aquifer unit occurring in Dendera area of Kwekwe District is investigated, with the object of providing quantitative data on the sustained availability of groundwater for small-scale irrigation projects.

Archaean Basement Schists and Pre-Cambrian gneissic granites, the Basement Complex rocks, underlie the entire study area. Overlying these are Upper Karoo sediments. Aeolian Kalahari sands unconformably mantle higher interfluves, while redistributed sands occur along valleys of major rivers and streams. The Karoo sediments, which predominantly consist of loosely cemented, fine- to medium-grained sandstone alternating with red siltstone and mudstone, constitute the main aquifer. The thickness of the Karoo sediment unit ranges from 30m to 80m.

The hydraulic parameters of the Karoo sediment aquifer were characterised in the field by constant discharge pumping tests and slug tests. Pumping tests indicated unconfined conditions and thus the Neuman's method of analysis has been used. Transmissivities from pumping tests are within the range 4.7 m^2/d to 13.6 m^2/d with an average of 8.9m^2/d. The low transmissivities seem to be a major limiting factor in the exploitation of the groundwater resources. Thus the sustainable borehole yields tend to be small, mean values ranging from 33 m^2/d to 253 m^2/d. Specific yield could not be determined from the pumping tests due to the lack of observation boreholes.

Low chemical concentrations render the water suitable for irrigation of all crops, while neither total nor any individual concentrations present health hazards to human or livestock.

An average recharge value of 47.7 mm/y was inferred from water table fluctuation method. Chloride mass balance technique in the same area indicates recharge value in the order of 67.4 mm/y. Because the chloride mass balance gives a long-term mean annual recharge, the recharge figure of 67.4 mm/y was adopted for the study area.

Based on the abstractable proportion of recharge, the sustainably exploitable volume of groundwater of the order of 2.68×10^7 m^3/y was established. This volume is more than 100 times the estimated current demand for groundwater (1.35×10^5 m^3/d), implying that there are large volumes of surplus water, which can be utilised for irrigation.

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1.0 INTRODUCTION

1.1 HISTORICAL BACKGROUND

The International Water Supply and Sanitation Decade declared by the United Nations Organisation on 10 November 1980, resulted in an increase in the emphasis placed on the provision of clean and safe water supply to the rural population in developing countries. The Decade was launched in Zimbabwe on 10 November 1982 with the outlining of the National goals and methods for their fulfilment. The present Government of Zimbabwe is, therefore, facing a formidable task of an extensive development programme to upgrade and improve the water supplies for the rural population. This has resulted in a tremendous amount of resources being invested in the programme countrywide.

It has been clearly documented in the National Master Water Plan (NWMP) for Zimbabwe (Interconsult, 1986) that the task and cost of developing the rural areas, including the provision of safe water supplies, was beyond Zimbabwe's internal financial resources. The international community was, however, expected to participate in development programmes by continuing to provide considerable financial support as well as technical assistance.

In line with the present government's plans and objectives Plan International, a Non-Governmental Organisation (NGO), has been supporting the implementation of the Integrated Rural Water Supply and Sanitation (IRWSS) project in Kwekwe District since 1993. This has been against the background that water-borne faeco-orally transmitted diseases were found to constitute the major cause of infant mortality (Plan International, 1990). The project has so far provided more than 250 borehole water sources, fitted with handpumps, to the rural communities of Kwekwe District within the past four years.

During the last few years, the Government's plans were to continue to improve and increase water supplies to rural areas, with special emphasis on development of irrigation schemes. Furthermore, the recurring drought years during the last decade have stimulated irrigation demands. Therefore, although the use of groundwater for irrigation in Zimbabwe has been limited in the past, there has been growing realisation of the potential of exploiting groundwater resources for irrigation. Plan International has already shown interest in complementing these Government efforts. For example, in early 1994 Plan International carried out a feasibility study into the possibility of establishing irrigated gardens at sites with high yielding boreholes in Kwekwe District

(GWDC, 1994).

Since the inception of this water programme through to 1996, Groundwater Development Consultants (Pvt) Ltd (GWDC) have been providing consulting services to the project with regard to hydrogeological/geophysical investigations to site boreholes and supervision of the drilling operation. Enormous amounts of geophysical and hydrogeological data have been gathered by the Consultant's personnel in the process of executing the water projects.

Through the study of this data, the Consultants (GWDC) has established that the Karoo sediments occurring in the programme area are likely to contain large groundwater resources. However, the current and planned developments of this aquifer unit are primarily for rural water supply using a point distribution system. Nevertheless, previous drilling in these sediments has shown that the maximum output of the boreholes far exceeds the demand for human domestic consumption in a village. This suggests that there is much under-utilised potential, which present development scenarios will not utilise. It has been realised that the surplus water may be usefully applied towards irrigation of small vegetable gardens, or even plots of cash crops so as to improve nutrition and to generate economic benefits for the rural communities. Consequently a study to better define the available resources and improve knowledge of the sustained availability of groundwater for irrigation is of critical importance. It is within this context that this study has been initiated and, as such, the thesis relied heavily on data already collected by the Consultants during the implementation of the water programme. Nevertheless, the importance of additional data gathered during the course of the research programme should not be overlooked.

1.2 OBJECTIVES OF STUDY

The objective of the study is to determine the long-term sustainable yield of the Karoo sediment aquifer unit within the communal lands of Kwekwe District and provide information on the sustained availability of the groundwater for small-scale irrigation projects.

The specific objectives of the study are;

- To determine the aquifer geometry through mapping of the Karoo Sedimentary basin so as to define its lateral extent and thickness within the study area.

- To determine the aquifer hydraulic parameters from pumping tests.
- To define the groundwater recharge conditions and calculate the rate and volume of recharge and predict the safe yield of the aquifer.

- To determine the hydrochemical properties of the groundwater and to establish its suitability for human domestic consumption and for irrigation purposes.

- To estimate the volumes of groundwater required for human domestic and livestock consumption and subsequently determine the quantities of surplus water which could possibly be utilised for small-scale irrigation projects.

1.3 PREVIOUS GEOLOGICAL/HYDROGEOLOGICAL WORK

No detailed geological or hydrogeological mapping has been conducted in the portion of Kwekwe District that surrounds the Dendera Business Centre (the study area). The only map which portrays the geology of this area is 1:1 000 000 Provisional Map of Zimbabwe published by the Geological Survey in 1977. The Zimbabwe Geological Survey Bulletin 80 (Stagman, 1978) attempts to give an explanation to the Geological Map, but only includes a generalised account on the Karoo and Kalahari systems occurring within the country.

A considerable amount of unpublished information concerning the groundwater resources of the study area has been compiled by GWDC as part of the on-going water programme in Kwekwe District being funded by Plan International. This information is available in the form of progress and terminal hydrogeological reports, hydrochemical reports and drilling logs prepared by the Consultant for the period between 1993 and 1996.

1.4 THE SCOPE OF THE GROUNDWATER RESOURCE EVALUATION

The groundwater resource evaluation fundamentally seeks to determine the feasibility of increased abstraction from an aquifer that has an apparent potential. The scope of this investigation can best be described by the following series of questions:

1. What is the long-term sustainable yield of the aquifer?
2. Are sufficient resources available to warrant increased abstraction? What is the amount of surplus water available for irrigation?
3. Is the groundwater of acceptable quality for the proposed use?

4. How many existing boreholes can be utilised? Where should further abstraction be located if required? What are the recommended pumping rates?

The study, which is required to provide answers to these questions, can be conducted in phases as set out in Figure 1.1.

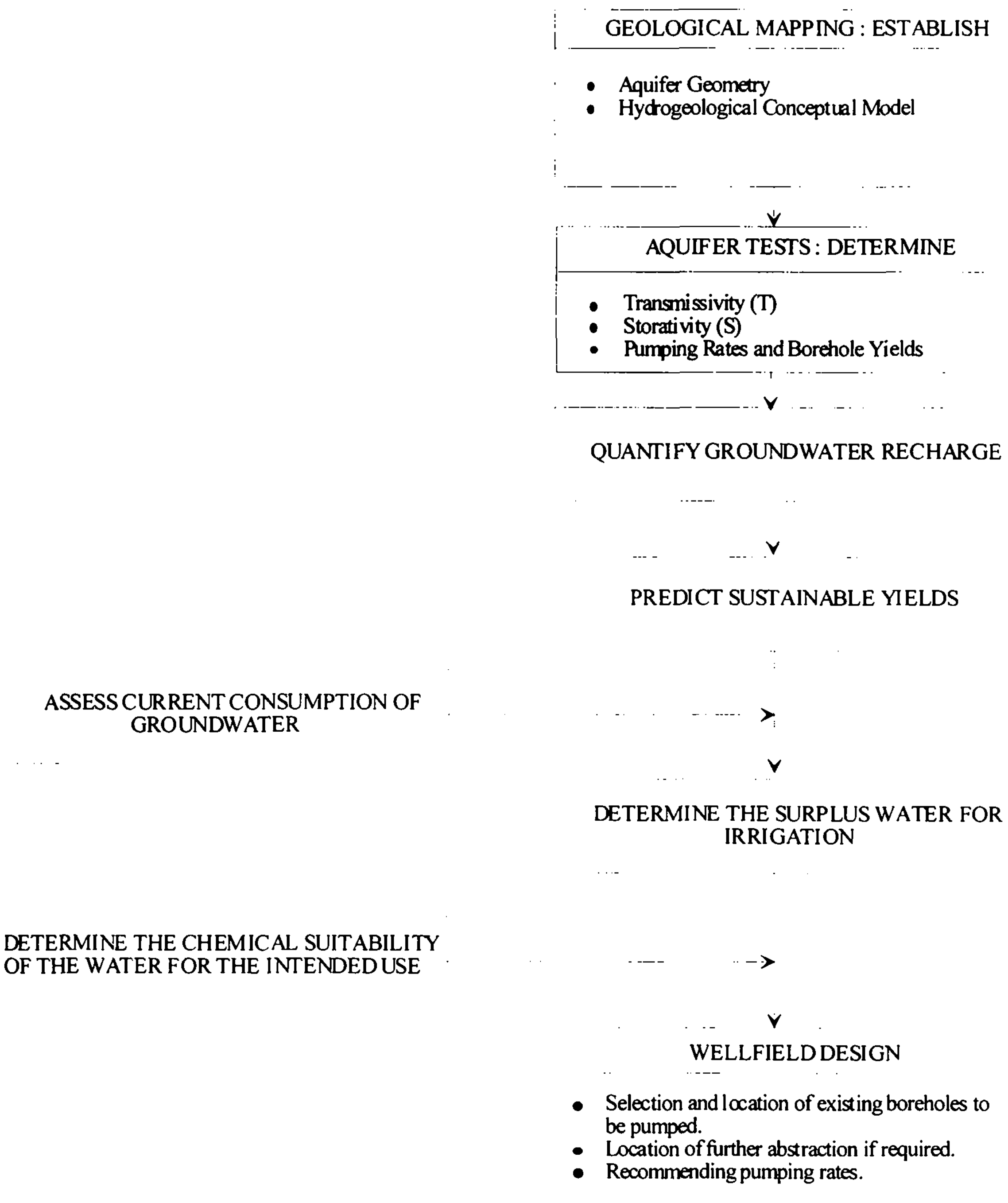


FIGURE 1.1 - The various elements of the Groundwater resource evaluation

1.5 THESIS STRUCTURE

The emphasis of this thesis is placed on evaluation of the groundwater resources in the Dendera area. However, the thesis also goes further to cover aspects of the sustained availability of the groundwater for small-scale irrigation.

Chapter 2 provides background information with regard to the physical setting of the study area. This includes a description of the location, topography, climate and soils.

The rest of the thesis has been structured in much the same way as the phasing of the study outlined in previous Section 1.4. The methods employed in carrying out the tasks for each phase and the manner in which the data was collected and analysed have been discussed under chapters covering aspects of each of the respective phase. Firstly the geological mapping and delineation of the aquifer unit is considered in Chapter 3. Chapter 4 deals with the conducting of aquifer tests and the analysis and evaluation of the pumping test data. The quantification of groundwater recharge by means of chloride mass balance and water table fluctuation methods is given attention in Chapter 5. The hydrochemistry of the area is considered in Chapter 6, and an assessment of the current consumption of groundwater is presented in Chapter 7. Finally in Chapter 8 the sustainable aquifer yield and the available surplus water are analysed, and the well field design is discussed.

The thesis is concluded by a main conclusion, Chapter 9, which summarises the finding of the study and provides possible answers to issues arising from the study objectives.

2.0 PHYSICAL SETTING

2.1 LOCATION AND SIZE OF STUDY AREA

The study area is situated in Kwekwe District, which falls under Midlands Province and is located approximately at the geographical centre of the country of Zimbabwe. It is delimited by the administrative boundaries of three wards in which it occurs. The three wards included in the area of study are; Kwayedza - Ward XVII, Chitepo - Ward XIII and Chaminuka - Ward XVI. This part of the District is commonly known as Dendera area. Figure 2.1 shows the position of Kwekwe District relative to the rest of Zimbabwe and the location and boundaries of the study area on the map of Kwekwe District.

The study area covers approximately 800km^2 and is bound by latitudes 28^{0}51' and 29^{0}18' south and longitudes 18^{0}31' and 18^{0}48' east.

2.2 TOPOGRAPHY AND DRAINAGE, AND GEOMORPHOLOGY

2.2.1 Topography and Drainage

The surface drainage of the area consists primarily of tributaries of the Gweru and Ngondoma Rivers, but these major rivers do not flow through the study area. The Gweru River flows northwesterly in the south, a few kilometres beyond the southern boundary, whilst the Ngondoma River is westerly flowing and follows the northern boundary over a short distance (7km). Figure 2.2 depicts the topography and drainage pattern of the Dendera (study) area.

Along the central portion of the area is a local watershed, which forms a surface water divide between short streams flowing southwards to the Gweru River and streams draining northwards either to the Ngondoma River or to Mangwizi stream. Mangwizi is a prominent southwesterly flowing stream which runs along the northwestern boundary and which ultimately joins the Gweru River on the extreme northwestern corner of the study area.

Remnants of a once continuous blanket of Kalahari and Karoo deposits are preserved on the local (minor) watershed between the two river systems; the Karoo sediments are the subject of this study. The central upland watershed follows an east-west trend from the western edge near Mkobokwe stream to St. Judes Sec, School in the east, a stretch of

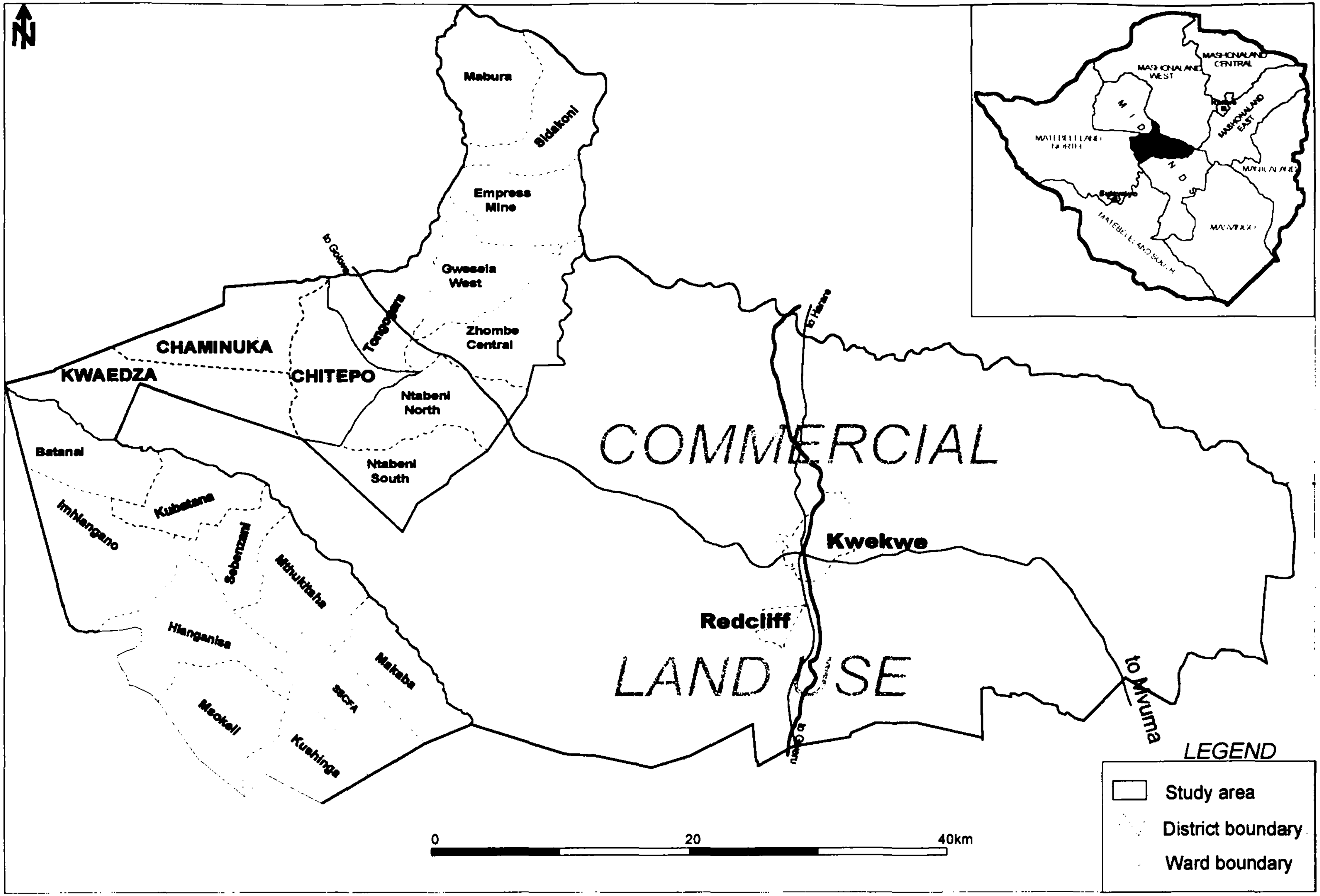


FIGURE 2.1 – Map of Kwekwe District showing the study area

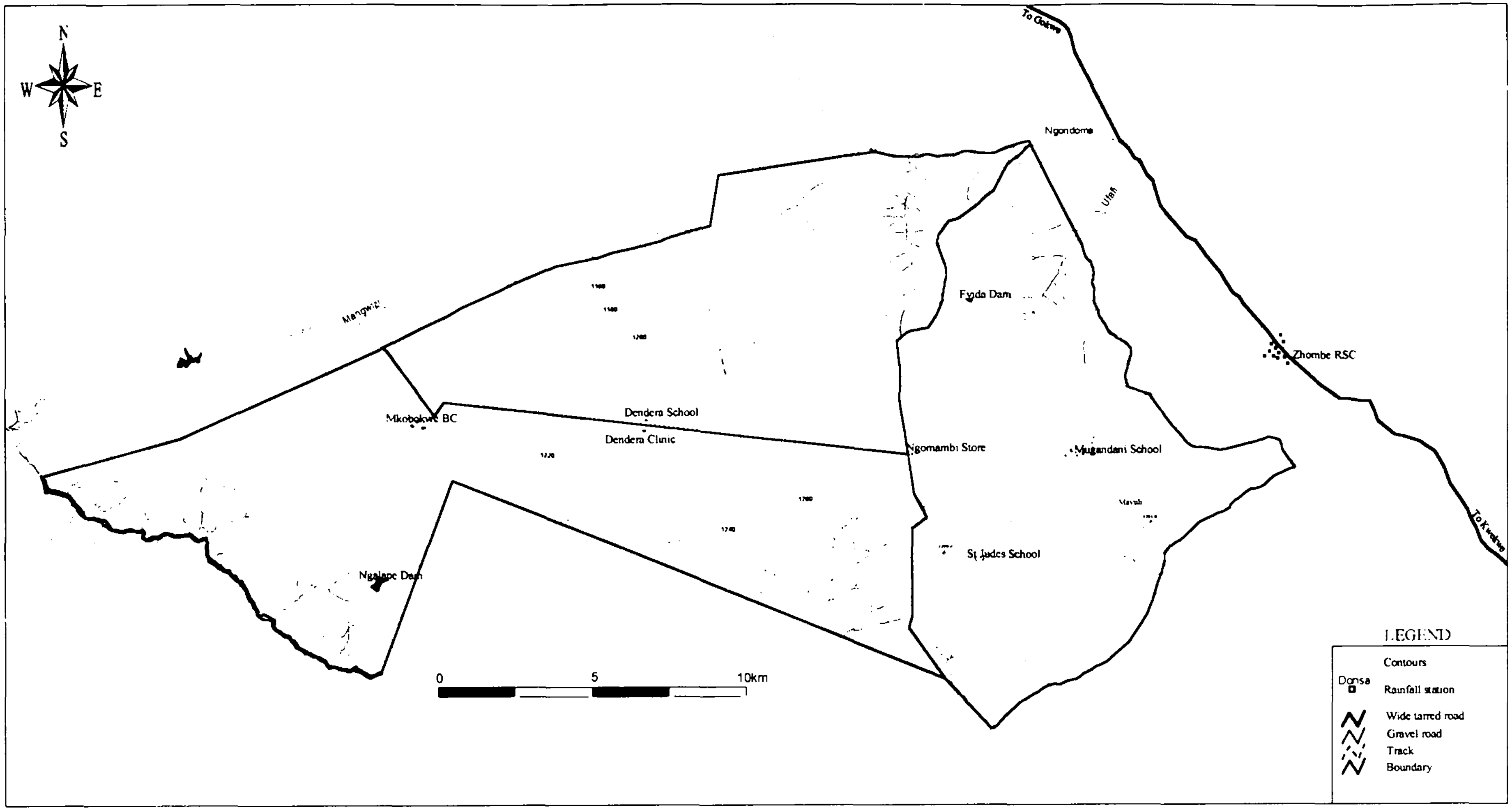


FIGURE 2.2 – Map showing the topography and drainage pattern of the Dendera area

approximately 20km. It is about 5 km wide midway between Mkobokwe and St Judes School, but on approaching the eastern margin this watershed narrows and there is little separation between the two river systems. There is a general rise eastwards from 1220 metres above sea level near Mkobokwe to 1280 metres in the region of St. Judes School. The highest point in the region is the Dendera Peak (1300m). It is situated on the extreme eastern part of the watershed, just 2km west of St Judes School.

North and south of the watershed the surface elevation falls gently towards the major river courses and the north and south flowing streams flow down these broad, gentle rises of deep sand. The drainage channels across the deposits are generally shallow such that nowhere within the study area do they cut through the Kalahari and Karoo sediments to expose the underlying Basement Complex rocks. In the northwestern portion of the area the Mangwizi stream and its northward-draining tributaries form characteristic shallow vleis across the surface of the Kalahari and Karoo sediments. These vleis are evidence that much of the drainage passes underground owing to the flat nature of the surface.

Mavule Hill, at 1279 metres, presents a prominent topographic feature lying on the extreme southeastern part of the study area. Mavule is a flat-topped tableland, where the Karoo basalt caps the less resistant sandstone beds.

Apart from the Basement Complex granitic rocks on the western corner, the geology of the study area is almost entirely Upper Karoo sediments extensively covered by deposits of Kalahari Sand. The Karoo basaltic lava only outcrops on the Mavule Hill.

2.2.2 Geomorphology

The Kalahari sands are widespread in the area west of St Judes School and cover approximately 65% of the study area. The deposits are part of the main Kalahari Basin occurring to the west of the country. Although now irregularly distributed, during earlier times, the Kalahari deposits formed a more continuous cover across the underlying Basement and Karoo rocks, possibly in the form of a ubiquitous blanket over the entire northwestern and central parts of Zimbabwe. Subsequent erosion has removed the unconsolidated sediments along the river valleys so that the Kalahari deposits in the area represent some of the remnants of a once continuous cover. For example, a little further southwards of the study area, granites and schists outcrop across the Gweru River valley, which clearly shows that this river has cut down through the Kalahari blanket.

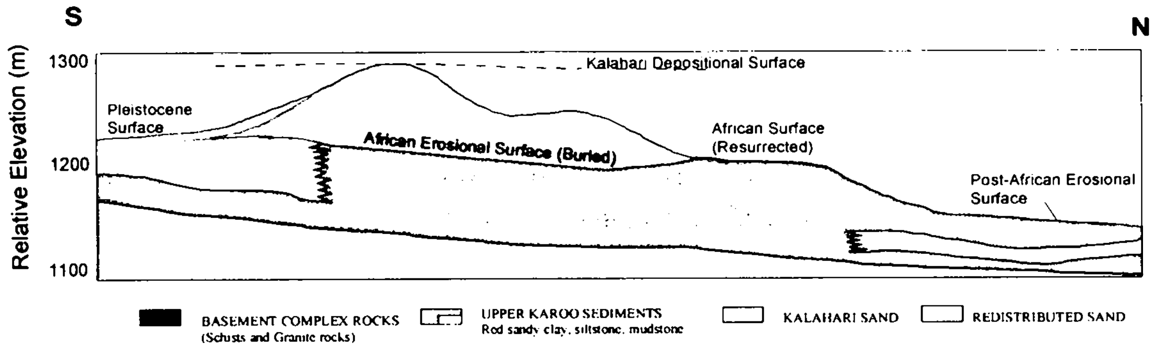


FIGURE 2.3 – Cross-section of cyclic land surfaces of Dendera area

The bulk of the Kalahari deposits are aeolian sands of probable Miocene/Pliocene age. The floor of these deposits is most likely the African or Post-African erosional surface (Lister, 1987). The large expanse of Kalahari Sand, found on the higher areas of the local watershed, exhibits only the Kalahari depositional cycle of Tertiary and Quaternary age. Thus unburied erosion surfaces do not occur across this portion of the area, where effects of erosion have been negligible since the time of deposition of the sands. Figure 2.3 is north-south geological section that shows the cyclic land surfaces.

However, along the eastern fringe of the Kalahari System the encroaching Post-African erosional cycle has removed the loose Kalahari sands to expose the underlying older basal deposits. These include calcretes, chalcedonies and agates, which were probably developed at the end of the African erosional cycle of the late Oligocene (Lister, 1987). Typical basal deposits have been recognised on a gravel pit (QK368277) about 3km to the north of St. Judes School. Similarly, in many places on the southern margin of the Kalahari system, as observed around Mabhidhli School (QK282270), basal deposits have been exposed and here they commonly include ferricretes or Kalahari ironstone. These ferricretes are considered to be secondary resulting from leaching of iron out of the overlying sands and its concentration along the less permeable floor, as described by Lister (1987).

While the large spreads of sands on the higher watershed area belong to the main phase of Kalahari System of Miocene/Pliocene age, redistributed Kalahari sands are found bounding the major valleys. Such redistributed sands overlie the Pleistocene erosion surfaces. The redistributed sands are generally found where the rivers have cut through to older rocks, and were derived from the resulting scarps of older sands. The most notable occurrence form a gentle rise of sand, on the upper slope of the Gweru river valley between the margins of the main phase of Kalahari System and the Basement

Complex outcrop that follows this river. Although, these redistributed sands form a belt up to 8 kilometres wide, only a narrow strip occurs within the limits of the study area. In the northern-most portion of the area, the redistributed sands have been developed along the strip following the Mangwizi stream and much smaller occurrences are found along its south bank tributaries, which include Mkobokwe, Rufuse and Baparara.

On the eastern and northeastern extremity the Ngondoma River and its tributaries, such as the Ntombankala and the Ufafi, have dissected the area giving rise to the Post-African land-surface. The encroaching Post-African erosional cycle has stripped the Kalahari blanket to re-expose the underlying Karoo sediments and basalts. Whereas the Karoo basalts only occur capping the sediments on the Mavule Hill on the extreme eastern portion, the Upper Karoo sediments occur extensively beneath the entire Kalahari outcrop in addition to these areas where they have been re-exposed by erosion. However, the exposures of Upper Karoo sediments are limited to the courses of the Ngondoma and Ufafi Rivers as they are generally obscured by a thin blanket of either redistributed Kalahari Sands or Post-Kalahari soils.

Westwards, beyond the Mkobokwe River, the surface level continues to drop gently until it reaches the lowest point (1050m) on the western corner of the study area, which coincides with Gweru-Mangwizi River confluence. Narrow strips of granitic outcrop follow both rivers roughly 15km upstream from the confluence. However, the belt along the Gweru River continues beyond the boundary of the study area. A narrow band of Upper Karoo sediments occurs between the granitic outcrop and the eastern edges of the Kalahari deposits. A sudden fall in elevation of 50 metres over a distance of 1½ kilometres corresponds to the margin of the Karoo sediments and the granites. It is the Post-African erosion cycle that has clearly cut down through the Kalahari blanket to re-expose the granites and Upper Karoo sediment in this part of the study area.

2.3 SOILS

Soils in the Kalahari Sand area are characteristically made up of a thick sandy profile. Deep sands also occur over much of the area where the underlying formation is the Karoo sediments; that is in places where the Kalahari Sand mantle is absent. This makes these sands the most widely occurring soil type in the area, possibly covering 80% the study area. Noteworthy is the fact that the Karoo sediment outcrop is probably covered extensively by a veneer of redistributed Kalahari sands, moreover the sediments weather to produce sandy soil very similar to that formed on Kalahari Sand outcrop. According to the soil classification used in Zimbabwe (Nyamapfeni, 1991), these soils are classified under the Regosol Group; a group which encompasses soils, which have less than 10%, combined silt and clay within the upper 2 metres. Since the parent material of these soils is aeolian desert sand soils, they contain very low reserves of weatherable minerals. Consequently their mineralogy is predominantly quartz with small amounts of feldspars and opaque minerals. The sand fraction of the soils is usually dominated by fine to medium sand size particles. In general they show little evidence of horizon development beyond the single horizon above the regic material. The soil horizon is differentiated from the regic material at depth by its humic content, generated from the vegetation cover. These soils are inherently infertile and are not very productive agriculturally.

Soils derived in-situ from the Karoo sediments are not widespread in the area. Their occurrence is restricted the relatively small Karoo outcrop area on the extreme western part of the study area. The soils are generally pale reddish-brown and have low content of weatherable minerals because of the paucity of such minerals in the parent rock. The clay minerals, originating from chemical breakdown of feldspar grains in the sandstone, tend to be carried downwards by percolating rain, so that below one metre the clay content increases to give rise to sandy loam (Beasley, 1983). However the sandy loam soil might itself be exposed on surface in small patches of land where erosion has stripped the rather loose surface sands.

Granitic rocks occupy a small area at the western corner of the study area at the confluence of the Gweru and Mangwizi rivers. The granite gives rise to light to medium textured soils, which are characterised by the presence of significant amounts of coarse sand. These granite soils are commonly shallow and usually reddish-brown in colour in well-drained positions.

2.4 CLIMATE

2.4.1 The Seasons

The climatological year in Zimbabwe begins in July. This avoids the splitting of the four-to five-month rainy season, which straddles the New Year, into two unrelated sections. On the basis of rainfall, the year can be basically divided into two parts: a long dry season from May to September, coinciding with the winter and summer rainy season from October to March. Relatively short periods mark the spring and autumn transitions. The climate of Zimbabwe is described in detail in the Climate Handbook of Zimbabwe (Torrance, 1981).

2.4.2 Rainfall

The rainfall pattern is typically unimodal with a well-defined rainy season and dry season. The rainy season commences in the second half of October and lasts for five months that is until the end of March. The main rains are due to the Inter-Tropical Convergence Zone (ITCZ).

The ITCZ involves the convergence of three air masses in this part of Central Africa.

(i) The North-East Monsoon from the Indian Ocean, which may be moist or dry depending on its recent track.
(ii) The relatively cooler dry air mass from the southeast - the South East Trades.
(iii) The Congo Air from the northwest, which is humid and associated with much rain and thunder activity. It originates from maritime air arising from semi-permanent anticyclonic circulation over the South Atlantic Ocean. Incursions of Congo Air into Zimbabwe occur when the low-pressure zones occur to the south or west and its presence is associated with good rains. These become heavy with an increase in low-level convergence.

The bulk of the rainfall is mostly of high intensity and concentrated in a relatively short time span. Normally small areas are affected by rainfall at any particular time. In general the rainy season is composed of alternations of rainy and dry spells. In the north of Zimbabwe, the rainy spells tend to occur more frequently and are often longer than those in the south. In the later region, within which occurs the study area, dry spells predominate.

Rainfall Records and Recording Stations

Although there are no official rainfall recording stations within the study area, three stations are situated just outside the bounds of the area. All the three rainfall stations are located within 7 kilometers of the area: (i) Donsa station is situated 2 kilometres from the boundary of the extreme western portion; (ii) Fairacres Estate Station lies 5 kilometres from the southern boundary of the western quadrant; and (iii) Zhombe Central Station is located 6½ km from the middle part of the eastern limits. The locations of these rainfall stations relative to the study area are shown on the topography and drainage map (Figure 2.2). The grid reference, and length of record for the three stations are presented in Table 2.1.

TABLE 2.1 - Rainfall Stations

Station	Grid Ref	Period of Records	Remarks
Donsa	QK0124	1956-77	Closed
Fairacres	QK1621	1966-79	Closed
Zhombe Central	QK4734	1966-96	Open

As it can be noted from Table 2.1, Donsa and Fairacres Estate Stations were open for far less than 30 years normally required for calculation of statistically significant long-term means.

Spatial Distribution of Rainfall

Mean Annual rainfall varies from a minimum of 637mm at Donsa Estate to a maximum of 651mm at Zhombe, a difference of only 14mm. Such a small difference between the means of Zhombe Central and Donsa stations, located on the either ends of the east-west stretching study area, indicates a very low spatial variability of the area's rainfall; indeed rainfall is almost evenly distributed over the whole area. Monthly and annual mean rainfall records for all three rainfall stations are listed in Table 2.2 and presented diagrammatically in Figure 2.4.

Variability of Annual Rainfall

The study area falls within a region of both low and erratic rainfall. The area often experiences drought conditions. Evidently, there is great variability in annual rainfall. The variation in annual rainfall is conveniently expressed by the coefficient of variability (CV), which is the standard deviation expressed as a percentage of the mean. The isopleth map of the coefficient of variability for the whole country has been included in the Climatic Handbook of Zimbabwe (1981). This map shows coefficients of variability ranging from 20% in the north (most reliable rainfall) to over 45% in the south (least reliable rainfall). The study area is in a zone where the coefficient is >30%. In fact the coefficients of variability (CV) calculated from the rainfall data of the three stations ranges from 25 to 33% (Table 2.2). It is, therefore, clear that the rainfall of the area is highly erratic.

TABLE 2.2 - Monthly And Annual Mean Rainfall (in mm)

Name of Station	Period of Record	Years Averaged	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total	CV (%)
Donsa	1957/68-1976/77	20	4.6	0.7	5.8	18.1	90.4	138.9	162.8	121.5	46.0	34.5	9.8	4.1	636.8	25
Fairacres Estate	1967/68-1978/79	12	0.7	0	2.1	21.5	73.1	163.6	144.9	125.4	78.3	28.9	5.2	0	638.2	33
Zhombe Central	1967/68-1997/98	31	0.7	0.3	3.8	23.5	69.3	176.6	165.2	104.1	77.3	26.6	2.6	1.3	651.3	29

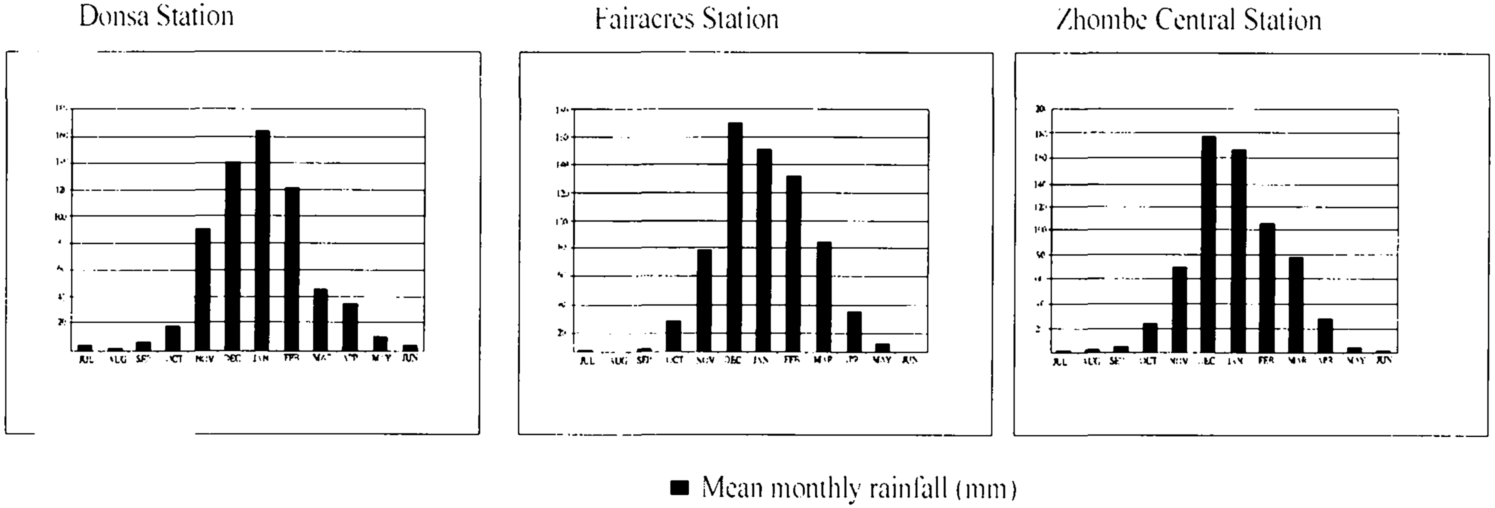


FIGURE 2.4 – Average seasonal distribution of Rainfall for the recording stations

Seasonal Distribution of Rainfall

In Zimbabwe, the rainfall pattern within every year is fairly even, with the bulk of the rainfall concentrated in a few months (Interconsult, 1985 – NMWP Vol. 2.1). In the Dendera area, the most reliable months for rainfall are December and January; for the three stations the wettest month is either of these two months (Fig. 2.4). For all stations February is the third wettest month, followed by November, March, April and October in that order. In most years the months of June, July and August are rainless; the low averages shown in Table 2.2 for the stations in any of these months are due entirely to sporadic falls recorded in very occasional years

2.5 GROUNDWATER SOURCES IN THE STUDY AREA

Boreholes are the main facilities used to tap groundwater in the study area and presently, up to 120 boreholes are in existence. They constitute the main source of domestic water for the local communities. The uses of the water for domestic requirements fall under four categories, which are as follow;

- drinking
- food preparation and cooking
- personal hygiene, washing and cleaning
- livestock watering

Apart from one borehole equipped with a diesel engine/Mono-pump at Dendera clinic (QK212307) all the boreholes in the area are fitted with handpumps. Apparently the majority of the boreholes (70%) have been drilled recently, during the period between 1995 and 1997, under the Plan International-funded water projects. Nevertheless, it is worth noting that several old boreholes, whose drilling might date as far back as the 1960's, are still being used in the area. The Government's Department of Water Resources and Development have drilled these old boreholes.

Hand-dug wells are also common facilities for extracting groundwater within the study area. They amount to an estimated total of 75 wells. Unlike boreholes, which are exclusively used as communal water facilities at village level, the hand-dug wells are predominantly family water facilities constructed by individuals within their private properties, such as homesteads and vegetable gardens. The hand-dug wells are commonly located in depressions and low-lying areas where a shallow groundwater table may occur. The generally deep water table occurring along the watershed area make it impractical to dig wells and possibly explains why such facilities have not been situated on this part of the study area. The hand-dug wells vary from the simplest form where they are little more than a shallow water-hole which is dug into the water table to a relatively deep facility excavated to depths of over 30m. The majority of the wells are either unprotected or semi-protected. The water is commonly raised to surface by a windlass in combination with a chain/rope and bucket. Alternatively, a bucket and rope, without a windlass system, are employed to raise the water but only where the water levels are very shallow. Apparently none of the hand-dug wells has been equipped with either a hand-pump or motorised pump and as such the risks of their water being contaminated are quite high.

3.0 GEOLOGY

3.1 GEOPHYSICAL INVESTIGATIONS: AN OVERVIEW OF ELECTRICAL RESISTIVITY TECHNIQUES

3.1.1 Introduction

The principal aim of the geophysical survey was to supplement existing geological/hydrogeological information with particular regard to depth to solid bedrock and the thickness of the water-bearing strata.

A large number of different geophysical techniques are available for locating and assessing underground reservoirs of water. Commonly used methods for groundwater investigations are electro-magnetic, electrical resistivity, gravimetric and seismic methods. In principle, each of these four main methods is capable of furnishing useful information when applied to areas where the physical conditions satisfy the necessary requirements. In general, the electrical resistivity and seismic methods are mostly used because of their high-resolution power in respect of particular problems encountered in groundwater exploration (Kollert, 1969). However, price-wise and for the same depth of investigation, the resistivity method is appreciably cheaper to apply than the seismic method and it is more flexible and easier to operate (Van Zijl, 1985).

According to Van Dogen and Woodhouse (1994), the electrical resistivity method is the most widely used geophysical tool in search of groundwater in sub-Saharan Africa. From an inventory and assessment of more than 40 primary water supply projects, they found that the resistivity method had been applied in most hydrogeological environments encountered in this region. A number of recent investigations undertaken by GWDC (1995) and Prince (1997), in order to site boreholes in the study area and Kwekwe District as a whole, have demonstrated the worth of utilising the resistivity method in determinations of depth to bedrock and delineation of the buried Karoo aquifer

For this study, the technique used was the Resistivity Vertical Electrical Sounding (VES) with a Schlumberger electrode configuration. This method is particularly potent when used for the determination of the thickness of weathered overburden or loosely consolidated sediments above the Basement Complex bedrock, where the resistivity contrast between the overburden/sediments and bedrock is large. The theoretical considerations applicable to this method have been discussed in sub-sections below. During the study 24 VES surveys were carried out in attempt to define the surface of the basement bedrock buried beneath the younger sediments

3.1.2 The General Principles of Resistivity Surveying

In order to fully understand the principle of earth resistivity measurements it is necessary to appreciate the behaviour of electric current flowing in layered media, which is invariably the case rather than a homogeneous earth, and how this affects the distribution of electric potential within the ground (Vingoe, 1972). For quantitative interpretation of resistivity data the ground is considered as being made up of layers with approximately constant resistivity, bounded from each other by planar interfaces of differing resistivity.

The principle of electrical resistivity is based on Ohm's Law, which states that

$$\Delta V = IR \qquad (3.1)$$

where

ΔV is the potential difference between any two points (volts)
I is the current flowing in the medium between two points (amp)
R is the resistance of the medium between these two points (ohm)

The resistivity, ρ, of the material is defined as the resistance across a unit cube of the material. Thus, if current is following between two points of a conductor of cross-sectional area A, a distance d apart, the resistance between the two points is given by

$$R = \frac{\rho d}{A} \qquad (3.2)$$

If I is passed through a single electrode in homogenous earth of resistivity ρ, the potential at a point P, at distance d from the electrode, is

$$V = \frac{I\rho}{2\pi d} \qquad (3.3)$$

In practice, two current electrodes (A and B) are used through which a known current is passed into the earth. Since the absolute potential in the ground is not measured, two other electrodes (M and N) are always required, between which the potential difference due to the current is measured.

3.1.3 Electrode Configuration

The simplest method of conducting resistivity survey is to arrange the four electrodes in a straight line on the surface of the ground as demonstrated in Figure 3.1.

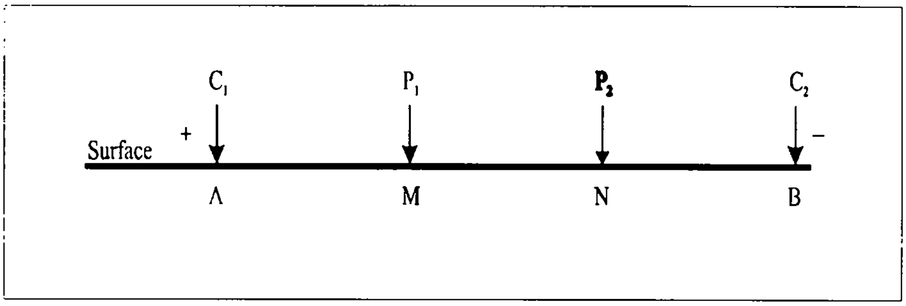


FIGURE 3.1 – General Resistivity array consisting of two current electrodes, A and B, and two potential electrodes, M and N

From equation 3.3 it can be shown that

$$V_M = \frac{I\rho}{2}\left\{\frac{1}{AM} - \frac{1}{AN}\right\} \quad \text{and} \quad V_N = \frac{I\rho}{2\pi}\left\{\frac{1}{BM} - \frac{1}{BN}\right\}$$

Therefore the potential difference between M and N is

$$V_M - V_N = \frac{I\rho}{2\pi}\left\{\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN}\right\} \qquad (3.4)$$

Hence the resistivity is

$$\rho = \frac{K\Delta V}{I} \qquad (3.5)$$

where

$$K = \frac{2\pi}{\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN}}$$

The coefficient K is calculated from the appropriate distances between the electrodes and has the dimensions of metres (m).

It is very clear from the foregoing discussion that the coefficient K is dependent entirely on the geometrical positions of the electrodes. For certain electrode configurations the calculation of the value of K can be simplified considerably. Although a great number of different electrode configurations have been introduced, the most commonly used configurations in resistivity surveying are those where all four electrodes are placed symmetrically in a straight line. These are (Van Zijl, 1985);

- the Schlumberger array where the distance MN between the potential electrodes is small compared with the distance AB between the current electrodes. If MN $\leq$ AB/5 (Fig. 3.2a) the coefficient K is given by

$$K = \frac{\pi.AM.AN}{MN} \qquad (3.6)$$

- the Wenner array in which AM = MN = MB = a (Fig 3.2b) and the coefficient K is given by

$$K = 2\pi a \qquad (3.7)$$

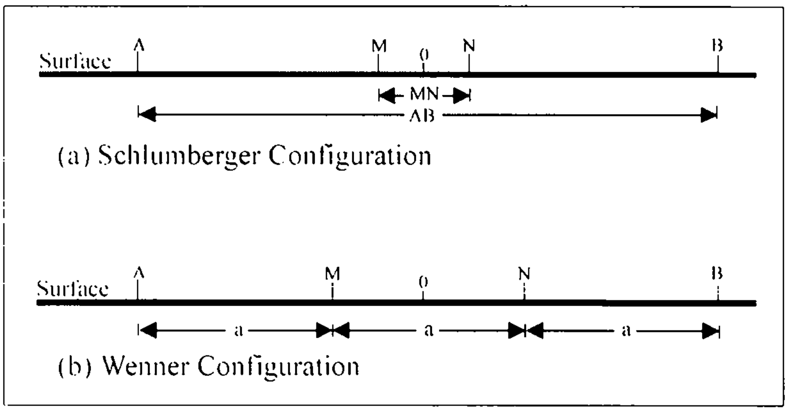


FIGURE 3.2 – Commonly used electrode configurations (a) Schlumberger and (b) Wenner Configuration

3.1.4 Resistivity of Rocks and Soils

The resistivity of rocks and soils varies within a wide range. Since most of the principal rocks forming minerals are practically insulators, the resistivity of rocks and soils is determined by the amount of conducting mineral constituents and the water content in pores and interstices. The latter condition is by far the dominant factor and in fact, the majority of rocks and soils conduct electricity because of water contained in pores and fissures. This is known as electrolytic conductivity.

The electrolytic conductivity of a rock depends on the conductivity of the pore water, the amount of water and the manner in which the water is distributed within the rock (Van Zijl, 1985). It is therefore evident that the resistivity of rocks varies with porosity, the degree of saturation and the total dissolved solids in the water. The widely differing resistivity of impregnating water alone can cause variations in the resistivity of rock formations; the resistivity of naturally occurring water may vary from a few tenths of an ohm-metre in the case of sea-water to more than a hundred ohm-metres in the case of fresh mountain water.

Different rock and soil materials are theoretically characterised by different resistivities, but the same formation may show wide variations in resistivity due to variations in the amount and type of impregnating water. Thus, since resistivity is not a characteristic parameter for the rock itself, it is difficult to identify a rock type solely by means of resistivity value. In general, however, sedimentary rocks are better conductors than igneous rocks. In addition, clayey material has a higher conductivity than material of sandy type; this is because ions cluster on surfaces of clay minerals and in so doing increase the current carrying capacity. Compacted material also is a better conductor than unconsolidated material. It is therefore possible to distinguish between the major groups of rocks.

It is very important to note that in many instances a strong relationship exists between resistivity and lithology, and electrical resistivity methods can enable the recognition of change in geology due to resistivity contrasts.

3.1.5 Apparent Resistivity

If the electrode configuration (Fig. 3.1) is altered by increasing the separation of the current (AB) electrodes in a systematic manner, current penetrates deeper and deeper into the ground. Thus the depth to which the resistivity is measured will increase accordingly. If the medium is homogeneous the resistivity ρ will remain constant with the alteration of the electrode configuration; true resistivity is calculated from equation 3.5. In a situation where layers of different resistivity are present (inhomogeneous ground), the value of the resistivity will vary as the AB electrode separation is changed. Hence on inhomogeneous ground the value of ρ obtained from equation 3.5 is known as apparent resistivity and is usually denoted by ρ_a. In general terms apparent resistivity, ρ_a, is a measure of the effects of all the layers between the maximum depth of current penetration and the surface. The apparent resistivity depends upon the relationship between thickness and true resistivity of each individual layer of the ground. It must be emphasised, however, that ρ_a is not simply a mean of resistivities within some appropriate volume around the electrodes (Vingoe, 1972).

3.1.6 Techniques of conducting Resistivity Surveys

There are two fundamentally different techniques of carrying out resistivity investigations; (i) the horizontal profiling method and (ii) the vertical electrical sounding (VES) method. The method of horizontal profiling is used to determine the variations in apparent resistivity in a horizontal direction within a pre-selected depth range. Contrary to the horizontal profiling, the method of vertical electrical sounding furnishes detailed information on the vertical succession of different conductivity zones and their individual thickness and true resistivities around a fixed point O.

With the availability of various resistivity survey methods and electrode configurations it is of paramount importance to make an appraisal of the problem to be solved and to try and plan the survey procedure, before actual commencement of field investigations (Vingoe, 1972). The present study sought to establish the depth to the bedrock upon which the Karoo sediments have been deposited. The method of electrical soundings with Schlumberger's array of electrodes – which exclusively will be discussed further in this section – was found to be the most applicable technique for the purpose of this study.

In Schlumberger's electrical sounding the mid-point of the electrode configuration, is fixed at the observation station while the length of the configuration is gradually increased. As a result, the current penetrates deeper and deeper; the apparent resistivity measured at successively increasing distances between the current (AB) electrodes becomes more and more affected by the resistivity conditions at larger depths. In execution of the sounding the potential (MN) electrode spacing is kept constant while AB is increased progressively. Since only two electrodes are moved the field procedure with the Schlumberger array is labour saving as compared to those sounding techniques where all four electrodes are moved simultaneously, for example Wenner's array. In addition, since the MN electrodes are kept fixed, the effects of local shallow inhomogenities near to them are kept constant for all measurements. However, if at any stage the potential difference between the MN electrodes becomes to small to be measured accurately, then the MN separation should be increased accordingly and thereafter the AB separation is again increased and so on. The apparent resistivity is calculated from Equation 3.5, which the coefficient K is obtained from equation 3.6.

The data is usually presented graphically, the so-called resistivity curve, with apparent resistivity on the ordinate plotted against half the AB separation on the abscissa. The interpretation of the curve with the ultimate aim to determine the thickness and the true resistivities of individual sub-surface layers is carried out by matching the field curve with theoretical type curves.

3.1.7 Quantitative Interpretation of VES Curves

Numerous master curves have been constructed for many different combinations of homogeneous isotropic layers with different thicknesses and resistivities; these include the albums for theoretical curves generated by the CSIR for South African geoelectrical conditions (Joubert, 1977).

The first step in interpretation of VES data is to define the type of field curve. The three-layer curves are generally divided into four types (H, K, A, Q). These are illustrated in Figure 3.3 and described below.

(i) H-type curves (bowl shaped curves): The middle layer has a lower resistivity than both the layers above and below it.

(ii) K-type Curves (bell shaped curves): For this, the opposite is true, where the middle layer has a higher resistivity than those above and below.

(iii) A-type curves (ascending curves): The middle layer has a resistivity higher than the layer above it, but lower than the one below it.

(iv) Q-type curves (descending curves): The middle layer has a lower resistivity than the one above, but higher than the one below.

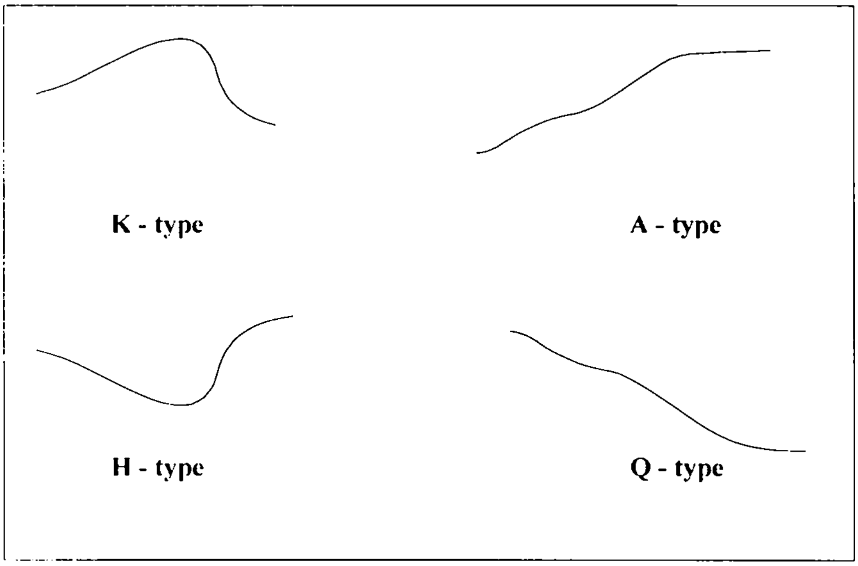


FIGURE 3.3 – Types of three-layer resistivity curves

In the interpretation of VES data, the field curve is superimposed on a similarly shaped set of theoretical curves until the best fit of the data is obtained, with the axes of the two graphs parallel. Then the co-ordinates of the point of intersection on the field curve axes of the axis 1,1 are read off in ohm-metres and metres. These values correspond to ρ_1 (true resistivity of top layer) and h_1 (thickness of top layer). The resistivity ratios given on the master curve yield the values for the resistivity of the other layers and the parameter on each curve is the ratio of the second layer thickness to that of the first. Thus the true resistivities and thicknesses may be obtained. An example of this is shown in Figure 3.4. (Rijkwaterstat, 1969) Here the field curve has been compared with the series of master curves and the best fit has been obtained with $\rho_1/\rho_2/\rho_3$ = 1.0 /0.04/1.0 and with h_2/h_1 = 2. The field curve is moved around, keeping the axes parallel, and the best fit corresponds to intercepts giving ρ_1 = 460 ohm-metres and h_1 = 4.3 metres. Thus the approximate layering is

(1) top layer, true resistivity 460 ohm-metres, thickness 4.3m
(2) middle layer, true resistivity 18.4 ohm-metres, thickness 8.6
(3) lower layer, true resistivity 460 ohms-metres

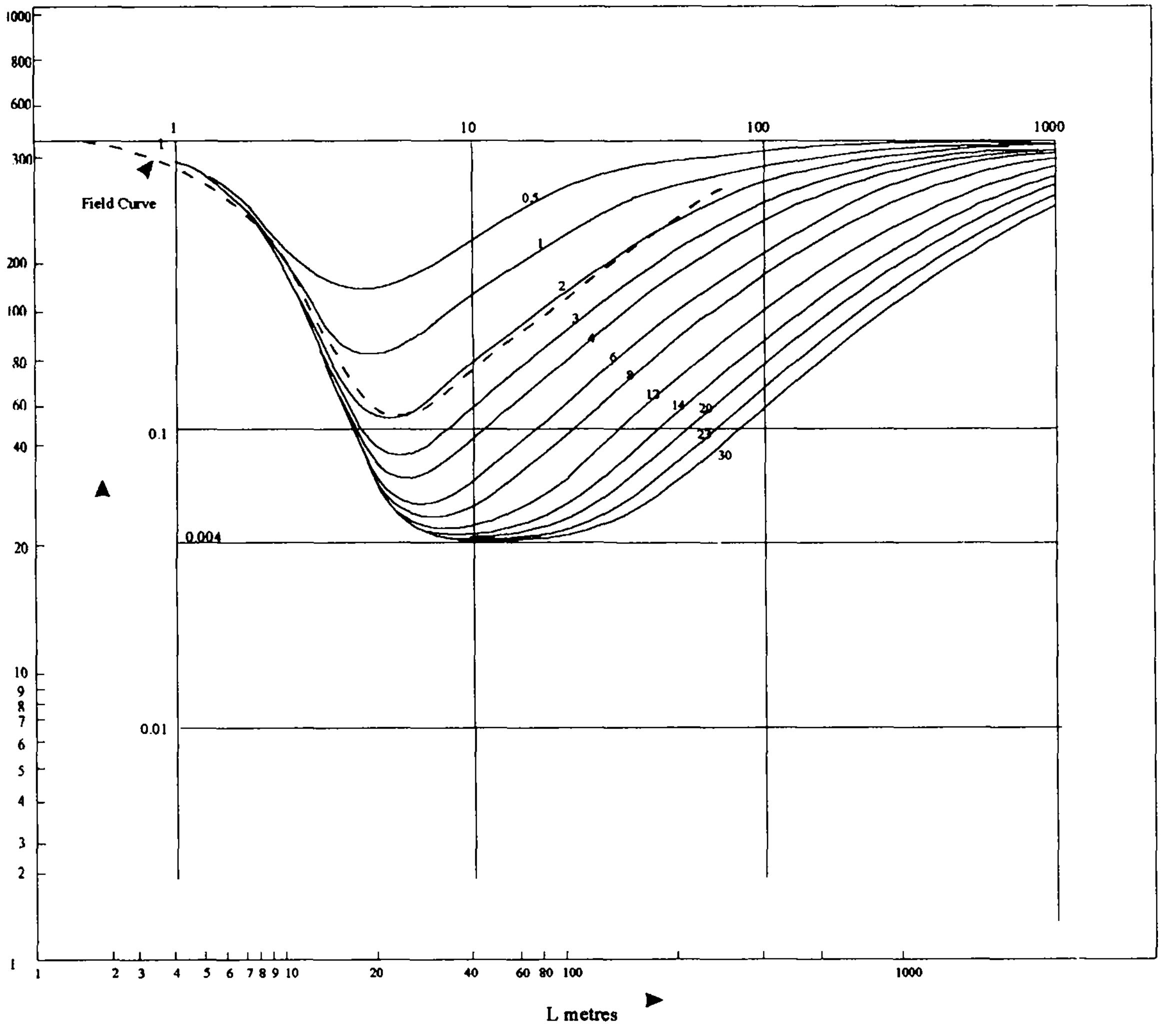


FIGURE 3.4 - Interpretation of VES data using the curve matching method

3.2 GEOLOGIAL MAPPING

3.2.1 Study of the Existing Geological Data

There has been no detailed survey of the geology of the area prior to the commencement of the study; thus no geological maps at an adequate scale were available. Furthermore, there is no comprehensive borehole data in Zimbabwe and the records that do exist are scattered between the Department of Water Development and District Development Fund – Water Division. Data on boreholes drilled in the study area from these sources is very rudimentary and the geological logs, water quality data, and pumping test data are often missing. In actual fact the computer records and completion forms for boreholes drilled in the area before 1996 are not amenable to quantitative use for the following main reasons:

- The data is obtained from driller's records of limited accuracy and with limited field control.
- The grid references are often inaccurate; it is thus difficult to match the data with actual borehole position in the field.
- The geology reported does not always accord with the known geology of the area.

An exception is the data obtained during the implementation of the Plan International supported IRWSS Programme between 1996 and 1999, which provides a comprehensive record for about 74 boreholes drilled in the study area. The relevant geological information was available in the various final hydrogeological reports compiled at the end of each phase. This included geological logs for each borehole (Appendix 1), which provided stratigraphical information not evident in field exposure. Figure 3.5 presents a map, which shows the locations of these boreholes.

3.2.2 LANDSAT Imagery and Aerial Photograph Interpretation

Photogeological mapping was performed using 1:100 000 LANDSAT Images obtained from SIRDC. The images used for the mapping were produced from LANDSAT bands 2, 4 and 7. The emphasis of the interpretation was to distinguish the various lithologies across the study area and to map the major faults and lineaments. The lithological boundaries and geological features inferred from images were then transferred to 1:50 000 topographical maps published by the Surveyor General.

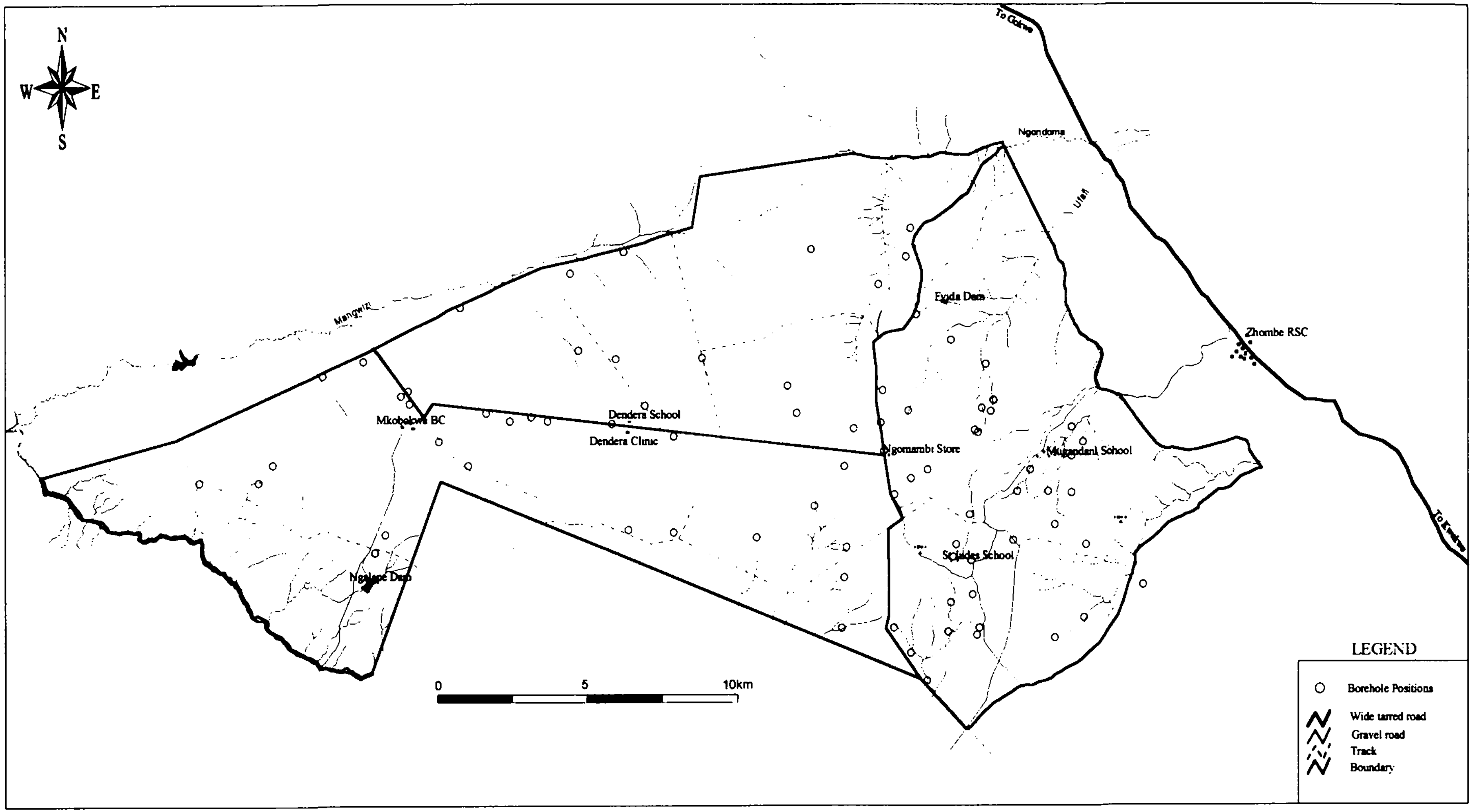


FIGURE 3.5 – Map showing borehole positions in the Dendera area

Black and White aerial photographs with stereographic cover at scale 1:25 000 were also available for the whole study area. However, the photographs were not found to be particularly useful for photogeological interpretation because there are insufficient changes in colour or texture, for one to be able to distinguish the various lithologies. Furthermore, there was no obvious evidence of structural deformation, such as faulting, from the photographs. Probably, geological features may have been obscured by the thick blanket of unconsolidated and structureless deposits, the Kalahari Sand and redistributed sands.

Following the photogeological interpretation field checks were carried out to verify both the lithological boundaries and stratigraphy.

3.2.3 Field Geological Mapping

Geological mapping in the field was done on the base photogeological map compiled from the LANDSAT Imagery. As the photogeological map had been superimposed on 1:50 000 topographic maps, it was possible to locate positions accurately using a hand-held Global Positioning System (GPS); thus lithological boundaries and geological features plotted on the base map could be easily verified.

Except for two or three sandstone and basalt inliers of Karoo age, outcrops of consolidated rocks are rare because much of the area is covered by structureless sands of Kalahari and Pleistocene age. Therefore, it has been difficult to work out the sub-Kalahari geology. The numerous motorable sandy tracks cutting across the area were used for making traverses with a four-wheel drive vehicle. Changes in colour of soils along the roads and on anthills were noted during the traverses. Several wells sunk for water and pits dug for construction of latrines were visited to study the rocks below the sands. This was done by examining soil and rock spoils around the wells and pit latrines.

The geological map, presented later in this chapter, is a synthesis of all available lithological and surface characteristics inferred from the LANDSAT interpretation, geological data contained in previous reports and the field geological mapping.

3.2.4 Geophysical Surveys in the Study Area

Equipment

The Terrameter SAS System, resistivity equipment, was used on the survey. The equipment, manufactured by Atlas Copco ABEM AB of Sweden, consists of a basic unit called the terrameter SAS 300C. SAS stands for Signal Averaging System, a method whereby consecutive readings are taken automatically and the results averaged continuously. The continuously up-dated running average is presented on the display. This continues until the operator is satisfied with the stability of the result. SAS results are more reliable than those obtained using single-short systems.

Data Collection

The principal aim of the electrical resistivity programme was to determine the depth to the top of the Basement rocks (bedrock). In order to achieve this a total of 24 VES surveys were conducted. The locations of the soundings are shown in Figure 3.6. Selection of the sounding sites was largely dependent upon the availability of tracks and roads as accessibility was generally poor due to the sandy conditions. Nevertheless, efforts were made to cover all parts of the study area where either drilling information was lacking or where boreholes did not intercept the bedrock. The geophysical team comprised the hydrogeologist (Author) and two assistants.

A typical AB expansion was between 200 and 500m. In most cases the sounding was deemed complete when the final portion of the curve was ascending at 45^0 and defined by at least four points, indicating resistive bedrock. In some cases, however, this was impossible to achieve because at large distances, especially when the electrode contact resistance was high, the instrument's 15-volt battery seemed incapable of delivering enough current for a potential difference to be measured across the MN electrodes. The presence of very high contact resistances due dry sand gave rise to the measurement of abnormally high earth resistances thereby resulting in strong distortion of the sounding curve. In order to reduce the contact resistance in some cases the ground around each electrode was soaked with salty water.

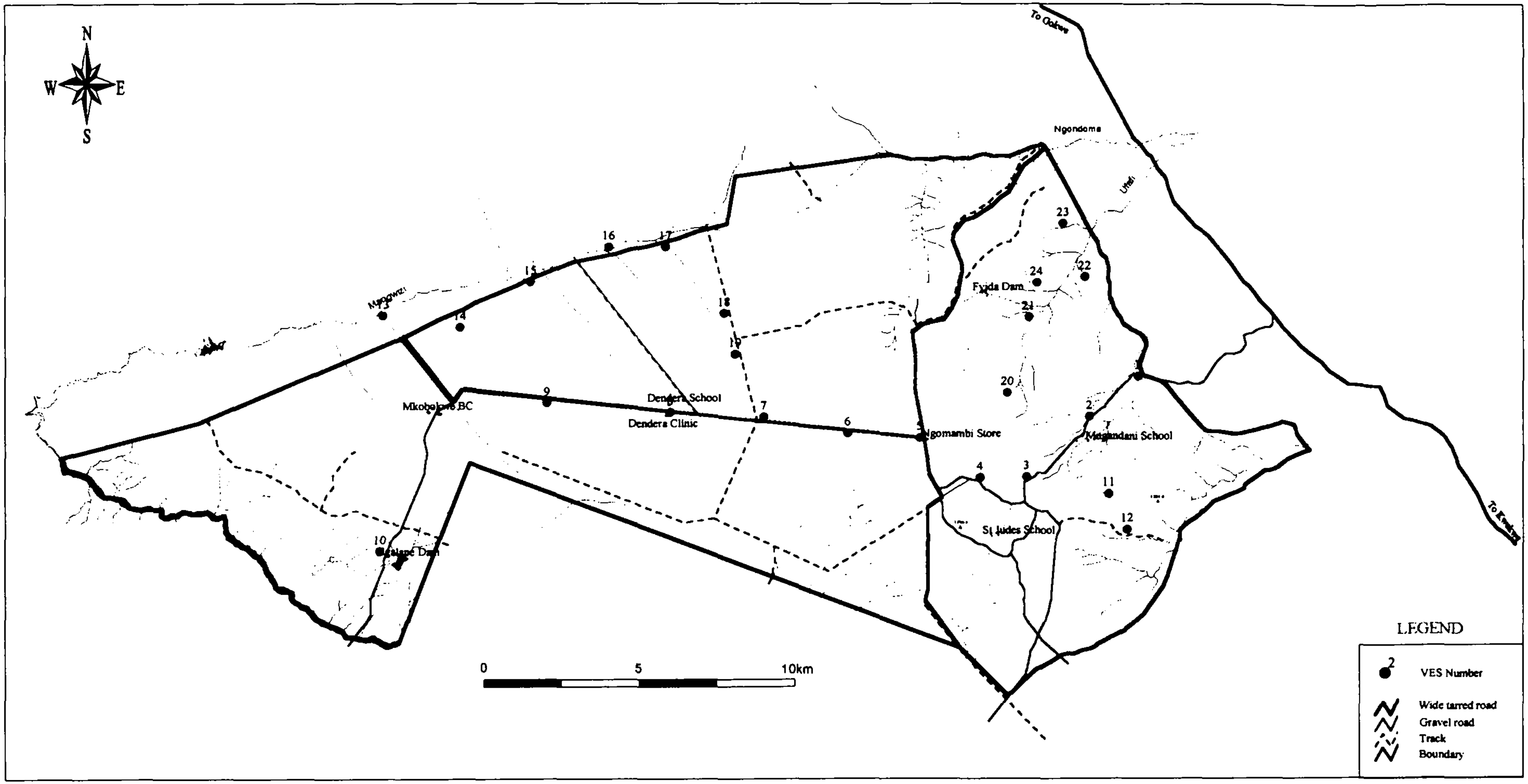


FIGURE 3.6 – Map showing the location of vertical electrical soundings (VES)

In all cases the data obtained were entered onto the pre-prepared tabulated sheets in the field. The apparent resistivity was then calculated and the data plotted on standard 62.5mm bilogarithimic transparent graph paper, with the apparent resistivity on the y-axis and the $^{AB}/_2$ distance on the x-axis. This enabled a qualitative estimate of the geoelectric nature of the earth at the VES point to be made, and provided information on whether it was necessary to increase the AB separation or not.

Interpretation of Data

Interpretation of the VES curves was carried out using standard type curves, and curve matching, as described for example by Vingoe (1972). The only necessary tools were a set of theoretical curves of two and three layer types (Sec.3.1.7). Several albums of theoretical curves are available for this purpose. The depths to bedrock derived from the VES surveys performed in the study area are given in Table 3.1.

3.3 STRATIGRAPHY

3.3.1 Outline of the Geology

The area is underlain by rocks of the Archaean Basement Complex and almost entirely blanketed by later Karoo, Kalahari and recent deposits. Figure 3.7 illustrates the surface geology of the study area, while Figure 3.8 gives the geological sections across the Dendera area.

The Archaean rocks consist of Basement Schists and Pre-Cambrian gneissic granites. Within the study area these rocks crop out in a very restricted area on the western margin where they have been exposed by denudation of the Karoo and Kalahari deposits along Gweru River. While only the gneissic granites are found on this western margin, Basement Schists are extensively exposed along the valley of the same river just outside the limits of the study area. Several boreholes have been drilled through the whole thickness of the Kalahari and Karoo deposits in the study area and all have intercepted either the granitic rocks or Basement Schists.

TABLE 3.1 – Vertical Electrical Sounding (VES) results: depths to bedrock

VES No.	Grid Ref.	Surface Elevation (m)	Depth to Basement (m)	Basement elevation (m)
1	QK200300	1144	35.2	1108.8
2	QK300500	1171	50.6	1120.4
3	QK710930	1216	120	1096.0
4	QK800906	1225	121	1104.0
5	QK300604	1243	124	1119.0
6	QK313800	1258	135	1123.0
7	QK854500	1251	133	1118.0
8	QK000700	1229	128	1101.0
9	QK900100	1220	115	1105.0
10	QK100800	1137	60	1077.0
11	QK100214	1207	49.3	1157.7
12	QK849710	1185	42.3	1142.7
13	QK133810	1137	41.3	1095.7
14	QK793319	1158	50.6	1107.4
15	QK207243	1153	66	1087.0
16	QK462721	1194	71.5	1122.5
17	QK800721	1158	66	1092.0
18	QK216900	1177	55.5	1121.5
19	QK660162	1161	60.5	1100.5
20	QK905514	1178	77	1101.0
21	QK801724	1139	65	1074.0
22	QK108430	1125	67.6	1057.4
23	QK200702	1130	85	1045.0
24	QK122176	1139	65.6	1073.4

During the early part of its geological history, Zimbabwe was in the centre of continental mass of Gondwanaland, which consisted of South America, Africa, India, Madagascar, Antartica and Australia. Gondwanaland underwent polar glaciation during the Carboniferous to Lower Permian. Melting of the ice sheet gave rise to the deposition of the Dwyka Group sediments, the oldest of the Lower Karoo sediments. As the temperature gradually rose freshwater lakes formed in the north-west and south-east parts of present day Zimbabwe and continued to enlarge in the following Ecca and Beaufort times (Lower and Upper Permian); the main areas of deposition were the Zambezi and Sabi-Limpopo basins respectively. Uplift, causing a break in deposition, was followed by widespread subsidence and spreading of the lakes towards the central watershed of the

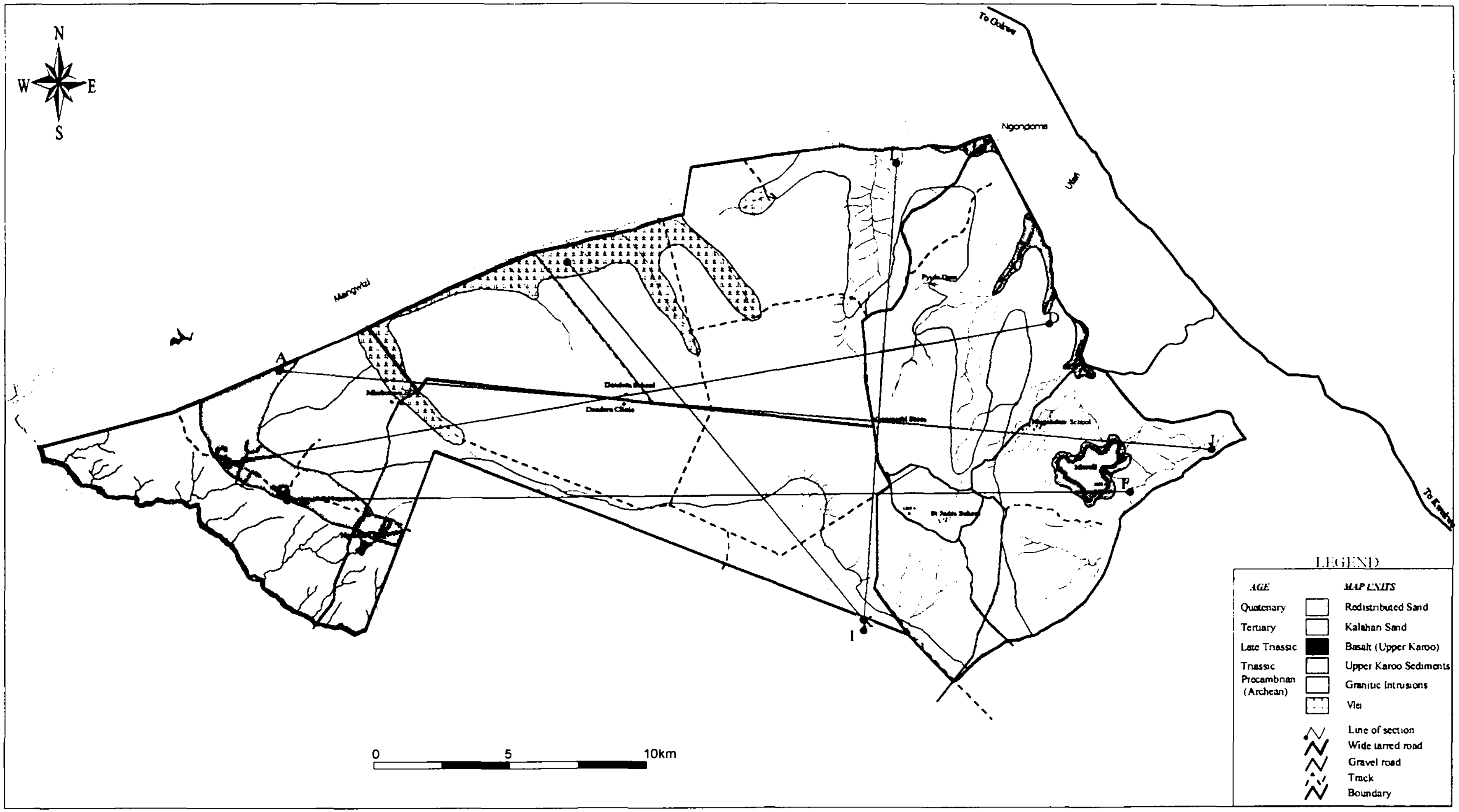


FIGURE 3.7 – Map showing the surface geology of the study area

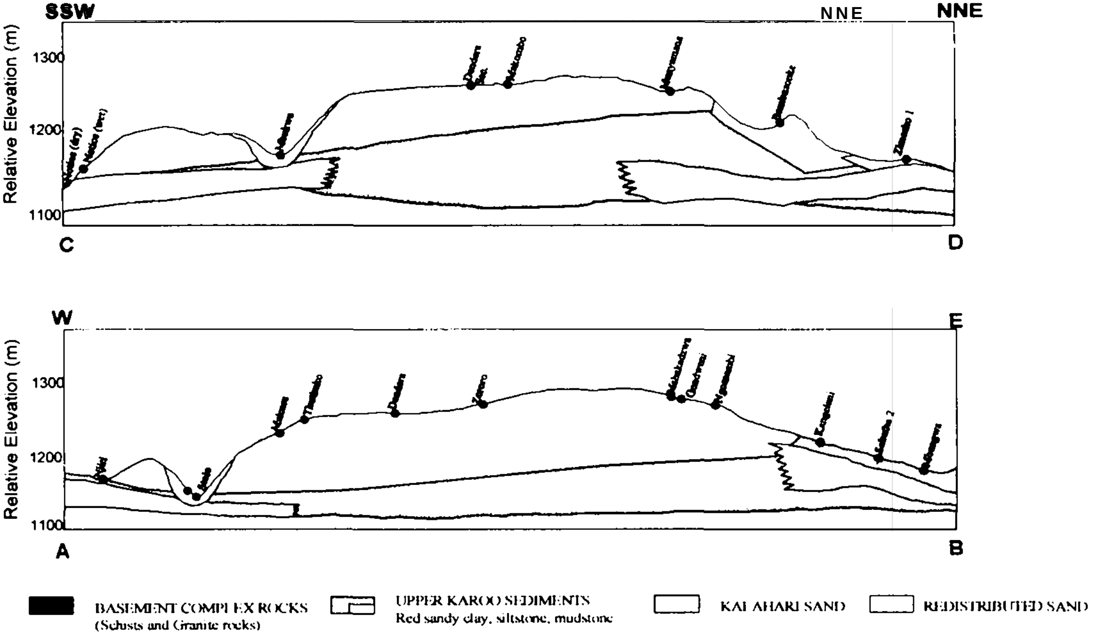
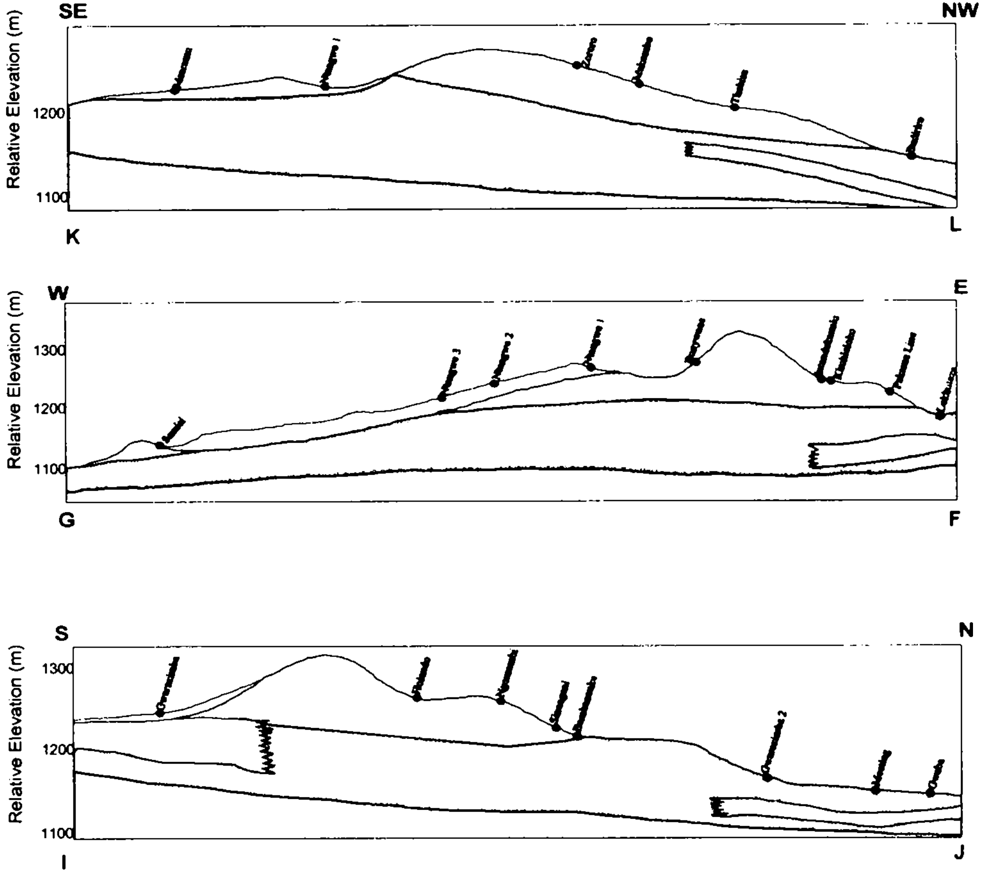


FIGURE 3.8 - Geological sections around Dendera area


SE
NW
Relative Elevation (m)
1200
1100
Zororo
K
L
W
E
Relative Elevation (m)
1300
1200
1100
G
F
S
N
Relative Elevation (m)
1300
1200
1100
I
J

country. Deposition of the Upper Karoo, Stormberg Series (Triassic age), was influenced by the continued warming up of the climate. Because arid conditions prevailed just before and during the eruption of the basalts, which terminated the Karoo Cycle, aeolian desert sands were deposited. In actual fact these sediments and lavas have been named the Karoo System, after the area in South Africa where most complete sequence is preserved and where this group of rocks was first described

The Dendera area is at the south-eastern margin of the former Zambezi Basin, with the result that only late stages of the sequence were deposited in the area as sediments gradually overlapped onto an ever increasing proportion of the Archaean Basement of the basin. These rocks consists of red siltstone, mudstone and fine sandstone typically overlain by fine and coarse grained sandstone, representing the middle part of the Stormberg Series – the last of the four Series which comprise the Karoo System in South Africa. The former sequence is lithologically similar to the Fine Red Sandstone Member, whilst the later most probably represent the beds of the Pebbly Arkose Member.

Except for the basalt capping the Mavule Hill – a tableland feature on the extreme eastern part of the area – the basalt lavas, which probably covered the whole area, were removed by denudation before the deposition of the Kalahari Sand.

Unconsolidated aoelian sand of Kalahari age, Tertiary to Recent, are preserved on a local plateau area, the watershed between the Gweru River and Ngondoma River systems. The Kalahari Sand possibly represents remnants of a once continuous blanket of sand, which covered much of the western half of Zimbabwe. The Kalahari Sand consists of upto 50m of uniform red-brown fine-grained moderately rounded sand. During the Pleistocene period, roughly the last million years of geological time, finishing touches were put to land as we now see it (Stagman, 1978). While there are no great deposits of sediments dating from this period, redistributed Kalahari sands are found where rivers have cut through the older rocks, and were derived from the resulting scarps of older sands. In the study area, zones of redistributed sands of Kalahari type have developed through a similar process, especially along valleys of major rivers and streams such as Gweru, Mangwizi, Ngondoma and Fafi. It appears, however, that the loose sand covering the eastern margin of the area, around Mavule Hill, may in fact be recent soils shed from weathered Karoo sediments

The geological formations in the area are shown in Table 3.2 and in the following Sections the formations are described in ascending order.

TABLE 3.2 - Stratigraphic Table for Dendera Area

QUATERNARY	
Soil Ferricrete and Silcrete	Pleistocene
Redistributed Kalahari Sand	And Recent
TERTIARY	
Aeolian Kalahari Sand	Late
Slight uplift and erosion; unconformity	Tertiary
KAROO SYSTEM	
Batoka Basalt lava flow	Lower
Minor unconformity	Jurassic
Pebbly Arkose Member: Sandstones	Triassic
Minor unconformity	
Fine Red Sandstone Member	Triassic
Major Sub-Karoo unconformity	
OLDER GNEISSIC GRANITE (Archaean Basement Complex)	Early
Gneissic granite	Precambrian
BASEMENT SCHISTS (Archaean Basement Complex)	Early
Maliyami Formation; andesitic and felsic lavas	Precambrian

3.3.2 Basement Schists

The oldest rocks in the area are the Basement Schists, so-named because they generally have schistose texture, and they are the foundation upon which all younger rocks have been deposited. These ancient rocks, being masked by the Kalahari and Karoo deposits, are nowhere exposed in the study area. However, some of the boreholes drilled in the area for rural water supply have in fact intercepted the Basement Schists. Moreover, the schists crop-out just outside the southern limits of the study area, along the Valley of Gweru River; this area was mapped by Amm (1946) and more recently was included in a geological bulletin by Harrison (1981).

The Gweru River exposure is actually the terminating edge of a tongue of schists, which extends northwestwards from the City of Kwekwe. This is a direct continuation of the Kwekwe Greenstone Belt, but evidently it is concealed beneath the younger deposits in the study area. The rocks of this part of the Kwekwe Greenstone Belt belong to the Bulawayan Group; the other two groups of the Basement Schists of Zimbabwe, the Sebakwian and Shamvaian, do not occur in the Dendera area.

In the outcrop area, the dominant rocks of the Bulawayan Group are little altered amygdaloidal and porphyritic andesitic lavas with interbedded agglomerates, tuffs and minor basaltic units. The most abundant type of andesite lavas are pale, greenish grey to slightly bluish grey, fine to medium grained rocks. These andesites are allocated to the Maliyami Formation (Harrison, 1981). The rocks resemble and directly adjoin the andesites of Maliyami Formation of the Kwekwe area (Harrison 1970).

The andesites of the Maliyami Formation are characterised by the abundance of fresh pyroxene. The pyroxene owes its existence to a very low-grade metamorphism compared to that of the rocks surrounding the formation. In other Greenstone Belts, however, pyroxene is virtually unknown, and Basement Schist lavas have been so metamorphosed that green minerals, particularly hornblende, are abundant – these minerals, impart a distinct green colour to the rocks, with the result that the terms 'greenstone' and 'greenschist' have been applied to these rocks wherever they occur.

In the Gweru River exposure tonalitic intrusions, such as the Stephenson Estate and Fairacres Tonalites, have pronounced metamorphic aureoles wherein the andesites are converted to hornblende schist and epidiorite. Apparently these altered rocks are indistinguishable from other greenstones of the Basement Schists. Thus, the altered andesites encountered by boreholes, which penetrated to the basement probably, represent aureoles of other tonalitic bodies intruding the andesites beneath the younger cover.

3.3.3 Granitic Rocks

The granitic rocks are exposed in a single area at the confluence of Gweru River and Mangwizi Stream on the western extremity of the study area. The granitic intrusion is slightly gneissic, medium - to coarse grained and of tonalitic composition. The body is a direct continuation westwards of the tonalite described by Harrison (1981) as occurring on the northwestern margin of the greenstone belt in the Gweru River Valley. In addition, several discrete granitic bodies, all of tonalitic composition, intrude the greenstone belt of the Gweru River Valley just outside the southern limits of the study area; the Fairacres Estate and Stephenson Block intrusions being the most prominent. The overall similarity in the lithology of all these intrusions leaves little doubt that they belong to the same period of granitic intrusion. In the north both the Fairacres Estate and Stephenson Block intrusions are evidently covered by Karoo and Kalahari deposits. It is possible that these and other separate tonalitic bodies are the granitic rocks encountered in several boreholes drilled for water in the study area.

3.3.4 Karoo System

Upper Karoo Sediments

The rocks of the Upper Karoo occur in the whole of the Dendera area, either at surface or below superincumbent rocks, except in a relatively small part on the western margin where the granitic rocks crop out. However, being extensively covered by Kalahari and redistributed sands, the Karoo sediments are poorly exposed in the area. Important exposures of the rock are found along the deeply incised channels of Ngondoma and Ufafi Rivers on the eastern extremity of the study area. On the western part of the area larger occurrences of Karoo sediments were noted forming a narrow band along the margin of the granitic outcrop and the younger deposits. Evidence from boreholes drilled in the area indicated a maximum thickness of the sediments of about 80m. Generally, the Karoo sediments dip gently to the northwest.

The Upper Karoo of the Dendera area equates with the Stormberg Series of the South African Karoo Super-Group. In this present study the lack of palaeontological data precludes direct chronological correlation between lithological units of this area with those of the South African succession. The lithological units are thus referred to as members using old established names based in many cases, on dominant rock type. On lithological grounds the Upper Karoo rocks of the area may be equated with the Fine Red Sandstone Member and Pebbly Arkose Member of the Mafungabusi area, which in turn have been assigned to the Red Beds Stage of South African Karoo by Sulton (1979).

Fine Red Sandstone Member

The Fine Red Sandstone Member occurs at the base of the sedimentary deposits of the area; thus it rests unconformably upon the basement. The member consists of fine-grained sandstone alternating with siltstone and mudstone and these have a distinct red colour. Commonly, a paler red or pink medium - to coarse - grained sandstone forms the base of the succession, but where it is absent the fine - grained red beds rest on the basement. The former coarser sandstone has a maximum thickness of 30m, whilst the thickness of fine-grained red beds ranges from 5m to 50m.

During this present study, it has been found extremely difficult to establish the uppermost limit of the Fine Red Sandstone Member because the lithostratigraphic information of the area was primarily derived from logging of drill-cuttings from boreholes drilled by percussion method, which generally causes mixing and winnowing of samples. Furthermore, the fine-grained sandstones that are similar to the Fine Red Sandstone Member occasionally occur within the overlying Pebbly Arkose Member; thus the lowermost part of the latter member can mistakenly be placed under the Fine Red Sandstone Member.

Pebbly Arkose Member

The sandstone, which makes up the larger part of the Pebbly Arkose Member, is typically medium - grained although in places the rock often grades to either finer or coarser grained sandstone. It is generally pale red, pink or buff to white in colour. However, red fine-grained sandstones similar to those of the Fine Red Sandstone Member commonly occur as relatively thick horizon in this sequence. Occasionally quartz pebbles were found within the sandstones during logging of drill cuttings - these possibly indicate the occurrence of pebble beds.

Karoo Basalt

The Karoo Basalt caps Upper Karoo sediments forming a tableland feature, namely the Mavule Hill. Mavule is a remnant of what used to cover the whole region. The basalt being exposed only on top of the hill was not investigated in detail during this study as it is of no hydrogeological importance in the area. However, fairly fresh basaltic boulders found at the bottom of the hill were studied. Freshly - broken rock is generally fine-grained dark bluish-black and porphyritic.

3.3.5 Kalahari Sand

In the Dendera area the Kalahari Sands mantle the interfluves and they represent the remains of a once continuous cover. Outliers as far east as Mvuma demonstrate that the sands were even more extensive in the past; they used to cover the entire western half of Zimbabwe before being stripped by denudation, especially along major river valleys (Lister 1987). Present - day basal contacts, lie between 1150 and 1200m above sea level and the Kalahari base tends to descent from east to west in the Dendera area. Over the whole study area the sands rest unconformably on the Upper Karoo Sediments. Maximum thickness, deduced from logging of drill-cuttings from percussion - drilled boreholes, is about 50m.

The Kalahari sand is orange-red or brown-red coloured structureless aeolian sand. Although uncemented the sand contains sufficient fines and clay to stand unsupported in trenches and pits. Throughout the study area no discernible bedding or lateral change in character is apparent within shallow excavation. The sand is composed of rounded to well-rounded quartz grains with frosted surfaces; the largest grains are very well rounded millet-seed grains. There is a high proportion of fine dust. Though there is no cement, grains are coated with iron (ferric) oxide, which imparts a reddish-brown or orange colour to the sand deposits as a whole.

3.3.6 Redistributed Sand

The redistributed sand of the area has been derived mainly from the Kalahari Sand. This younger sand, formed as a result of redistribution by recent water action of the leached white sand and also the red sand during wetter periods, occurs along the valleys of major rivers and streams. The scarps, which resulted from the rivers having cut into the older sands, are almost completely smoothed by the expanse of redistributed sand.

The redistributed sand is quite thin, generally less than 15m. Commonly it is yellowish grey or buff to white in colour, but in some places the sand retains a reddish colour of the parent Kalahari Sand. In contrast to the Kalahari Sand, the redistributed sand contain an abundance of fine silt and clay produced by the winnowing action of water. Typically, its terrain is of wide grass vleis such as along the Mangwizi and Mkobokwe streams. The widespread redistributed sands obscure large tracts of Upper Karoo Sediments on the eastern part around Mavule Hill, but overlie the older Kalahari Sand along the fringes of the local watershed.

3.4 DISTRIBUTIONS, AREAL EXTENT AND THICKNESS OF AQUIFER UNIT

Groundwater in the area appears to be derived almost entirely from the Upper Karoo sediments. Although the Kalahari sands are fairly thick, attaining a maximum thickness of 50m on the crest of the local watershed, they are virtually unsaturated. According to Prince (1997), it seems unlikely that this formation could act as an underground reservoir of any significance. The water-table in the Dendera area lies below the base of the Kalahari Sand hence it has been suggested that groundwater supplies from the Karoo aquifer are recharged through the Kalahari (Prince, 1997). Apart from playing a part in recharging the underlying aquifer, these sands are of little importance hydrogeologically within the study area; thus the distribution and thickness of the Kalahari Sand will not be discussed further. Evidently, assessment of the thickness of the Karoo sediments, the main water bearing formation of the area, is of paramount importance to the present study.

Sedimentary rocks of the Upper Karoo occur in the whole area, either at surface or below superincumbent sediments, except in relatively small part on the extreme west. It is noteworthy that the Karoo sediments are rarely exposed, because in areas where the Kalahari sands and basalt lavas have been completely stripped, outcrop is also obscured either by the redistributed Kalahari sands or a thin veneer of sandy soils derived from weathering of these sediments.

Although numerous boreholes were drilled in the area for rural water supply, only 35 are known to have penetrated the full thickness of the Karoo Sediments to the bedrock. The basement floor, underlying the Karoo rocks (Fig. 3.9) was deduced from the borehole intersections, in conjunction with geophysical determinations of the depth to bedrock. Geological cross-sections, given in Figure 3.8, were constructed using the basement elevation map, the surface topographical maps and known elevations of the Karoo Sediment/younger deposits contact in boreholes.

The greatest thickness of the Karoo Sediments coincides with the crest of the local watershed, between Ngomambi Store (QK324296) on the east and Dendera School (QK209310) on the west. None of the boreholes drilled in this part of the study area penetrate to the basement. However, the thickness of the sediments in this area was extrapolated from surrounding boreholes which had penetrated the full thickness of this unit, from overlying Kalahari/redistributed sands to the basement floor; this was achieved through construction of geological sections (Fig 3.8), as mentioned earlier. The sediments attain a maximum thickness of approximately 80 metres in this central part of the study area.

Although the Karoo sediments are preserved below the Kalahari Sand on the local watershed, they have a tendency of thinning westwards (Fig 3.10); indeed on the western most part the thickness of the sediments is less than 40m. This decrease in thickness is clearly not due to effects of recent erosional activities, as the sediments are noticeably preserved by the Kalahari Sand. It is probable, however, that successively larger quantities of sediments were removed by erosion towards the west, prior to the deposition of the Kalahari System; evidently the pre-Kalahari surface slopes gently from east to west at a gradient of 4m per kilometre.

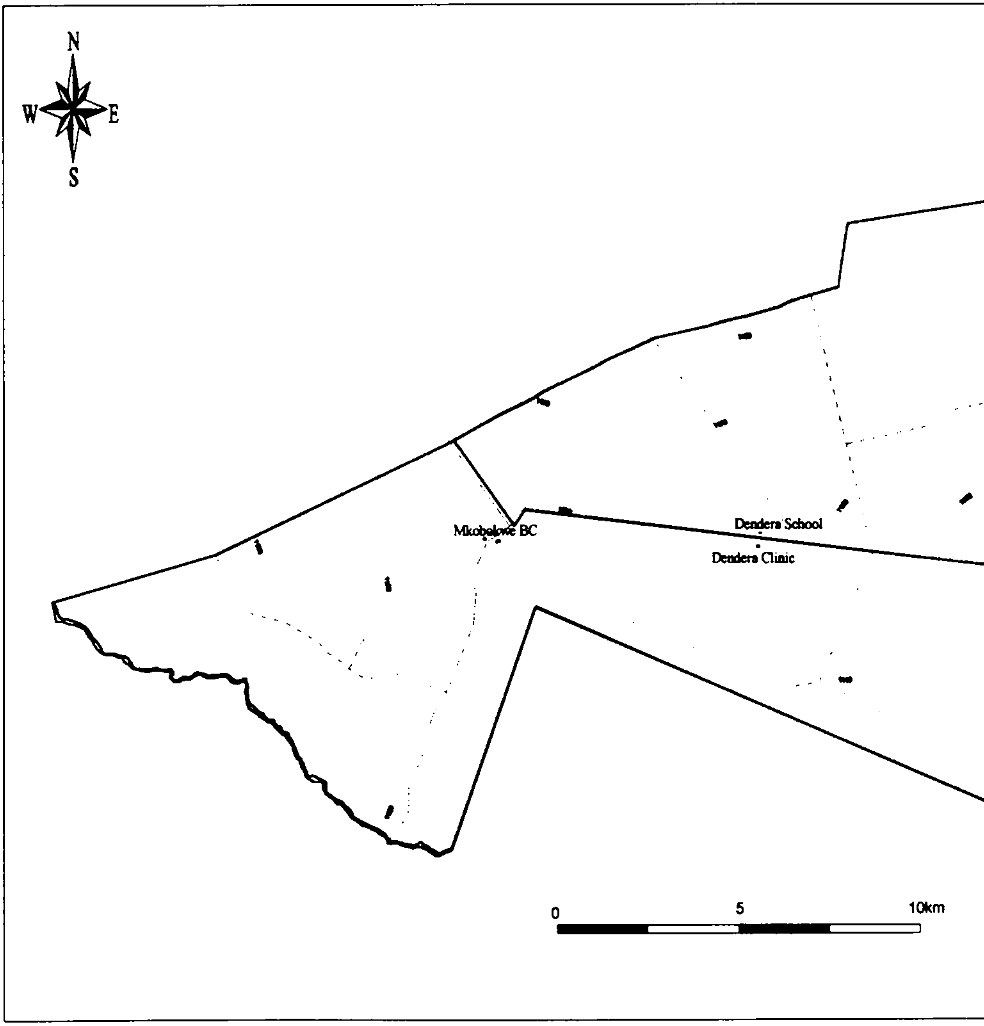
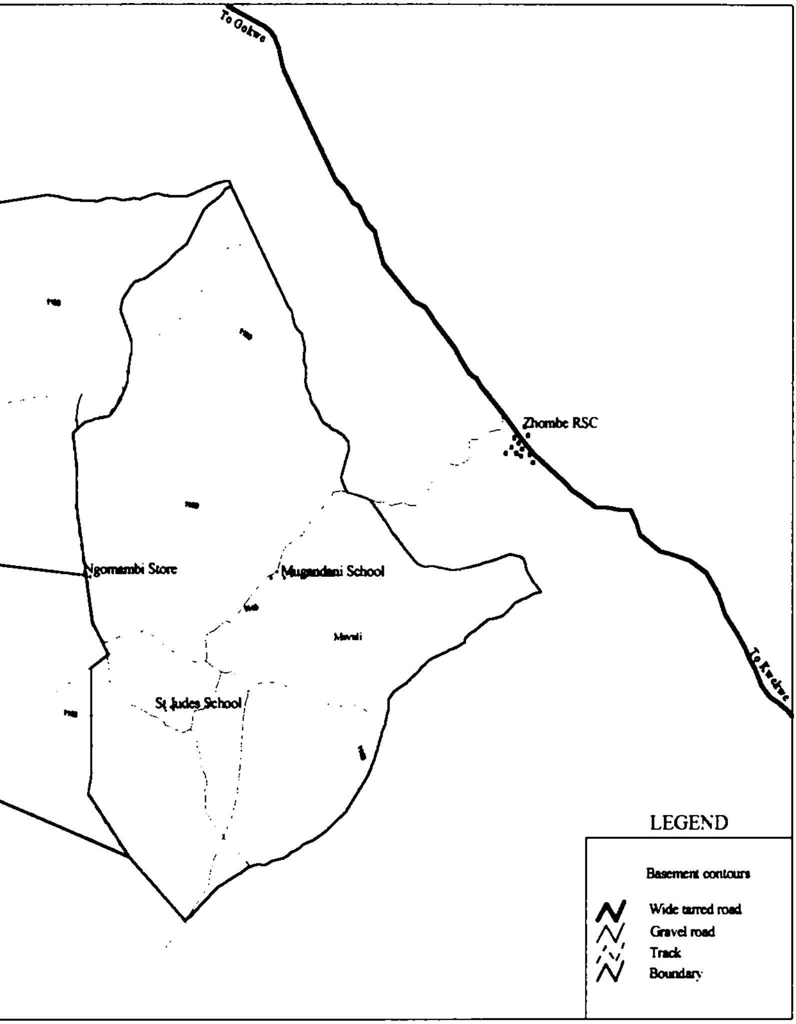


FIGURE 3.9 – Map showing the basement topography


To Gokwe
Zhombe RSC
Ngomambi Store
Mugandani School
Mavuli
St Judes School
To Kwekwe
LEGEND
Basement contours
Wide tarred road
Gravel road
Track
Boundary

In parts of the area further away from the local watershed the Kalahari mantle was stripped and subsequent denudation has resulted in rapid decrease in thickness of Karoo sediments towards the major drainage features: north-west towards the Mangwizi Stream; southwards to Gweru River; and east and north-east towards the Ngondoma/Munyati River System. In actual fact denudation has completely removed Karoo Sediments in the small portion at the junction of Gweru River and Mangwizi stream on the northwest.

To summarise, the Karoo Sediments are present in the whole study area except for a small part of the extreme west where granitic rocks are exposed. Generally its thickness ranges from 30m to 80m. The thickness is, of course much less than 30m in the vicinity of the granitic exposure on the west.

An attempt was also made to plot an isopachyte map of the Karoo sediments and this is presented in Figure 3.10.

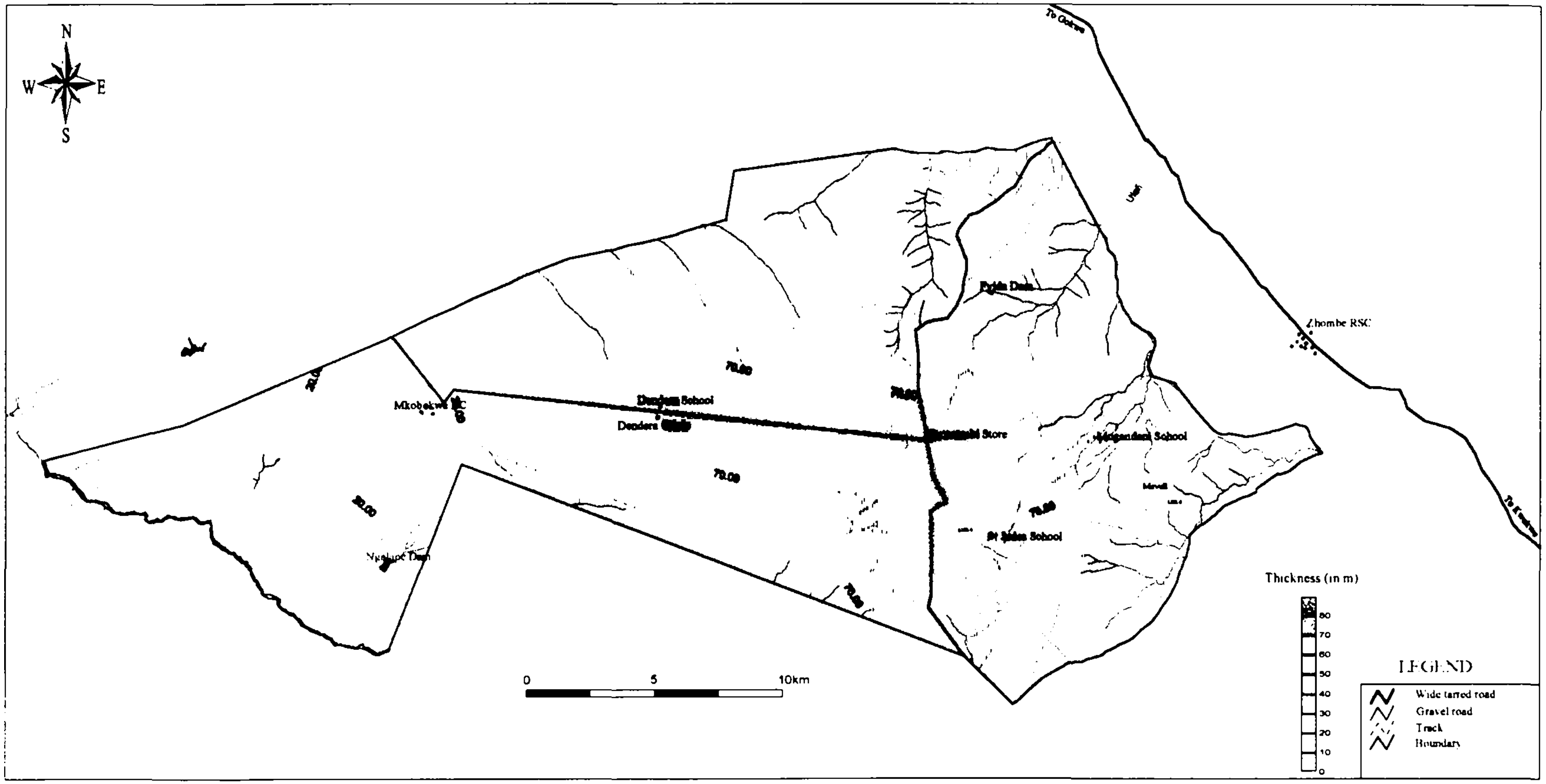


FIGURE 3.10 – Isopachyte map showing the distribution of the Karoo Sediment thickness

4.0 HYDRAULIC PARAMETERS AND AQUIFER TESTS

4.1 BASIC CONCEPTS AND DEFINATIONS

4.1.1 Hydraulic Head

Groundwater flow through the aquifer is controlled by physical laws of potential and kinetic energy. The forces driving the water forward must overcome the frictional forces set up between the moving water and the grains of the aquifer material. The direction of flow in space must be away from regions in which the mechanical energy per unit mass of the fluid, water, is higher toward regions in which it is lower. Therefore, as clearly described by Freeze and Cherry (1979, pg. 19), water at any point within an aquifer has a fluid potential, ϕ, which is made up of three components: gravitational potential energy due to its elevation (z) above an arbitrary datum level; kinetic energy due to its velocity of flow (v); and potential energy owing to the surrounding pressure (p) acting upon it. The fluid potential, ϕ, is thus given by the Bernoulli equation:

$$\phi = gz + \frac{v^2}{2} + \frac{p}{\rho} \qquad (4.1)$$

where g is the gravitational constant and ρ is the fluid density.

The velocity of groundwater flowing in porous media under natural gradients is generally very low, and as such the kinetic energy component always may be safely ignored in groundwater flow. The formula then becomes

$$\phi = gz + \frac{p}{\rho} \qquad (4.2)$$

If a small diameter borehole is drilled vertically to a point of interest and the bottom tip screened to allow inflow of water at one point, it is known as a piezometer. It measures the hydraulic head, h, at the point under consideration in the aquifer. The water level in the piezometer is in direct proportion to the total fluid potential (ϕ) at the point at which it is open to the aquifer material. Hubbert (1940) showed how the components which make up the fluid potential ϕ are related to the hydraulic head h: at equilibrium the fluid potential in the aquifer is simply the product of the hydraulic head (h) at the point and the acceleration due to gravity (g):

$$\phi = gh \tag{4.3}$$

Since hydraulic head (h) is simple to determine in the field it commonly used as a convenient measure of fluid potential at a point in an aquifer.

Combining Eqn. 4.2 and 4.3 yield

$$\phi = gz + \frac{p}{\rho} = gh \tag{4.4}$$

or, dividing through by g,

$$h = z + \frac{p}{\rho g} \tag{4.5}$$

For a fluid at rest the pressure at a point is equal to the weight of the overlying water per unit cross-sectional area:

$$p = \rho g h_p \tag{4.6}$$

where h_p is the height of water that provides pressure head. Substituting into Equation 3.7 gives

$$h = z + h_p \tag{4.7}$$

Therefore the total hydraulic head, h, is the sum of the elevation head, z, and pressure head, h_p. This fundamental head relationship is basic to an understanding of groundwater flow.

4.1.2 Darcy's Law

The French engineer, Henry Darcy, was the first to establish empirical relationship between hydraulic head and the flow of water through porous material. This was through the study of the movement of water through a sand column. Darcy found that the rate of flow is proportional to the difference in the height of the water, the hydraulic head, between the two ends of the column and inversely proportional to the length of the flow path. He also found that this constant was proportionally dependent on the physical properties of the permeable material.

If the cross-sectional area of a column is A and rate of flow is Q the flow per unit cross-sectional area, known as Specific discharge, q, is expressed as

$$q = \frac{Q}{A} \tag{4.8}$$

If Q and A is measured in m^3/day and m^2 respectively, q will be in units of m/day; it thus has dimensions of a velocity. If h_1, and h_2 are heads at each end of the column the former being greater and l is the distance between the ends, then Darcy's relationship can be expressed as

$$q \; \alpha \; h_1 - h_2 \tag{4.9}$$

$$q \; \alpha \; 1/l \tag{4.10}$$

These equations of can be combined to give

$$q \; \alpha \; \frac{h_1 - h_2}{l} \tag{4.11}$$

When combined with the proportionality constant, K, the result is the expression known as Darcy's Law:

$$q = \frac{Q}{A} = -K \frac{h_1 - h_2}{l} \tag{4.12}$$

The expression on the right-hand side represents difference in head per unit distance or hydraulic head, and in different form can be written as dh/dl. Substituting in Equation 4.12 gives

$$q = \frac{Q}{A} = -K\frac{dh}{dl} \qquad (4.13)$$

The negative sign is a convention employed to indicate that flow is in the direction of decreasing hydraulic head.

4.1.3 Hydraulic Conductivity

The hydraulic conductivity, K, is the constant of proportionality in the Darcy's law (equation 4.13). Evidently, in the flow of groundwater, this parameter K is proportional to the physical properties of the porous medium. For example, it will be high for very permeable material such as uncemented well-sorted sand or gravel and low for well-cemented sediments or clay. An expression defining K may be obtained by re-arranging the equation for Darcy's Law:

$$K = -q\frac{dh}{dl} \qquad (4.14)$$

$$\text{or} \quad K = \frac{Q}{A} \bullet \frac{dh}{dl} \qquad (4.15)$$

The hydraulic conductivity, which is sometimes called the coefficient of permeability, particularly in older text books, can formally be defined as the volume of water that will move through a cross section of the aquifer of unit thickness and width under unit hydraulic gradient. Hydraulic conductivity can have any unit of Length/Time, for example m/d.

The term, intrinsic permeability, which at times is confusingly used in place of hydraulic conductivity, also needs to be defined. The intrinsic permeability, k, which is also known as permeability, depends only on matrix properties, unlike the hydraulic conductivity where the properties of the fluid are also important factors. In sediments, the permeability is basically a function of several matrix properties: the size and distribution of pore openings, the shape of pores, the surface area which the fluid contacts; and degree of cementation.

4.1.4 Storativity

Storativity, S, or the coefficient of storage of an aquifer represents the quantity of water released from storage per unit surface area of aquifer per unit change in head. The description of storativity cannot be completed without mentioning the concepts of specific yield, S_y, and specific storage, S_s.

The specific yield is defined as the volume of water that an unconfined aquifer releases from storage per unit decline in the water table, due to gravity drainage of pore spaces. Clearly, this concept is not applicable to a confined aquifer because the lowering of head does not dewater the aquifer material.

The specific storage of an aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head due to: (i) the compaction of the aquifer caused by drop in pore water pressure, which reduces effective porosity; and (ii) the expansion of pore water caused by decreasing pressure. In a confined aquifer the water released comes from the entire thickness of the aquifer and all of it is released by the compaction of the aquifer skeleton and the expansion of the pore water; the aquifer remains fully saturated. The storativity of a confined aquifer, therefore, is the product of specific storage (S_s) and aquifer thickness (b):

$$S = bS_s \qquad (4.16)$$

For unconfined aquifers the release of water from storage is primarily due to the specific yield of the aquifer unit. As water level drops, water is released from storage because of gravity drainage of pore spaces and thus the level of saturation falls with release of water from storage. Water is also expelled depending on the specific storage of the aquifer unit; it is released by compaction of aquifer and expansion of water due to decline in pressure.

Therefore, for an unconfined aquifer the storativity is found by the formula

$$S = S_y + hS_s \qquad (4.17)$$

where h is the saturated zone thickness.

The value of the specific yield (S_y) is much greater than hS_s for an unconfined aquifer such that the storativity (S) is taken to be the same as the specific yield of the aquifer. The value of S for unconfined aquifer range from 0.01 to 0.3. The storativity is much lower in confined aquifers because pore space is not drained during pumping and any water released from the storage is obtained primarily by compression of the aquifer and expansion of water when pumped. Its value commonly ranges from 10^{-5} to 10^{-3}.

4.1.5 Transmissivity

In Section 4.1.3 the capability of an aquifer to transmit water was defined in terms of the permeability (k) and hydraulic conductivity (K), but unfortunately these parameters are not necessarily constant throughout the aquifer thickness nor are they easily measured. Consequently it is more practical to consider the concept of aquifer transmissivity, T, which represents the transmission capability of the entire thickness of the aquifer. Transmissivity is defined as the rate that water can be transmitted horizontally by the full aquifer thickness per unit width under a unit hydraulic gradient.

The transmissivity is equivalent to the integral of the hydraulic conductivities over the saturated thickness of the aquifer:

$$T = \int_{z_1}^{z_2} K \, dz \qquad (4.18)$$

where z_1 and z_2 are elevations of bottom and top of the saturated portion of the aquifer, and K_i is the hydraulic conductivity at z_i. T may also be regarded as the product of average hydraulic conductivity, K and the saturated thickness b:

$$T = bK \qquad (4.19)$$

The storativity (S) and transmissivity (T) are especially important because they define the hydraulic characteristics of a water-bearing formation. The transmissivity indicates the rate of which water can move through a formation, and the storativity indicates how much can be removed by pumping or draining. Knowing of these two parameters for a particular aquifer makes it a possible to determine aquifer behaviour in response to pumping so that prediction can be made of;

(i) Drawdown in the aquifer at various distances from a pumped well.
(ii) Drawdown in a well at any time after pumping starts.
(iii) Drawdown in the aquifer at various pumping rates.

4.1.6 Hydraulic Gradient and Groundwater Contour Maps

If the value of the hydraulic head (h) is variable in an aquifer, a contour map may be constructed showing lines of equal value of h. The lines connecting points of equal h are called equipotential lines. The resulting map is referred to as potentiometric map and for unconfined aquifer it is also called water table map.

As previously noted, water moves from region of high hydraulic head to regions of low hydraulic head, flow being in the direction of maximum hydraulic gradient (Δh). This implies that for isotropic aquifers the direction of flow is parallel to Δh, which means that it is also perpendicular to the equipotential lines (the potentiometric surface contours). Lines drawn so that they cross successive contours orthogonally represent groundwater flow paths and such lines are known as flow lines. The system of intersecting flow lines and the potentiometric surface contours (Fig. 4.1) is called a flow net. The construction of flow nets and their application in the analysis of groundwater flow is not further discussed as this is beyond the scope of the present study. Complete discussions of flow net analysis are found in numerous standard hydrogeological textbooks.The potentiometric surface map can be used to;

- determine the direction of groundwater movement; this is its most obvious use.
- determine areas of recharge and discharge
- determine areas of high transmissivity
- determine river-aquifer interactions
- detect the presence of impervious zones or faults
- delimit the ground water divide

- determine changes in storage if S is known and two maps from different times are superimposed
- calculate the transmissivity (T) when closed contours occur due to heavy pumping

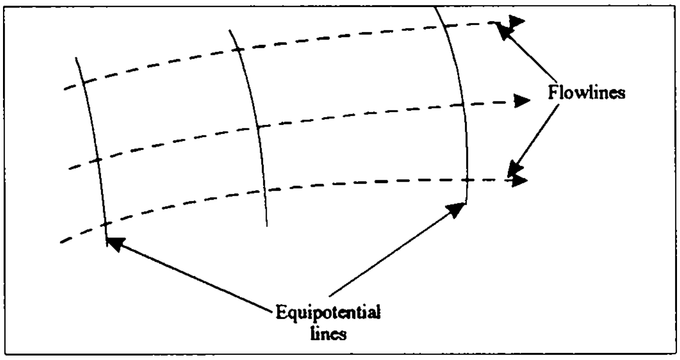


FIGURE 4.1 – A flow net

In the interpretation of potentiometric maps, the following should be noted (Domenico and Schwartz, 1990).

1. A potentiometric map must be related to a single aquifer.
2. Flow in the aquifer is assumed to be horizontal, that is, parallel to the upper and lower confining layers.
3. Head losses between equipotential lines are equal and the Δh varies inversely with distance between lines of equal head.

While, it has been stated that in an isotropic medium, the flow is perpendicular to equipotential lines this condition is not satisfied in anisotropic media. Thus the condition of isotropicity is another assumption in the interpretation of potentiometric maps.

The spacing of equipotential lines as protrayed on a poteniometric map can reflect a variety of conditions: (i) potentiometric contours become more widely spaced in the direction of increasing hydraulic conducitvity (Fig. 4.2); (ii) potentiometric contours become more closely spaced due to a gain in flow by recharge from surface for example – the opposite applies when water is lost such as by discharge to streams; and (iii) when the aquifer thickness increases in the direction of flow the potentiometric contours become further spaced. Noteworthy is the fact that if both conductivity and aquifer thickness increase in the direction of flow, the wider spacing becomes more pronounced.

Conversely, aquifer conditions can be inferred from convergence and divergence of flow lines; convergence indicates increasing conductivity or discharge of water from aquifer by discharge (Fig. 4.3a and 4.3d), while divergence indicates decreasing conductivity or recharge to the aquifer (Fig. 4.3 and c).

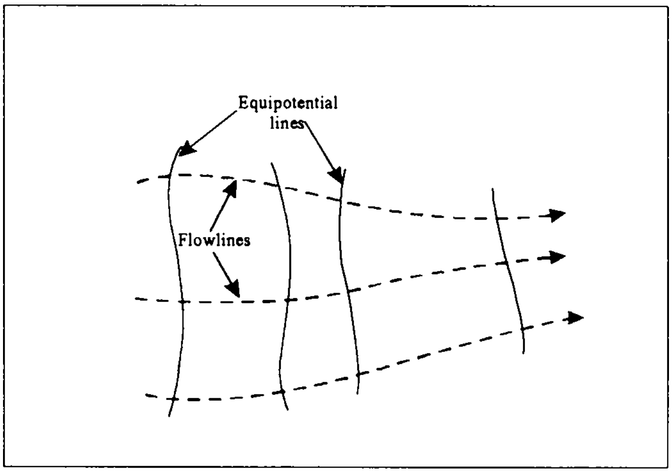


FIGURE 4.2 – Potentiometric map and intersecting flow lines for a non-homogeneous aquifer

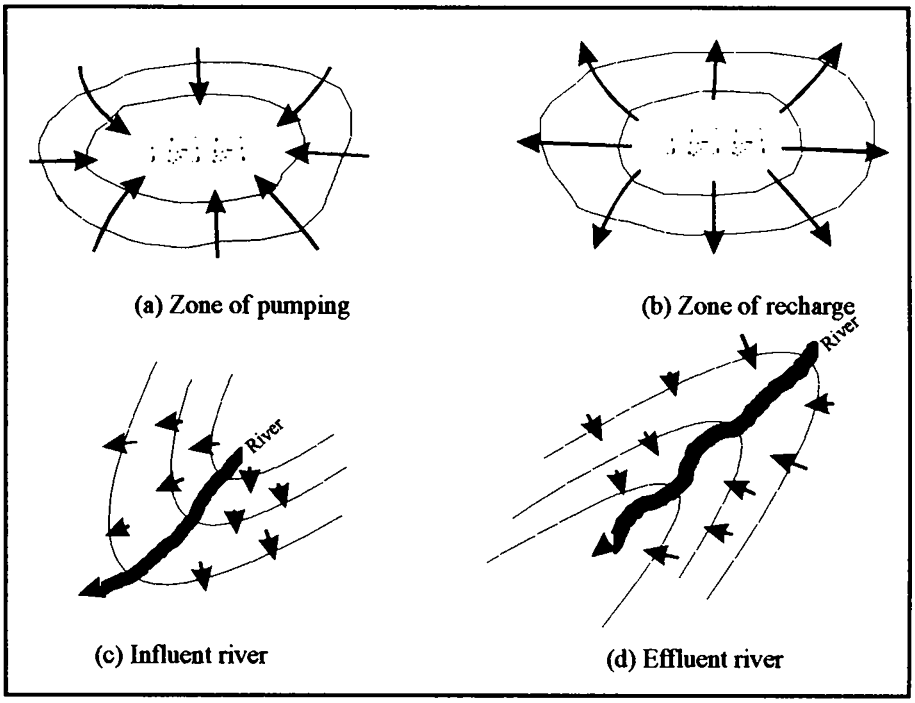


FIGURE 4.3 – Convergence of flow lines and aquifer conditions

4.2 GROUNDWATER FLOW TO WELLS IN UNCONFINED AQUIFERS

The abstraction of groundwater from an aquifer results in the decline of the water level, that serves to limit the abstractable yields. Consequently, the prediction of the drawdowns in aquifers under proposed pumping schemes constitutes an important facet of groundwater resource evaluation. There is vast literature on the topic of flow to wells under different hydraulic conditions. This section only deals with aspects, which are relevant to the unconfined aquifer as it is the only aquifer condition likely to be applicable to the study area.

4.2.1 Ideal Aquifer Conditions Assumed for Radial Flow to Wells

In the mathematical analysis of the flow to wells several assumptions are commonly made about the hydraulic conditions in the aquifer and about the pumping and observation boreholes. The equations for radial flow to wells are generally based on the following assumptions (Fetter, 1994):

1. The aquifer is underlain by an aquiclude.
2. The aquifer is infinite laterally and made of geologic formations that are horizontal.
3. The water table or potentiometric surface is horizontal before commencement of the pumping.
4. All changes in position of the water table or potentiometric surface are due to the effects of the pumping borehole alone.
5. The aquifer is homogenous and isotropic.
6. Groundwater flow is horizontal and radial toward the well.
7. Groundwater has a constant density and viscosity.
8. The pumped borehole and observation wells penetrate and are in full hydraulic communication with the full thickness of the aquifer.
9. The pumping-rate is constant.
10. The pumping borehole is 100% efficient.

For analytical solutions to be obtained, it is necessary to make specific assumptions about the particular aquifer conditions so that a correct method can be selected. Since, only the unconfined aquifer condition is relevant to the present study only analytical solutions appropriate to this condition are of interest and these usually include additional assumptions:

1. The aquifer is unconfined
2. The influence of the unsaturated zone upon the drawdown in the aquifer is negligible.
3. Water initially pumped comes from the instantaneous release of water from elastic storage (S_s).
4. Eventually water comes from storage due to gravity drainage (S_y).
5. The drawdown is negligible compared with the saturated aquifer thickness, hence T is constant with time.
6. The specific yield (S_y) is at least 10 times the elastic storativity (S_s).

4.2.2 Radial Flow to a Well

When a fully penetrating borehole pumps an unconfined aquifer, the influence of pumping extends radially from the well with time. Flow toward the well is termed radial flow. The pumping of the well causes a dewatering of the surrounding aquifer and creates a cone of depression in the water-table. As the pumping continues, the cone of depression expands and deepens and flow towards the well has a clear vertical component. The flow of water in the unconfined aquifer towards a pumping well is described by the following equation:

$$K_r \frac{\delta^2 h}{\delta r^2} + K_r \frac{\delta h}{\delta r} + K_z \frac{\delta^2 h}{\delta z^2} = S_s \frac{\delta h}{\delta t} \qquad (4.20)$$

where

h is the saturated thickness of aquifer (m)
r is radial distance from pumping well (m)
z is elevation above the base of the aquifer (m)
S_y is specific storage
K_r is radial hydraulic conductivity (m/day)

K_v Vertical hydraulic conductivity (m/day)
t is time (days)

The equation takes into account that the hydraulic head and drawdowns around a well will possess a radial symmetry in the ideal unconfined aquifer system.

4.2.3 Response of Unconfined Aquifer to Pumping

A well pumping from an unconfined aquifer extracts water from two mechanisms discussed earlier in Section 4.1.4. A small proportion is initially derived from aquifer compaction and expansion of water. The aquifer also yields water due to gravity drainage from aquifer interstices as the water table declines according to its specific yield (S_y).

One problem encountered in unconfined aquifers is that of a delayed water table response (delayed yield), which invalidates one of the assumptions of well flow equations - "release of water from storage is immediate in response to drop in water table". Delayed yield results from lag time of water draining from a previously saturated zone to a falling water table. Therefore, before dealing with the analytical solutions to the flow to wells in unconfined aquifers, a qualitative description of the response of a water table well to pumping may be helpful.

Aquifer response in the vicinity of an observation borehole shows three distinct phases of time-drawdown relations. On logarithmic plot the curves usually show a typical elongated S-shape, which in fact clearly reflects three segments corresponding to each of the phases; early-time segment, a flat intermediate-time segment and a relatively steep late-time segment (Fig. 4.4). The three time segments of the curve may be explained as follows (Kruseman and de Ridder, 1990);

1. For a brief period after commencement of pumping the drop in pressure result in the release of a small volume of water from storage due to the expansion of water and compaction of the aquifer. During this time the aquifer reacts in the same way as the confined aquifer. Thus the time-drawdown data follow the Theis non-equilibrium curve, a curve defining response of ideal confined aquifer, and the storativity is in the order expected for confined conditions. Flow is horizontal during this period, as the water is being derived from the entire aquifer thickness.

2. With increased time the effects of gravity drainage are noticed. At this stage both the horizontal and vertical flow components are present. The drawdown-time relationship is a function of the ratio of horizontal-to-vertical conductivities of the aquifer, the distance to the pumping well and the thickness of the aquifer. There is a decrease in the slope of the drawdown-time curve relative to the Theis curve such that after a few minutes to a few hours of pumping the drawdown-time curve may approach the horizontal (Fig. 4.4). This is because the water delivered to the well by the dewatering that accompanies the falling water table is greater than that which would be delivered by an equal decline in a confined potentiometric surface.

3. As time progresses, the rate of drawdown decreases and the contribution to drawdown by gravity drainage diminishes. The flow in the aquifer is again essentially horizontal and the drawdown-time curve once again tends to conform to the Theis type-curve; the aquifer reverts to behaving like a confined aquifer. Actually, the Theis curve now corresponds to one with a storativity equal to the specific yield of the aquifer.

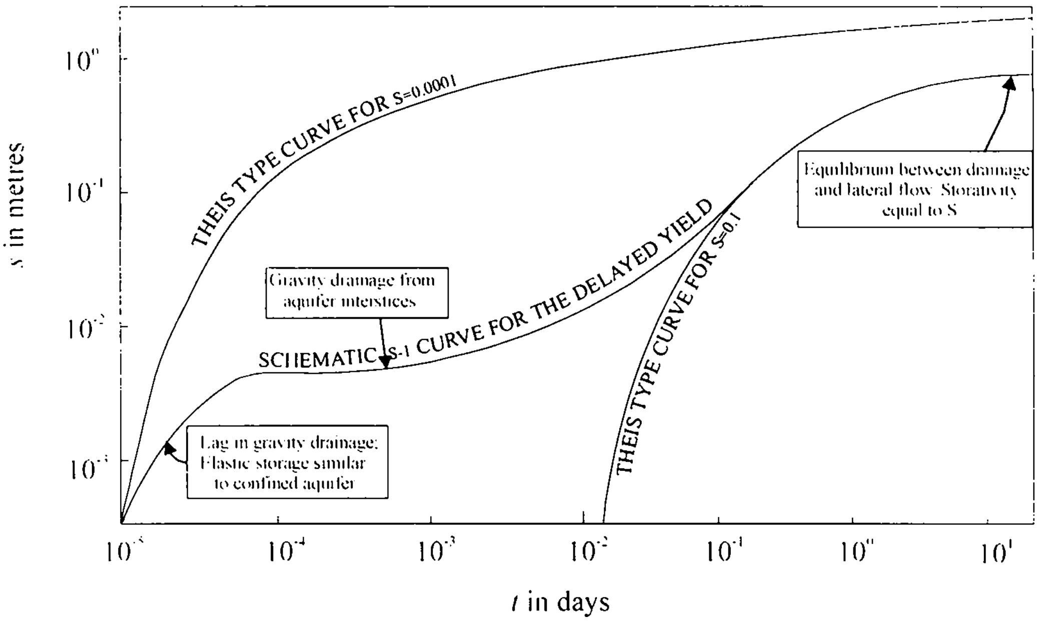


FIGURE 4.4 – Time-drawdown response of an unconfined aquifer

In 1972 Neuman (in: Fetter, 1994) developed a theory of delayed water table response, which is based on well-defined physical parameters of an unconfined aquifer. Neuman produce a mathematical solution that reproduces all the three segments of the time-drawdown curve in an unconfined aquifer. His complex solution for drawdown (h_o-h_l), can be represented in simplified form as

$$h_o - h = \frac{Q}{4\pi T} W(u_A, u_B, \beta) \qquad (4.21)$$

Where W (u_A, U_B, β) is known as the unconfined well function and its values are given in standard tables, for example those presented by Fetter (1994).

Under early-time conditions, this equation describes the first segment of time-drawdown curve (Fig. 4.4) and reduces to

$$h_o - h = \frac{Q}{4\pi T} W(u_A, \beta) \qquad (4.22)$$

where

$$u_A = \frac{r^2 S}{4\pi T} \qquad (4.23)$$

S_A is the elastic storativity responsible for instantaneous release of water to well. Under the late-time conditions equation 4.21 describes the third segment of time – drawdown curve and reduces to

$$h_o - h = \frac{Q}{4\pi T} W(u_B, \beta) \qquad (4.24)$$

$$u_B = \frac{r^2 S_y}{4Tt} \qquad (4.25)$$

where S_y is the specific yield.

Neuman's parameter β is defined as

$$\beta = \frac{r^2 K_v}{D^2 K_h} \qquad (4.26)$$

where

K_v = hydraulic conductivity for vertical flow (m/day)
K_h = hydraulic conductivity for horizontal flow (m/day)
D = initial saturated thickness of the aquifer (m

4.3 DETERMINING HYDRAULIC PARAMETERS BY AQUIFER TESTS

4.3.1 General

The purpose of conducting pumping test is to determine: (i) the performance characteristic of the well and, (ii) the hydraulic parameters of the aquifer. The well-performance test simply involves the recording of the drawdown at various discharge rates so as to calculate the specific capacity of the well at various discharge rates; the measure of the productive capacity of a well. This information may be needed for the selection of the pumping equipment to be installed. However, of greater importance, particularly for the purpose of this study, is the determination of the hydraulic parameters from the pumping tests, which are usually undertaken by constant rate tests. The pumping tests provide data from which the principal factors of aquifer performance - transmissivity (T) and coefficient of storage (S) - can be calculated. This type of test is called an aquifer test because it is primarily the aquifer characteristics that are determined.

In an aquifer test a well is pumped at a known constant rate and the rate of decline of the water level in the pumping well and nearby observation wells is noted. The time-drawdown data are then interpreted to yield the hydraulic parameters of the aquifer.

Steady state radial flow, a condition whereby drawdown variations are zero, seldom occurs in an unconfined aquifer. Many aquifer tests will never reach an equilibrium; that is, the cone of depression will continue to grow during the test. These are known a non - equilibrium or transient flow conditions. Thus in the following section only methods of determining aquifer parameters under transient flow conditions are described.

4.3.2 Determining of Aquifer Parameters from Time-Drawdown Data

Aquifer parameters are calculated from time-drawdown graphs using appropriate formulae, relating T and S to the pumping rate, distance between pumped and observation borehole, and drawdown at specific moment in time. Analysis of the time-drawdown data from an observation well can be used to determine both the transmissivity and storativity of an aquifer. If there is no observation borehole, the time drawdown data from the pumping borehole during the constant discharge phase or its recovery can be used to determine the aquifer transmissivity but not the storativity.

A graphical method for analysis of an aquifer test in an unconfined aquifer was developed by Neuman in 1975 (Fetter, 1994). The method of analysis is based on the Neuman's drawdown equations, for early-time drawdown data, (eqn. 4.22) and later-time drawdown data, (eqn. 4.24) described in Section 4.2.3. These can be expressed in logarithmic form as

$$\log(s) = \log\frac{Q}{4\pi T} + \log W(u_A,\beta) \quad \text{(for early drawdown data)} \qquad (4.27)$$

$$\log(s) = \log\frac{Q}{4\pi T} + \log W(u_B,\beta) \quad \text{(for late drawdown data)} \qquad (4.28)$$

where s is drawdown below the static water level. Equations 4.23 and 4.25 define parameters u_A and u_B, which can be rearranged as

$$t = \frac{r^2 S}{4T}\frac{1}{u_A} \quad \text{and} \quad t = \frac{r^2 S_y}{4T}\frac{1}{u_B}$$

in logarithmic terms become

$$\log t = \log\frac{r^2 S}{4T} + \log\frac{1}{u_A} \quad \text{(for early drawdown data)} \qquad (4.29)$$

$$\log t = \log\frac{r^2 S_y}{4T} + \log\frac{1}{u_B} \quad \text{(for late drawdown data)} \qquad (4.30)$$

If two graphs are drawn, one of log s against log t (the data curve) and the other of log $W(u_A,\beta)$ against log $1/u_A$ for various values of β (the type curves), for any particular value of t there will be corresponding values of (s), $1/u_A$ and $W(u_A,\beta)$. Equation 4.27 and 4.29 (for early drawdown data) imply that for any particular set of these four variables log s will always be greater than log $W(u_A,\beta)$ by a constant quantity log $Q/4\pi T$ while log t will always be greater than $1/u_A$ by a constant log $r^2S/4T$.

Since $Q/4\pi T$ and $r^2S/4T$ are constant during a test the relation between log (s) and log t must be similar to the relation between log $W(U_A,\beta)$ and log $(1/u_A)$. This in turn implies that the two graphs will be exactly the same shape, so if they are superimposed corresponding values on the graph scales will be displaced by distances equal to the constants, (Fig. 4.5). This same principle is applied in dealing with the late drawdown data as the curve is basically similar to that of the early time-drawdown curve. This is the basis of Neuman's curve matching method of analysis.

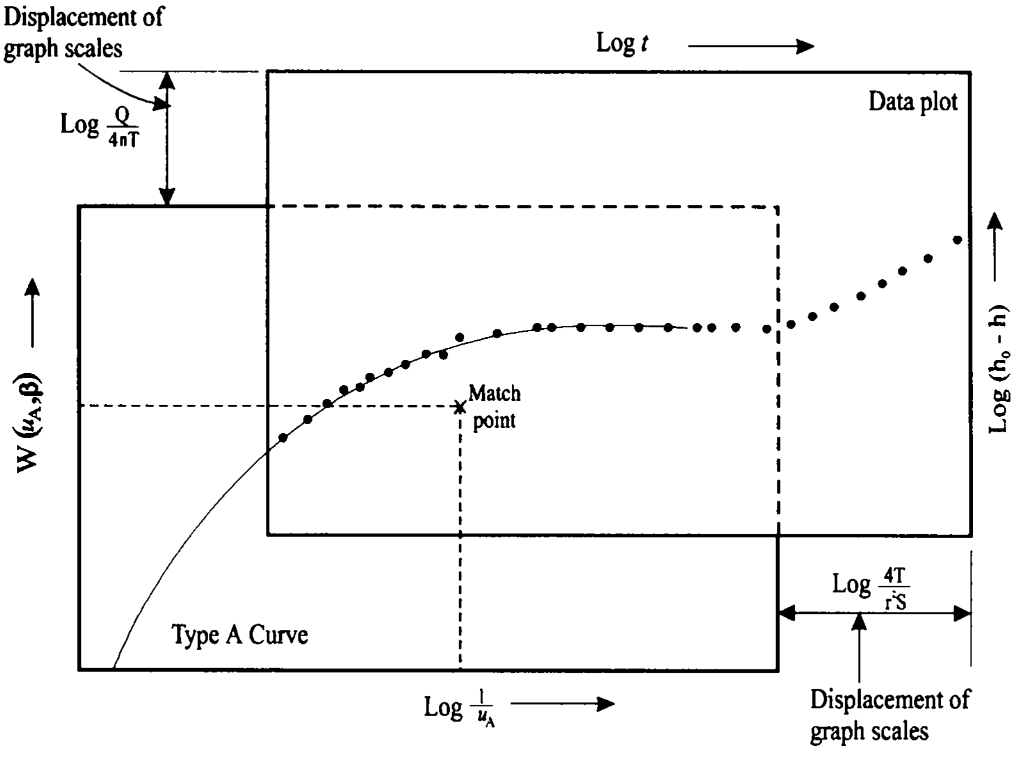


FIGURE 4.5 – Superposition of field data on the type curve to obtain aquifer parameters

Neuman's graphical method is essentially an analysis method in which the drawndown curve is matched against a set of type-curves for various values of parameter β. Figure 4.6 is a plot of type curves for $W(u_A,U_B\beta)$ versus $1/u_A$ $1/u_B$ for different values of β.

The field data of time and drawdown are plotted on logarithmic paper for the same scale as the type curve. The early time portion of the time-drawdown curve is matched against an appropriate type-A curve. Instead of measuring the graph-scale displacement when the curves are matched, the same result is conveniently obtained by observing values of t, s, $1/u_A$ and $W(u_A,\beta)$ at any match-point, and substituting these match-point values into equation 4.27 and 4.29 to determine the constants from which storativity and early-time transmissivity are calculated.

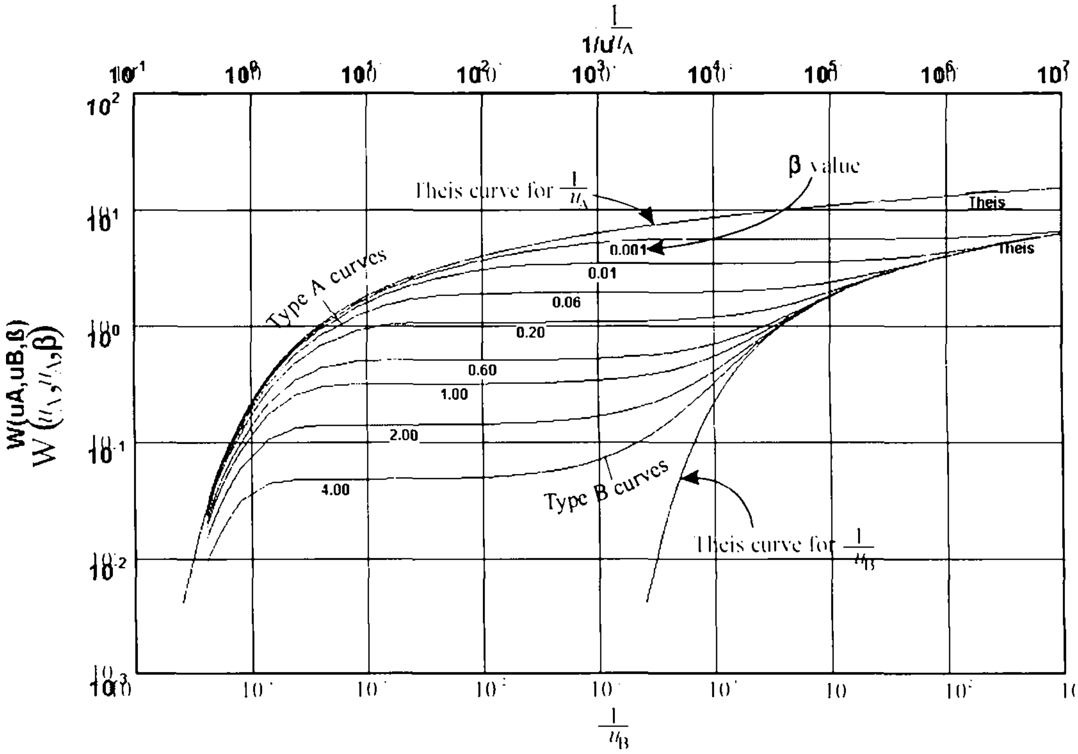


FIGURE 4.6 - Family of Neuman Type Curves: $W(u_A,u_B,\beta)$ versus $\frac{1}{u_A}$ and $\frac{1}{u_B}$ for an unconfined aquifer

It should be noted that the match-point is any arbitrary point, which does not necessarily have to be on the curve but should be within the field common to both graphs. Similarly, the later portion of the time-drawdown curve is matched with the type-B curve with the same β value as the selected type-A curve and a new set of match points are determined.

The transmissivity is then calculated from equation 4.28 and should be approximately equal to that computed for type-A curve. Equation 4.30 can be used to compute the specific yield.

4.3.3 Recovery Tests After Constant – Discharge Tests

When pumping is stopped the water levels in the borehole and observation boreholes will start to rise. The remaining drawdown compared to the original static water level is known as residual drawdown, s'. It is defined as the difference between the original water level before start of pumping and water level measured at time t' after the cessation of pumping. If the residual drawdown can be measured after cessation of pumping it may be possible to determine the aquifer transmissivity and possibly the storativity if water levels are measured in observation boreholes. Residual drawdown data are more reliable than pumping test data because recovery occurs at a constant rate, whereas constant discharge during pumping is often difficult to achieve.

The analysis of a recovery test is based on the principle of superposition, which states that drawdown at any point in an aquifer in which more than one borehole is being pumped is equal to the sum of drawdowns that would arise from pumping each of the boreholes independently (Freeze and Cherry, 1979). Because the principle applies for recharge as well as discharge, it can be assumed that after cessation of pumping, the borehole continues to be pumped at the same discharge as before and that imaginary recharge, equal to the previous discharge rate, is injected into the borehole.

According to Theis recovery method for confined aquifers (Kruseman and de Ridder 1990), the residual drawdown after a pumping test with a constant discharge is

$$s' = \frac{Q}{4\pi T}\left\{\ln\frac{4Tt}{r^2S} - \ln\frac{4Tt'}{r^2S'}\right\} \qquad (4.31)$$

where

s' = residual drawdown (m)
r = distance from borehole to piezometer (m)
T = Transmissivity of aquifer (m^2/day)

S' = Storativity during recovery (dimensionless)
S = Storativity during pumping (dimensionless)
t = time since start of pumping (days)
t' = time since cessation of pumping (days)
Q = rate of recharge = rate of discharge (m^3/day)

Where S and S' are constant and equal and T is constant, equation 4.31 reduces to

$$\Delta s' = \frac{2.3\,Q}{4\pi T} \log \frac{t}{t'} \tag{4.32}$$

where $\Delta s'$ is the drawdown per log cycle of t/t'.

In 1975 Neuman showed that the Theis recovery method discussed above and described in detail in several reference textbooks (e.g. Kruseman and de Ridder), is applicable for unconfined aquifers, but only for late-time recovery data. At late-time, the residual drawdown data will fall on a straight line in a semi-log s' versus t/t' used in the Theis recovery method.

4.3.4 Slug Tests

In a slug test, a small volume (or slug) of water is quickly injected into or removed from a borehole and the rate of fall or rise of water level is measured. Because the rate of fall or rise of water level is controlled by the aquifer characteristics, the aquifer's hydraulic transmissivity and hydraulic conductivity can be determined from the water level measurements.

The slug test is one of the most common techniques for the in-situ estimation of hydraulic conductivity in unconfined flow systems. This technique has become so prevalent as a result of several factors (Hyder and Butler, 1994) and these include (i) the small amount of equipment and manpower required for a test, (ii) piezometers or observation boreholes are not needed (iii) the relatively short duration of a test; (iv) the perceived ease of the data analysis; and (v) the need for only a small amount of water (if any) to be added or removed from the well in order to initiate a test. Thus slug tests are used widely in studies to evaluate regional groundwater resources because they can provide preliminary estimates of aquifer conditions both cheaply and quickly. In addition, they are also useful in providing the hydraulic conductivity of low permeability aquifers where pumping tests are not practical. Nevertheless, slug tests cannot be regarded as a substitute for conventional pumping tests. The disadvantages of the slug test method are that the hydraulic conductivity and transmissivity obtained are representative only of the formation in the immediate vicinity of the test borehole and may not be representative of the aquifer material.

The Bouwer and Rice method for the analysis of data from slug tests (Bouwer and Rice,1976), is commonly used for tests performed in boreholes that fully or partially penetrate unconfined aquifer. This method can be applied to determine the hydraulic conductivity of open or screened boreholes, which can either be fully or partially penetrating. The Bouwer and Rice's method can be used if the following assumptions and conditions are satisfied (Kruseman and de Ridder, 1990):

(i) The aquifer is unconfined;
(ii) The aquifer is infinite laterally;
(iii) The aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the slug tests;
(iv) The water table is horizontal at the start of the test;
(v) The head in the borehole is lowered instantaneously; the drawdown in water table around the borehole is negligible; there is no flow above the water table;
(vi) The inertia of water column in the borehole and the linear and non-linear well losses are negligible;
(vii) The borehole is either fully or partially penetrating;
(viii) The borehole storage is not negligible; thus it cannot be neglected;
(ix) The flow to the well is in a steady state;
(x) There is no near borehole zone of disturbance created by drilling or development.

The geometry of a borehole for the Bouwer and Rice slug test analysis is shown in Figure 4.7. The Bouwer and Rice equation for calculating the hydraulic conductivity (K) from a slug test is written as;

$$K = \frac{r_c^2 \ln(R_e/R)}{2L_e} \, \frac{1}{t} \ln \frac{H_t}{H_0} \qquad (4.33)$$

where

K = hydraulic conductivity (m/day)
r_c = the radius of the borehole

R = the horizontal distance from borehole centre to undisturbed aquifer (m)
R_e = the effective radial distance over which head is dissipated (m)
L_e = the length of the screen or open section of the borehole (m)
H_0 = the drawdown at time t=0 (m)
H_t = the drawdown at time $t > t_0$ (m)
T = time since $H = H_0$ (day)

Since K, r_c, R, R_e and L_e in equation 4.33 are constants, (1/t) ln (H_t/H_0) is also constant. Thus, when the values of H_t are plotted against t on semi-logarithmic paper (with H_t on the logarithmic scale), the data points will fall on a straight line. From the straight line drawn through the plotted points, the value of (1/t) ln (H_t/H_o) can be calculated for an arbitrarily selected value of t and its corresponding value of H_t. R_c, the effective distance over which the induced head is dissipated, can not be known for a tested borehole. Consequently, Bouwer and Rice have presented a method of estimating the dimensionless ratio ln (R_e/R) (eqn. 4.33). The method of determining this ration has been described in detail in several reference books (e.g. Kruseman and de Ridder, 1990).

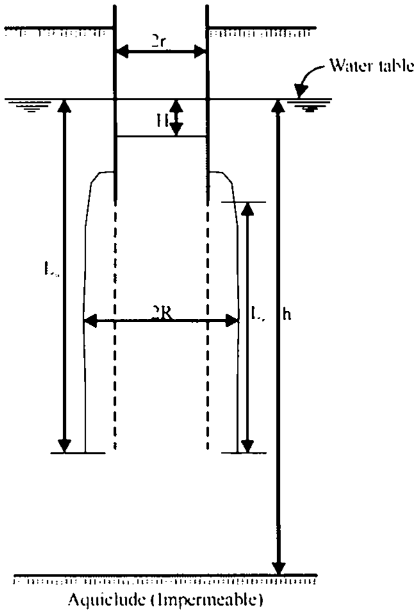


FIGURE 4.7 – Geometry and symbols for a slug test on a partially penetrating screened well in an unconfined aquifer with gravel pack around the screen (From: Fetter, 1994)

4.4 EXPERIMENTAL METHODS

4.4.1 Introduction

Pumping tests are both capital and labour intensive, requiring a pumping borehole, observation boreholes within the radius of influence of a pumping borehole, considerable amount of equipment, large running costs and many operatives. In this study, pumping tests were carried out only at four boreholes. This was due not only to the expenses, but also due to lack of pumping equipment with capacity to pump deep boreholes amongst the private drilling contractors in Zimbabwe. In fact, on different occasions two contractors attempted pumping tests at one of the deep boreholes, but failed to obtain reliable results. Eventually pumping tests were carried out by staff of the Ministry of Water Development..

Details of the boreholes used for pumping tests are given in Table 4.1

TABLE 4.1 - Boreholes Used For Pumping Tests

Test Number	Borehole Name	Borehole Number	Grid Reference	Borehole Depth (m)
1.	Inthandokazulu	6 kwek – 204	OK 354261	89
2.	Chitwara	6 kwek – 235	QK 286313	90
3.	Rufuse	6 kwek – 234	QK 195338	33
4.	Gondweni	6 kwek - 237	QK 311307	107

Because limited information could be derived from pumping tests, slug tests were conducted in order to improve the information of the hydraulic conductivity and transmissivity. In this study eleven boreholes were slug tested (Table 4.2)

TABLE 4.2 – Slug-Tested Boreholes

Test Number	Borehole Name	Borehole Number	Grid Reference	Borehole Depth(m)
1.	Maaramu	6kwek - 260	QK 306228	71
2.	Dzimiri	6kwek – 268		
3.	Inthandokazulu	6kwek – 204	QK 354261	89
4.	Makombo	6kwek – 251	QK 223316	95
5.	Mocheni	6kwek – 261	QK237264	
6.	Ntangwe I	6kwek – 168	QK 270264	111
7.	M. Ntenezi Line	6kwek – 203	QK 361255	110
8.	Phumula	6kwek – 262	QK182310	
9.	Sabatha II	6kwek – 191	QK 385291	83
10.	Zvaitika	6kwek – 258	QK 214377	
11.	Gwarazimba	6kwek - 215	QK 328227	84

4.4.2 Pumping Test in the Study Area

Equipment

A crew from the Ministry of Water carried out pumping test. The testing equipment consisted of a Lister Cylinder diesel engine mounted on a small lightweight trailer. The equipment is belt driven, with belt connected from pulleys on the 'mono' head to pulleys on the engine. Lengths of 50mm galvanised rising main were connected from the 'mono' head and 16mm shafting with rubber 'bobbin' bearings ran throughout the length of the rising main. A 'mono' pump was connected to the 'mono' column. A wide range of 'mono' pumps was available and these could pump water at discharge rates between 0.5 l/sec and 7.5 l/sec.

Field Methods

Immediately prior to the commencement of the test the static water level in both the pumped borehole and observation hole were measured. The test itself started when the pump was first switched on and this was recorded as time-zero of the test. During pumping the discharge rate was frequently measured so as to ensure that it is kept constant throughout the test. To determine the discharge rate, the time required to fill a 50 litres container was observed. This method was found to be simple and fairly accurate.

During pumping test water levels were monitored in the pumped borehole and, in one case where it was feasible, in both the pumped borehole and observation hole. The water level changes (drawdown) were measured by an electrical dip-meter. The drawdown in the pumped borehole was recorded on a standard form with pre-determined time intervals. However, at the observation hole drawdown was not necessarily recorded at precisely pre-determined time intervals, but the correct interval from time-zero and the corresponding drawdown were recorded on record sheets specifically designed for this purpose.

The water delivered by the borehole was conducted by pipes and discharged at a distance of about 150m from the test-site. This prevented the water from infiltrating back into the aquifer during the period of the test.

Upon completion of the constant discharge test, marked by the switching off of the pump, the rise of water level in both the pumped borehole and observation hole was monitored. This phase is commonly referred to as recovery test.

The pumping test data was analysed by curve matching techniques using Aquitest Software package by Waterloo Hydrogeologic Inc. (Roehrich, 1996).

4.4.3 Slug Tests In The Study Area

Slug tests were carried out by the author on sixteen boreholes. The slug-tested boreholes were selected to provide a general cover of the boreholes within the study area.

In each case, the slug test was carried out by instantaneously introducing a small volume of water into the borehole. This was achieved by rapidly pouring water from two 30-litre buckets concurrently. The subsequent fall of the water level to the pre-test level was monitored against time. An electronic dip meter and a digital stopwatch were used to measure the changes of the water level with time.

4.5 HYDRAULIC PARAMETERS FOR THE KAROO SEDIMENTS

4.5.1 Results of Pumping Tests

Inthandokazulu – Borehole 6kwek -204

At the test-site about seven metres of medium-grained Kalahari Sand overlie 86m of Karoo Sediments. The geological log (Appendix 1) shows that between 8m and 66m the Karoo Sediment is predominantly medium-to coarse-grained sandstone. Beneath the sandstone there are red clays and sandy clays to the bottom of the borehole at 89m. Although at 89m the borehole had not fully penetrated the Karoo Sediment to intercept the basement, it was deduced from the Basement Topography Map (Fig. 3.9) that the basement is at 93m, and it seems probable that the clay formation continues to the basement. The static water level is about 53m below ground surface and the aquifer is apparently unconfined. This implies a saturated thickness of 13m if the clay horizon at the bottom is discounted as being non-permeable.

Borehole 6kwek-204 was an obvious choice for a pumping test, because an observation borehole was present. The observation borehole was in fact another existing borehole located 97m from the test-site. This borehole was found within the premises of nearby school and supplied domestic water to the staff and pupils of the school. The data plot for drawdown in the observation borehole could not be easily matched with type curves because the drawdown, about 0.05m, was too small for any meaningful analysis to take place.

The drawdown plot in the pumped borehole was analysed by the Neuman's type curves (Appendix 2). The early-time part of the plot produces a fairly good match with the Neumann's type-A curves confirming water-table conditions and giving transmissivity and hydraulic conductivity values of 4.33m^2/d and 0.333m/d respectively. The late-time part, the data-points could not be matched satisfactorily with the corresponding Neumann's type-B curve as there is a distinct deviation, above the type curve, of the data points after about 420 minutes of pumping. This indicates that the cone of depression may have intercepted a lower permeability boundary in the lateral direction. However, the match of late-time data-points before the deviation gives a transmissivity of 5.46m^2/d and conductivity of 0.489m/d, thus showing fair agreement with the results from the early-time data match.

Recovery in the pumped borehole was analysed by Theis and Jacob recovery method for unconfined aquifer. The resulting transmissivity 8.39m^2/d is about twice that obtained from pumping test data.

Chitwara – Borehole 6kwek –235

At this site 66m of Kalahari sands overlie Karoo sediments. Although the borehole terminated in the Karoo sediments at 90m, the Basement Topography Map (Fig. 3.9) shows that the Basement rock is at about 130m; thus the thickness of Karoo sediments is 64m. The Karoo sediments are predominantly medium- to coarse-grained sandstone with a large silt fraction, and red silt and clay interbeds. The geological log for this borehole is included in Appendix 1. The static water level is 60m below surface , implying the saturated thickness is about 70m inclusive of the clay beds. It is apparent from the hydrogeological conditions that the aquifer is unconfined.

The pumping test data plot for the pumped borehole was analysed by the Nueman's method (Appendix 2). The two portions of the data plot (early-time and late-time) were analysed separately, giving transmissivity of 11.5m^2/d and 14.5m^2/d respectively; both portions matched satisfactory with the respective type curves.

A Theis and Jacob recovery analysis for the recovery of the pumped borehole produced a transmissivity value of 14.8m^2/d, agreeing with results from pumping test. However, the residual drawdown data-points seem not to trend towards zero when t/t'=1. In fact the residual drawdown regressed line trends towards increasingly negative values of drawdown, implying that the recorded initial water level was too low. It seems probable that the water level at the commencement of the pumping test had not fully recovered from the previous pumping.

Refuse - Borehole 6kwek-234

At this site the borehole, drilled to a depth of 33m, did not penetrate the full thickness of Karoo sediments to the basement. The Basement Topography Map (Fig. 4.6) indicates that the Basement rock is possibly at 72m. The drilling-log (Appendix 1) records 18m of Kalahari Sand overlying the Karoo sediments, implying a thickness of about 54m for the sediments. The Karoo sediments are predominantly medium-grained sandstone interbedded with thin horizons of red-orange clay and silt. As the static water level is 11.6m below ground surface, the saturated thickness is about 60m.

Neuman's solution for the early-time and late-time data-plots produced transmissivity values of 4.4m^2/d and 4.94m^2/d respectively. A good match was obtained for both portions with the type-A and type-B curves respectively.

The recovery test data is unreliable and in addition the data-points are too few for any meaningful analysis to be carried out.

The pumping test data and analyses are included in Appendix 2

Gondweni Borehole 6kwek-237

Drilling samples show 52m of Kalahari sands overlying Karoo sediments to the end of the hole, about 107m. The Karoo sediments are predominantly medium- grained sandstone with abundant silt fraction. Although the borehole did not fully penetrate the sandstone, the Basement Topography Map (Fig 3.9) shows that the basement is at 118m. The static water level is 73m below ground surface and therefore the saturated thickness is about 45m, and the aquifer is evidently unconfirmed.

The pumping test data plot produced a good match with Neuman's type curves. The early-time and late-time parts of the data plot were analysed separately giving values of transmissivity of about 12.0m^2/d and 13.4m^2/d respectively (Appendix 2).

The Theis and Jacob recovery analysis give a value of transmissivity of 11.5m^2/d. The transmissivity accords quite well with results from pumping despite the solution being unreliable, as the data points were quite few.

4.5.2 Discussion of Pumping Test Results

Hydraulic parameters from pumping tests are summarised in Table 4.3, whilst the graphical plots and pumping test results are presented in Appendix 2.

TABLE 4.3 - Summary of Results of Pumping Tests.

BOREHOLE NAME AN NUMBER	HYDRAULIC CONDUCTIVITIES				TRANSMISSI VITIES			
	Early-Tim K (m/d)	Late-Time K (m/d)	Recovery K (m/d)	Average K (m/d)	Early-time T (m^2/d)	Late-Time T (m^2/d)	Recovery T (m^2/d)	Average T (m^2/d)
Inthandokazulu 6 kwek-204	0.333	0.420	0.645	0.466	4.33	5.46	8.39	6.06
Chitwara 6 kwek-235	0.551	0.693	0.705	0.649	11.5	14.5	14.8	13.6
Rufuse 6 kwek-234	0.176	0.197	-	0.187	4.4	4.94	-	4.7
Gondweni 6 kwek-237	0.343	0.385	0.329	0.352	12.0	13.4	11.5	12.3

The Neuman method of analysis proved to be the most appropriate because the drawdown data for all the pumping tests match fairly well the Neuman type-curves. This confirms that in the small area covered by the pumping tests the aquifer is unconfined.

Transmissivities range from 4.7 m^2/d to 13.6 m^2/d with a mean of 8.9 m^2/d. The variation in transmissivity is due to variations in saturated thickness, and to a lesser extent, due to the inhomogeneity of the aquifer itself. Hydraulic conductivity values range from 0.187 m/d to 0.649 m/d. The variation of the hydraulic conductivities confirms the inhomogeneity of the aquifer formation, though it appears to be not significant.

Due to the lack of observation boreholes in the vicinity of the pumped boreholes, the transmissivity hydraulic conductivity values were calculated using data from the pumped boreholes. Drawdown inside the borehole casing is translated by the pumping test software to be equivalent to the drawdown in the aquifer formation. However the drawdown inside the casing in the pumped borehole is normally greater than drawdown in the aquifer just outside the casing, giving rise to an underestimation of the value of the hydraulic conductivity. Regarding the storage coefficient, no accurate values could be derived using data from pumped boreholes. In one case where an observation borehole is presence, at Inthandokazulu test-site (6kwek-204), the drawdown in the observation borehole was too limited to enable the determination of the storage coefficient by the standard curve matching method.

4.5.3 Results of Slug Tests

All the slug-tested boreholes occur in localities where the aquifer is unconfined. While some of the boreholes were started in the Kalahari Sand, all the boreholes in fact tap groundwater from underlying Karoo sediment aquifer. All the boreholes, however, partially penetrate the aquifer. The entire depth of the boreholes was lined with 150mm diameter steel casing, which was perforated in sections adjacent to the water-bearing formation. The annular space between the casing's perforated section and borehole sidewall was filled with gravel pack comprising well-sorted and rounded quartz grains. The borehole construction and geological logs for eight of the boreholes are presented in Appendix 1, the remainder (three) were in fact very old boreholes whose drilling records are missing.

The slug test data was analysed by the Bouwer – Rice method (Bouwer and Rice, 1976) that is available in the Aquitest software package by Waterloo Hydrogeologic Inc. (Roehrich, 1996). Hydrogeological parameters determined from the slug tests are summarised in Table 4.4 and the graphical plots and the results of the slug tests analyses are presented in Appendix 3.

4.5.4 Discussion of Slug-Test Results

Hydraulic conductivities range from 0.0538 m/day to 0.559 m/day, with an average of 0.161m/day. The considerable variation in values of hydraulic conductivity is most probably due to inhomogeneity of the aquifer formation . Generally the hydraulic

TABLE 4.4 - Summary of Results of Slug Tests

Borehole Name	Borehole Number	Saturated Thickness (m)	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)
Maaramu	6kwek-260	40	0.123	4.92
Dzimiri	6kwek-268	64	0.0779	4.98
Intandokazulu	6kwek-204	13	0.136	1.77
Makombo	6kwek-251	45	0.0806	3.63
Mocheni	6kwek-261	20	0.559	11.18
Ntagwe I	6kwek-168	50	0.0587	2.94
Mtenenzi Line	6kwek-203	47	0.0668	3.14
Phumula	6kwek-262	42	0.224	9.4
Sabatha II	6kwek-191	28	0.0538	1.51
Zvaitika	6kwek-258	50	0.277	13.85
Gwarazimba	6kwek-215	41	0.118	4.84

conductivities tend to be in the low range and would require considerable available drawdowns to supply reasonable yields to boreholes. Transmissivities calculated from the saturated thickness and the hydraulic conductivities (Table 4.4) range from 1.51 m^2/day to 13.85 m^2/day, with an average of 5.65m^2/day.

The only slug-tested borehole that was also pump-tested is Inthantokazulu (Borehole 6kwek-204). The transmissivity value from the slug test (1.77m^2/day) is much lower than the value (4.9m^2/d) derived from pumping test. The main limitation on slug tests is that they are heavily dependant on the quality of screening and gravel packing. If the screen is corroded or clogged, the measured values may be highly inaccurate. Furthermore, borehole drilling and development may create a disturbed near-borehole zone, well skin, of properties differing from those of the formation as a whole. Depending on the drilling method, the type of development activities, and the nature of the formation, this well skin can be either lower or higher permeability than the formation in which the borehole is screened. Hyder and Butler (1994) state that the Bouwer and Rice estimates of hydraulic conductivity will tend towards the conductivity of the skin in the case of low-permeability skin, while estimates will be within 30% of the actual formation conductivity in the case of high-permeability skin. It is possible that a low-permeability skin was created during the drilling and development of Inthandokazulu borehole by the cable tool percussion method and this might have resulted in an underestimation of the actual formation conductivity. Similarly, the generally low conductivities derived from the slug tests performed in the study area may be due to low-permeability skins formed during drilling of the boreholes. This suggests that the slug test results are unlikely to be reliable.

4.5.5 Concluding Remarks

Average transmissivities of the Karoo aquifer of the study area are classified as low. Pumping tests interpretation gave transmissivity values ranging from 4.7m^2/d to13.6m^2/d. Slug tests, which covered a larger number of boreholes, similarly indicated low values ranging between 1.5m^2/d and 13.8m^2/d. In the context of some of the larger and highly exploited Karoo aquifers in Zimbabwe, the aquifer in the vicinity of Dendera area has considerably low transmissivities. An average transmissivity value of 40m^2/d for the Nyamandlovu aquifer was reported by Banda et. al. (1977). Beasley (1983) obtained transmissivity values ranging from 20m^2/d to 94m^2/d for the same aquifer.

5.0 GROUNDWATER RECHARGE

5.1 INTRODUCTION

An aquifer can be thought of as a pipe or conduit that transfers water from recharge area to areas of discharge, and which has a storage component (Hamill and Bell, 1986). In common with any storage system, groundwater resources of an aquifer must conform to a basic balance equation describing the movement of water into (recharge) and out of the unit (discharge). Thus, an equation representing flow through an aquifer is:

$$\text{Recharge to aquifer} - \text{Discharge from aquifer} = \text{change in groundwater storage} \qquad (5.1)$$

Clearly if outflow, for example abstraction by pumping boreholes, exceeds inflow there is a reduction in the amount of water stored in the aquifer and the water level falls. Obviously this can only continue until such time as the storage becomes exhausted. The maximum yield that can be obtained from an aquifer over a prolonged period is directly proportional to the average annual recharge. Matching of long-term withdrawals of groundwater to recharge is, therefore, one of the most important aspects of groundwater resource evaluation.

The region of Zimbabwe occupied by the study area is characterised by semi-arid climate and low and erratic rainfall (600-650mm/y). While abundant quantities of water are possibly stored in the Karoo aquifer in this area, groundwater may have only small natural recharge due to the low annual rainfall. This raises such issues as mining a non-renewable resource if current abstractions are increased in order to meet the demands of small-scale irrigation projects. Quantification of the current rate of groundwater replenishment (recharge) is thus a basic pre-requisite for sustainable development and efficient management of groundwater resources of the area. Unfortunately, of all the factors of evaluation of groundwater resources, this rate of aquifer replenishment is one of the most difficult to derive.

5.2 NATURAL GROUNDWATER RECHARGE

5.2.1 Definitions

Groundwater recharge may be defined as the process whereby water infiltrates the ground surfaces and flow downwards until it reaches the groundwater table, forming an addition to the groundwater reservoir. Recharge of groundwater may occur naturally from precipitation, rivers and lakes and this is commonly referred to as natural groundwater recharge. This term is adopted to emphasise that the process under consideration is a natural part of the hydrological cycle. This is totally different from artificial groundwater recharge, in which water is pumped down wells or spread on the ground surface so as to induce infiltration.

Two principal types of groundwater recharge are recognized and these are commonly referred to as direct and indirect recharge:

- Direct Recharge is defined as water added to the groundwater reservoir by direct vertical percolation of rainwater through the unsaturated zone.

- Indirect Recharge results from percolation to the groundwater table of redistribution from overland flow over permeable zones, water losses from surface runoff and seepage from surface storage bodies. As an example, many sediments at the surface near the banks of streams are highly permeable and water can flow easily into the groundwater system once a stream has temporarily risen above the groundwater table. A further example is where lateral and vertical infiltration and subsequent percolation to the groundwater reservoir occurs through depression and ponding after flooding. Inter-aquifer flows are also an important part of indirect recharge. Figure 5.1 indicates the various elements of recharge in an arid area. Similar processes may also be applied in describing the recharge mechanisms of the study area considering that this area receives low annual rainfall (651 mm) and thus is classified as semi-arid.

The porous character of the sands covering the entire study area, determines the nature of recharge, which is rapid and predominantly direct recharge. In most cases, recharge comes directly from rain falling on the sandy surface and flow through the unsaturated zone can be considered as a vertical percolation.

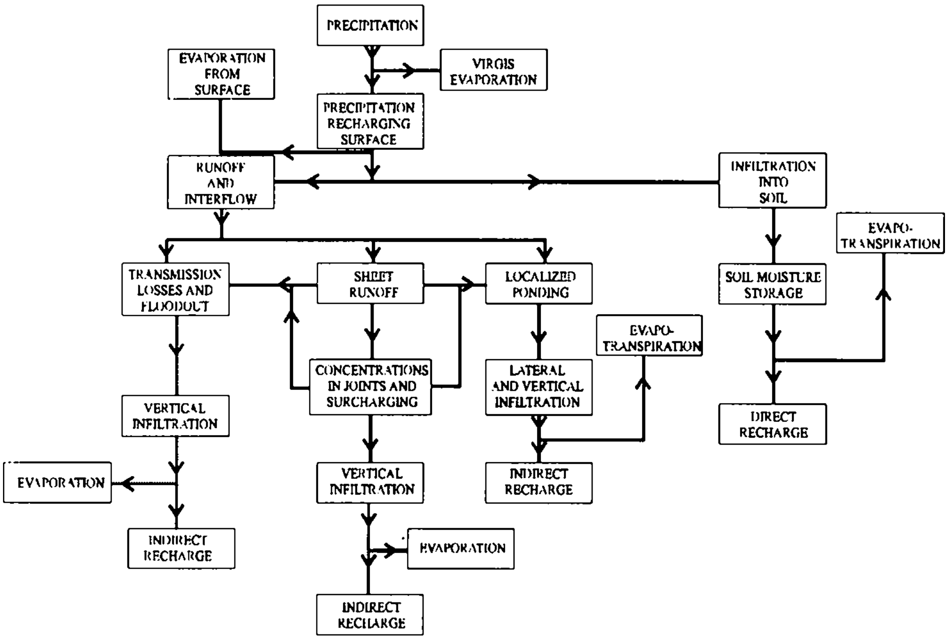


FIGURE 5.1 – The various elements of recharge in an arid area (Lloyd, 1986)

5.2.2 Techniques For Estimating Recharge

The methods of estimating recharge can be classified as follows;

(i) Unsaturated zone methods;
- Lysimeters
- Soil moisture balance
- Tritium profiles
- Chloride profiles

(ii) Saturated Zone Methods
- Groundwater level fluctuations
- Chloride mass balance
- Aquifer water balances
- Springflow discharge
- Saturated volume fluctuations
- Cumulative rainfall departure

(iii) Modeling Techniques

(iv) Rainfall recharge relationships

(v) Use of natural isotopes

TABLE 5.1- Comparison of Methods of Estimating Recharge

Method and Data Requirements	**Comments**
(i) Unsaturated Zone Method	
Lysimeters All collected on site	Lysimeters are expensive to construct and to monitor. Careful construction, regular maintenance and frequent observation are needed. A competent technician is required for daily monitoring. Long time is required for flows to settle back to a natural condition for the data to be collected (>1y) and longer in arid/semi-arid areas (>5 y). This is the only practicable method of measuring recharge flux and that gives reliable data regarding direct recharge.
Soil Moisture balance Daily meteorological data; knowledge of vegetation and cropping pattern.	Relatively quick and cheap if data is available. Mainly for humid climates and have less validity in arid and semi-arid areas. Good data on actual evapotransipiration is required, yet this item cannot be measured easily. The method provides point recharge values. The results may be of dubious accuracy.
Tritium profiles Tritium and soil moisture contents as a function of depth (tritium and soil moisture profiles by sampling).	Method requires deep sediment deposits where the 1963-bomb tritium peak still exists. The determination of the content of tritium requires special expertise and equipment. Provides fairly reliable recharge estimates, but only at a point and if applicable. Due to radioactive decay of the 1963-bomb tritium levels, the method is now rarely used.
Chloride profiles Long-term average chloride concentration in rainfall and in the soil moisture; long-term average annual rainfall; and the dry deposition flux of the chloride.	Relatively cheap and effective technique for estimating direct recharges and also for investigating recharge history. Assumes direct recharge by Darcian flow through a soil matrix and requires a steady state situation. Method gives mean annual historical average recharge at a point with a fairly good accuracy.
(ii) Saturated Zone Methods	
Groundwater level fluctuations Area of aquifer coverage; seasonal rise in water level; and average specific yield of aquifer materials.	The method is simple and cheap provided the boreholes do no have to be constructed to obtain the data. Uses the actual change in groundwater storage. Average values of variables such as the specific yield may be difficult to estimate. The method is very sensitive to specific yield estimates.
Chloride Mass Balance Average annual rainfall; average chloride concentration in rainfall; and chloride concentration in groundwater.	Relatively quick, cheap and easy method to implement as it uses data that is generally available; unlike the annual rainfall records and hydrochemical data, rainfall chemistry data are not always available. The basic concepts and assumptions for this method are the same as the chloride profiles method. As the chloride concentration in groundwater may originate from different flow components in the zone above the water table, the method calculates an areal total recharge rate.
Water Budget Aquifer recharge area; and either rainfall, actual evapotransipiration and runoff or known infiltration rate over recharge area.	Uses data that are generally available or can be easily obtained or estimated and so it is quick, cheap, easy method to implement. Useful for desk study and feasibility studies, but has a large data demand and may be of dubious accuracy. Estimates regional recharge rate.
(iii) Modelling Techniques	
Groundwater Modelling Water levels in aquifer, transmissivity, storativity, boundary conditions, flow mechanisms, pumping test data; extent of aquifer and its thickness; information on the hydrogeology of the area.; plus suitable hardware and software to solve flow equation.	Requires vast quantities of data to produce reliable model, which may be available only after a groundwater investigation is completed. Models may therefore be expensive to construct. Difficulties in establishing the spatial variation of transmissivity and storativity are commonly the limiting factors in the construction of models and subsequently deriving the recharge estimates.
(iv) Rainfall-Recharge Relationship	
Rainfall-Recharge Relationship Long-term average annual rainfall data; and knowledge of recharge values from other methods or from areas of similar hydrological and geological set-up.	The method provides an easy means of estimating recharge by using a simple rainfall-recharge equation. Accuracy of the method depends on the applicability of rainfall-recharge equation to a particular area. Relationship may not be transferable to other areas than those in which they were derived as they ignore the effects of parameters other than rainfall. The recharge equation gives estimates of variability and average groundwater recharge.

The data requirements for some of the more important techniques and their advantages and disadvantages are compared in Table 5.1. Only the two techniques used in the estimation of recharge for this present study, water table fluctuation and chloride mass balance, are described in more detail further below (Sec. 5.4 and 5.5)

5.3 HYDROGEOLOGICAL CONCEPTUAL MODEL

As noted in Chapter 3, the Karoo sediments form the only major aquifer in the area. They primarily consist of medium-grained loosely cemented quartz sandstone, although inter-beds of red clay and silt often occur in the sedimentary sequence. The sediments are present in most of the study area and attain a maximum thickness of about 80m at the centre of the local watershed.

In much of the area the Karoo sediments are overlain by unconsolidated aeolian sand of Kalahari System. The aeolian sands are composed of fine to medium, rounded to well-rounded quartz grains. The Kalahari sands have a maximum thickness of about 50m (Sec. 3.3.5). The sands are preserved on the local watershed.

The mean annual rainfall in the study area is 651mm. The potential evapotranspiration, estimated from pan evaporation data, is 1500mm per year. With such high evapotranspiration, a large percentage of rain-water infiltrating the soil zone may be consumed by evapotranspiration (Issar et al., 1985)

In arid and semi-arid regions groundwater systems may not be recharged by rainfall unless a certain minimum amount or threshold is exceeded. De Vries and Van Hoyer (1988), from groundwater studies in the Kalahari Sand of Botswana, estimated that a rainfall threshold of 400-500mm/y must be exceeded before any groundwater recharge takes place. This concept appears to be applicable to the study area since it is largely covered by thick beds of Kalahari, which have specific retention and evaporative processes similar to Botswana's Kalahari sands. Nevertheless, the mean annual rainfall of the study area (651mm) exceeds the rainfall threshold suggested by De Vries and Van Hoyer. Thus it appears that direct recharge from rainfall does take place in the study area.

On the local watershed where the Kalahari sands have been preserved, there is no evidence of surface run-off indicating that all rainfall infiltrates directly into the sands.

The porous character of the Kalahari sands is conducive to rapid infiltration of rain falling on the surface. However only a fraction of the rainfall infiltration eventually reaches the underlying Karoo aquifer, the remainder being returned to the atmosphere by evapotranspiration. Though the Kalahari sands do not constitute a significant aquifer in the area, they nevertheless play an important role in recharging the Karoo aquifer.

In patches where the Kalahari mantle has been stripped, the Karoo sediments are covered by either redistributed Kalahari sands or by a veneer of the superficial sandy soils derived from weathering of the parent Karoo rocks. In contrast to the Kalahari sands occupying the watershed, there are noticeable run-off features on the more recent sands originating from the fringes of the watershed. However, only a small proportion of rainfall runs off directly, because of the high infiltration rates promoted by the porous nature of these sands. Moreover, the drainage channels across these gentle rises of deep sand are small and shallow and carry ephemeral flows only during intense rainstorms. By virtue of the high porosity of the redistributed sands and superficial soils, infiltration is rapid and they promote replenishment of the Karoo aquifer in the same manner as the Kalahari sands.

Indirect recharge to an aquifer system may occur from flowing streams and rivers traversing the area. However there are no streams flowing over the Kalahari and redistributed sands, which arise from outside the study area. All the streams across the sands start from the fringes of the local watershed. Because of the ephemeral flow of these streams and the fact that the streams are fed by rain falling in the same region, replenishment of the Karoo aquifer by indirect recharge from flowing streams can as well be regarded as part of the rainfall recharge.

Unweathered granite and basement schist are, for practical purposes, non-porous and impermeable rocks and water can be contained and conducted only by fractures. These rocks are, therefore, of no hydrogeological importance in the area, except as an effectively impermeable base to the main Karoo aquifer. As the Karoo sediments lie directly on Basement rocks there can be no leakage from below. Thus leakage from contiguous strata is unlikely in Dendera area.

The Karoo aquifer is considered unconfined because it is not restricted by any confining layer above it and is bound below by an aquiclude. The rock above the Karoo aquifer consists of permeable Kalahari and redistributed sands (Sec.3.3), while the impermeable Basement rocks form its base.

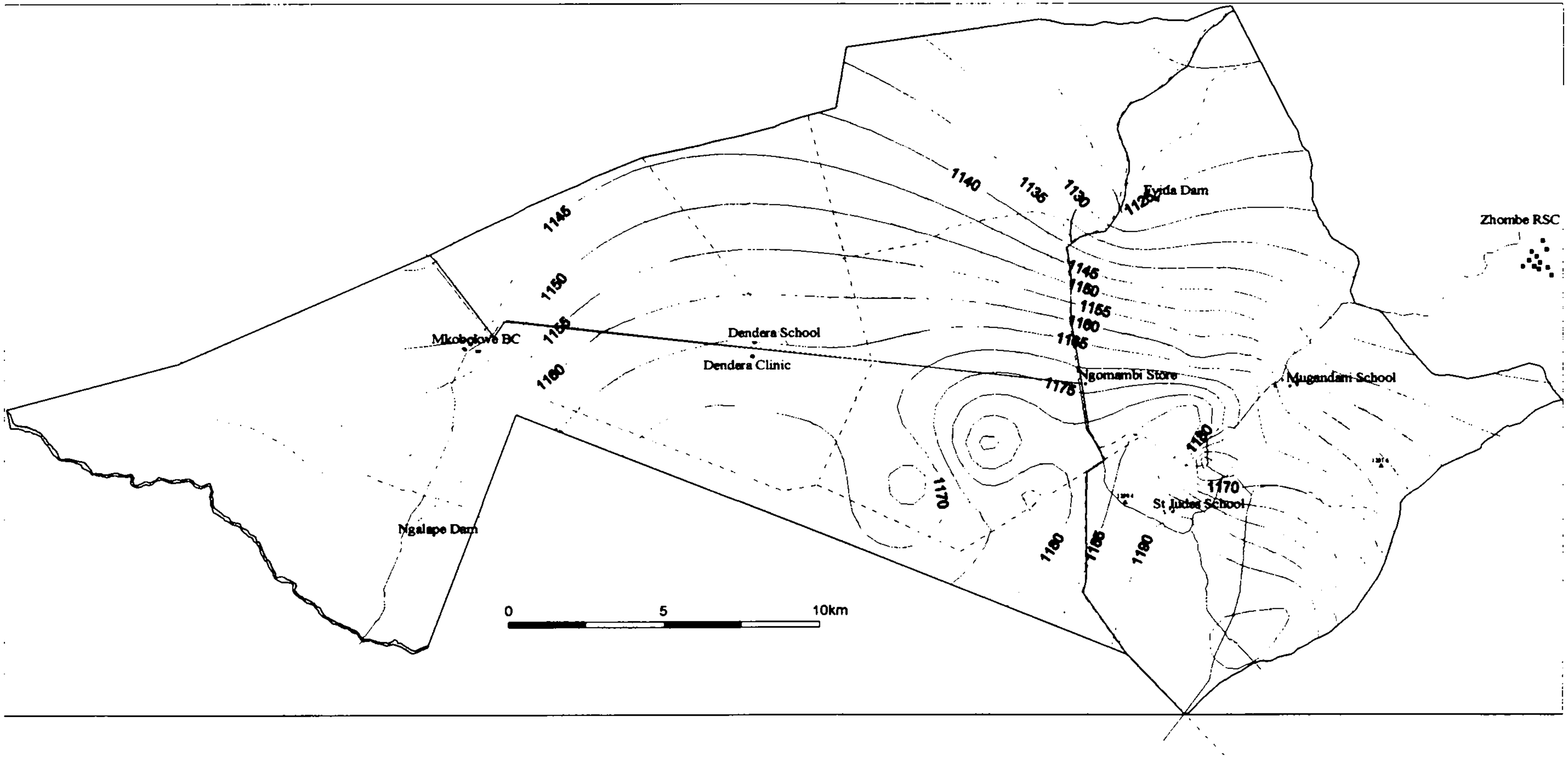


FIGURE 5.2 – Potentiometric Surface Map

Comparison of the potentiometric surface (Fig 5.2) with the topographic map (Fig. 2.2) shows that in general groundwater levels reflect in subdued form the surface topography. A high water level is noted on the southern part of the study area. Generally, groundwater flows northwards from this region. Conspicuously, it flows north- eastwards to the Nyandoma /Munyati River system and also north-westwards to the Magwizi/Gweru River System. Thus the surface water divide, which separates these river systems, is found to coincide with the groundwater divide. In the western part, the perennial nature of Magwizi River and its major tributaries, such as Makobokwe, show that groundwater is discharged in these topographic lows.

A simplified hydrogeological conceptual model for the Dendera area is presented in Figure 5.3. This diagram is a typical geological section through the centre of the study area.

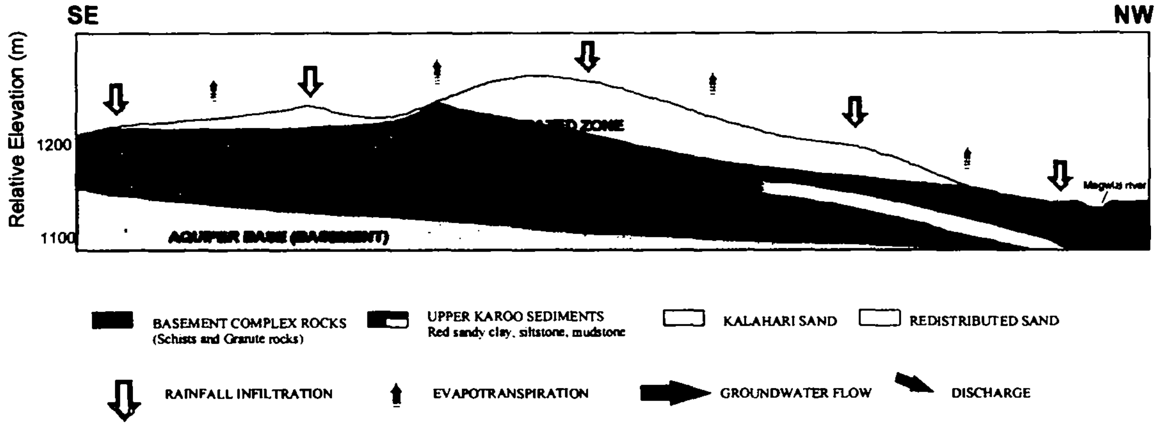


FIGURE 5.3 – Hydrogeological Conceptual model for Dendera Area.

5.4 ESTIMATION OF RECHARGE USING WATER TABLE RISE METHOD

5.4.1 Theoretical Outline

The total annual recharge to an unconfined aquifer can be estimated from the volume of water stored as the water table rises during the wet season. Clearly, the method only applies to aquifers with well-defined recharge seasons. A recharge estimate for a particular region or aquifer can be calculated by following a four steps procedure:

(i) The first step is to map and contour water level rises.

(ii) The second step is to calculate the change in saturated volumes between contours.

(iii) The third step is summing up the aquifer volume within which the variation in water level takes place

(iv) Finally, if the specific yield of the aquifer material (which is equal to storativity for unconfined aquifer) is known, the annual volume of recharge, Q, can be calculated as follows (Lenner, Issar and Simmers, 1990);

$$Q = S_y \; \Sigma_i \frac{(c_i + c_{i+1})}{2} A_i \qquad (5.2)$$

where

S_y is the specific yield of the aquifer material
c_i is the value of contour 'i' of water table rise (m)
A_i is the area between contours c_i and c_{i+1} (m^2)

Objective and reputable methods for contouring and estimating volumes exist. They include computer contouring packages and geostastical techniques, such as krigging. Krigging is a geostastical gridding method that has proven useful and popular for many fields, including the contouring of water levels in an aquifer. The method produces visually appealing contours and surface plots from irregularly spaced data points, such as water level data from boreholes scattered over a specified area of an aquifer. The only disadvantage of the method is its complexity and its reliance on computers. More importantly, the krigging method can not use the subjective information, such as position of pumping wells, faults and rivers, that experienced hydrogeologists would take into account in hand contouring.

While the water level rise method provides a very simple, cheap and quick estimate of annual recharge, it is often rather inaccurate, particularly if the aquifer is non-uniform with respect to S_y, as is usually the case. In fact for non-uniform aquifers the average values of the variables in equation 5.2 are difficult to determine. Furthermore the method is very sensitive to specific yield estimates so much that any error in the value of S_y will be directly proportional to the error in the recharge estimate. Unfortunately, meaningful estimates of S_y are difficult to obtain, with a wide range of values being possible from different methods for the same aquifer material.

5.4.2 Water Level Monitoring in the Study Area

The monitoring of water levels in the study area commenced in October 1996. The author or field assistant measured water levels once a month in 32 boreholes fitted with handpumps. All boreholes used for monitoring water levels were assigned a unique number for record purposes. The distribution of the boreholes used for water level monitoring is shown in Figure 5.4. While more than 90 boreholes were functional at the commencement of the present study, a large proportion of these had no access holes through which water level measurements could be conducted without dismantling the pump-head; such boreholes were not utilised for water level monitoring. Furthermore, boreholes were not evenly distributed over the whole study area, so that no boreholes were found in the northern most part, which accounted for about one-third of the area. This is because Chaminuka Ward (Figure 2.1), one of the three wards comprising the study area, was not covered by the Plan International Funded Water Programme until November 1997.

An electrical dip meter was used to measure the water levels. The dip meter is essentially a graduated tape on a cable reel with two wires running inside the tape and an electrode (a probe) connected to the end of the wiring circuit. A light and buzzer inside the cable reel indicate a closed circuit when the probe touches the water; the light comes on and the buzzer sounds. Flashlight batteries supply the current. The depth to the water is then read from the tape, which is graduated to an accuracy of 10mm. Each reading obtained in this manner and the date of measurement was recorded on a pre-printed water level monitoring form labelled with the locality name, borehole identification number and the grid reference.

5.4.3 Hydrographs

Hydrographs of 32 boreholes at which water levels were monitored in 1996/97 and 1997/98 climatological years are present in Appendix 4. Included with each of the hydrographs are the corresponding monthly rainfall graphs from Zhombe Central rainfall station for the 1996/97 and 1997/98 rainy seasons. Rainfall was in fact much higher than average and thus was above the threshold of 400-500mm/y, which must be exceeded before groundwater recharge takes place in areas covered by Kalahari sands (De Vries and Hoyer, 1988).

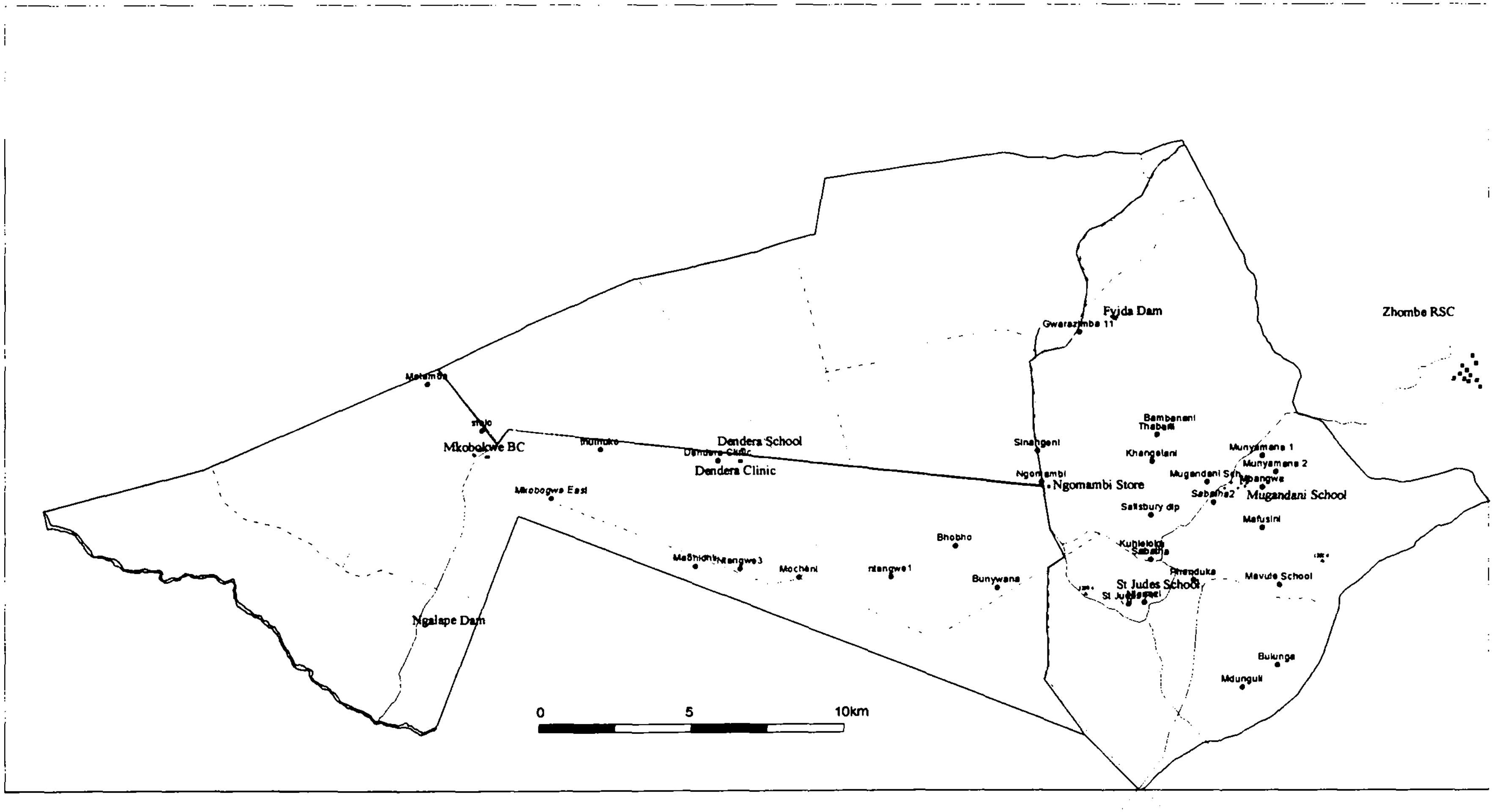


FIGURE 5.4 – Distribution of boreholes used for water level monitoring

The hydrographs show a close relationship with rainfall seasons. In general peaks occur between March and June, towards the end of the rains, while minimum water levels occur in October to November, before the onset of main rains (Fig.5.5). From the hydrographs, it appears that direct recharge of the Karoo aquifer does take place, with approximately two months lag time.

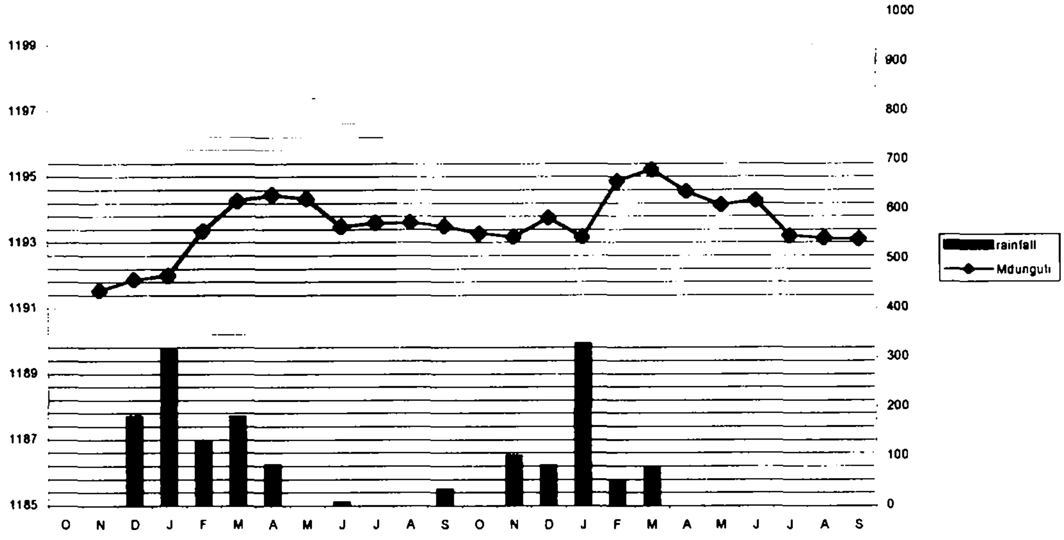


FIGURE 5.5 – Relationship between water level flactuations and rainfall during the 1996/97 and 1997/98 Rainy Seasons. The water level data used was recorded at Mdunguli – Borehole No. 6kwek-200 and the monthly rainfall data is from Zhombe Central Station.

5.4.4 Specific Yield for Karoo Sandstone

Specific yield is the principal aquifer characteristic required to estimate the recharge to an unconfined aquifer using the water table rise method. Meaningful estimates of specific yield are difficult to obtain, with a wide range of values being possible for the same lithology using different methods.

Pumping tests in the study area did not yield any value for specific yield of the Karoo aquifer (Sec. 4.4.5). Furthermore, scanty information is available on the specific yield of the Karoo sandstones of Zimbabwe, despite the considerable work, which has been undertaken on the Karoo aquifer. Majority of the studies done on the Karoo aquifer obtained values of storativity ranging from 0.0001 to 0.0005 – low figures characteristic of confined aquifers. This is probably because most of the studies have been restricted to the Nyamandhlovu aquifer on to the north-west of City of Bulawayo, which is largely confined.

The most comprehensive work to date on the Karoo sandstone is Beasley's thesis (1983) and he ascribed a specific yield of 0.1 to the sandstone. Weaver et al (1992) used the same value, taking it directly from Beasley but supporting it with values from similar formations in Botswana. Banda et al. (1977), from pumping tests in Nyamandhlovu area, obtained storativity values between 0.01 and 0.0001. It was assumed that 0.01 covers the unconfined conditions, while 0.0001 is for the confined conditions. By applying in-situ tracer techniques Banda et al. (1977) established an effective porosity of 0.038, which they considered as the specific yield.

From the previous hydrogeological work it is concluded that specific yield for the Karoo sandstones varies quite considerably. As an overall value 1% (Banda et al., 1977) may be considered rather conservative, while 10% from Beasley's thesis may be too high. A specific yield of 0.038 from the work of Banda et al. (1977) appears to be more realistic and has been adopted for the estimation of recharge in this present study.

5.4.5 Recharge Estimation

Water level fluctuations recorded in the monitored boreholes during 1996/97 and 1997/98 rainfall seasons are shown in Table 5.2, together with the annual rises recorded during each rainfall season. The water level raises were contored using the kriging method. Figure 5.6 and 5.7 show contour maps for water level rises for the 1996/97 and 1997/98 seasons respectively

Areas between contours were calculated using the GIS Arc View software. This was followed by the calculation of the volumes between the contours within which water rises. Summing the volumes between the contours provided the total volumes within which variation in water levels takes place. The total volume for the 1996/97-rainfall season is $5.023 \times 10^8 m^3$, while that for 1997/98 is $4.553 \times 10^8 m^3$. These volumes were converted to volumes of water by multiplying with the specific yield, 0.038. Thus total groundwater recharge for 1996/97 and 1997/98 seasons are respectively $1.909 \times 10^7 m^3$ and $1.730 \times 10^7 m^3$, which on a surface area of $3.815 \times 10^8 m^2$ translate to 50.0mm and 45.3mm. The average recharge for the two seasons is 47.7mm, which is 8% of the mean annual rainfall (651mm).

TABLE 5.2 – Highest and Lowest water levels and annual rises

LOCALITY	GRID REF	1996/97 SEASON			1997/98 SEASON		
		Highest water level (m)	Lowest water level (m)	Fluctuation (m)	Highest water level (m)	Lowest water level (m)	Fluctuation (m)
Sabatha	QK363270	36.262	35.23	1.032	36.76	35.36	1.4
Mugandani Sh.	QK383298	19.07	16.38	2.69	19.07	16.79	2.28
Mocheni	QK237264	54.59	53.86	0.73	54.41	53.99	0.42
Mabhidhli	QK200268	29.25	27.48	1.77	28.4	27.25	1.15
Dhlamayezi	QK307700	58.33	57.57	0.76	58.04	57.13	0.91
St Judes Pr.	QK355254	59.75	58.89	0.86	59.18	58.77	0.41
Salisbury Dip	QK363286	21.28	19.54	1.74	20.23	19.3	0.93
Dendera Clinic	QK208306	68.04	66.77	1.27	67.15	66.5	0.65
Bhobho	QK293275	62.82	61.96	0.86	62.25	61.98	0.27
Ntangwe3	QK216267	43.34	42.91	0.43	44.55	41.75	2.8
ntangwe1	QK270264	66.24	64.04	2.2	66.92	64.98	1.94
Thuthuko	QK166310	57.88	56.94	0.94	57.12	56.57	0.55
Stolo	QK124317	3.41	1.54	1.87	3.97	2.63	1.34
Matamba	QK104334	6.95	5.25	1.7	6.96	5.3	1.66
Mkobogwe East	QK146292	8.64	6.73	1.91	7.97	6.9	1.07
Bunywana	QK308260	70.91	70.59	0.32	71	70.65	0.35
Munyamana 1	QK403307	18.77	15.26	3.51	17.67	16.06	1.61
Munyamana 2	QK408302	19.42	15.21	4.21	19.31	17.46	1.85
Mbangwa	QK403296	20.13	16.48	3.65	19.18	17.31	1.87
Bambanani	QK370318	19.96	18.81	1.15	20.59	19.12	1.47
Gwarazimba 11	QK338352	33.77	33.09	0.68	34.3	33.16	1.14
Ngomambi	QK324298	71.33	70.47	0.86	71.64	70.17	1.47
Sinangeni	QK322309	51.69	50.69	1	50.76	50.07	0.69
Thabani	QK365315	22.42	21.16	1.26	21.43	20.58	0.85
Mafusini	QK403282	23.85	23.21	0.64	23.81	22.7	1.11
Sabatha2	QK385291	25.42	14.36	11.06	25.95	18.57	7.38
Phenduka	QK409261	26.53	22.01	4.52	27.01	24.06	2.95
Mavule School	QK433245	16.67	14.35	2.32	17.07	14.17	2.9
Bulunga	QK409232	15.69	13.98	1.71	14.7	13.1	1.6
Mdunguli	QK396224	11.46	8.55	2.91	9.87	7.78	2.09
Ntenezi	QK361255	52.67	51.91	0.76	53.13	51.56	1.57
Kuhleloku	QK360273	35.57	34.89	0.68	35.09	34.41	0.68
Khangelani	QK363305	29.46	28.37	1.09	28.47	27.57	0.9

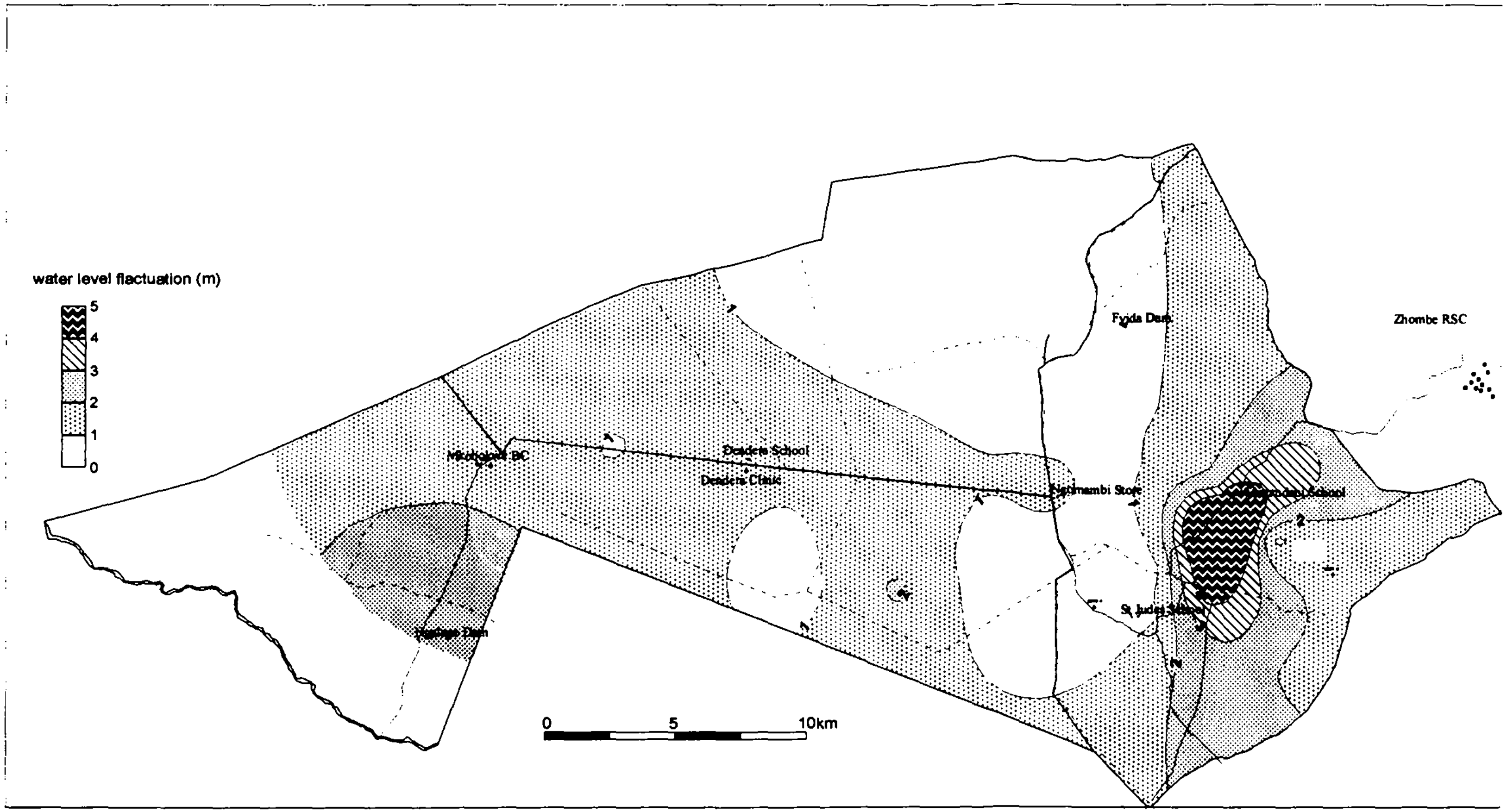


FIGURE 5.6 - Contour map for the water level rises during 1996/97 Season

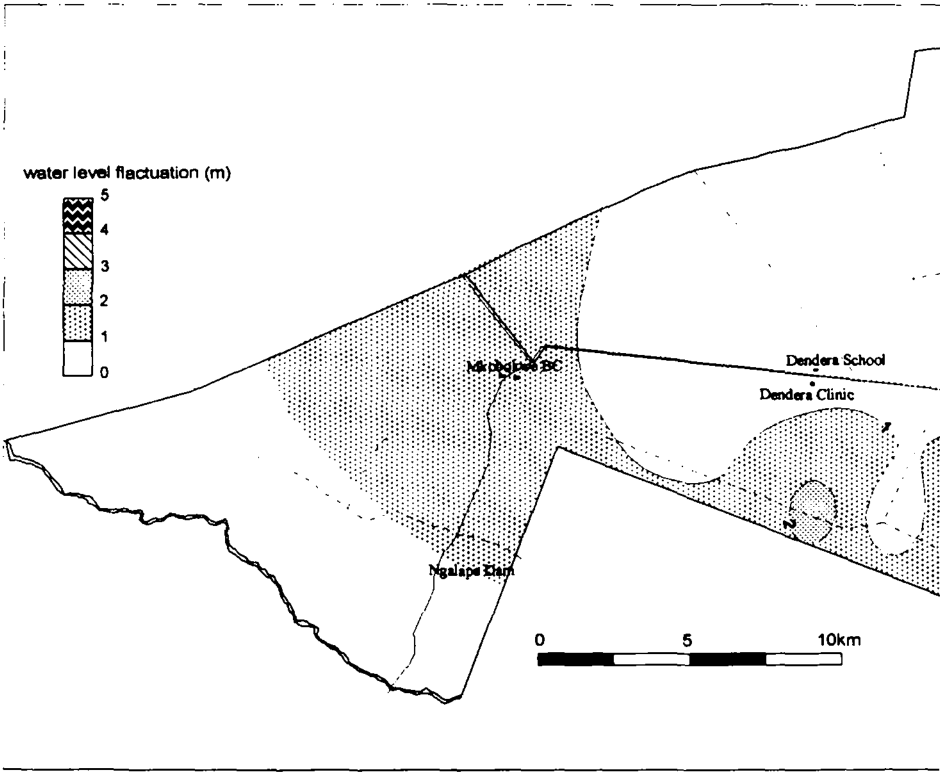
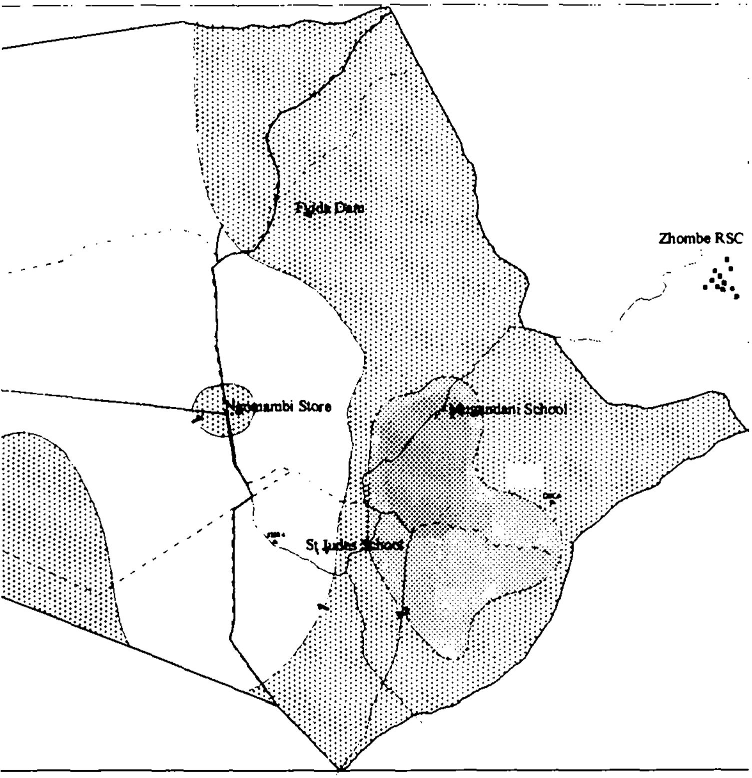


FIGURE 5.7 - Contour map for the water level rises during 1997/98 Season


Fyida Dam
Zhombe RSC
Ngomambi Store
Mtangandani School
St Judes School

5.5 QUANTIFICATION OF RECHARGE USING CHLORIDE MASS BALANCE TECHNIQUE

5.5.1 Theory and Basic Assumptions

The chloride mass balance technique is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux into the sub-surface. The input of chloride to the aquifer is assumed equal to the total atmospheric fall out, which is made up of rainfall (P) and dry deposition (D).

Chloride is considered as conservative tracer as there is no net release or storage in the soil or rock matrix since few minerals, except halite, contain significant amounts of chloride. Moreover chloride is not taken or released by soil or biological processes. Chloride from rainfall is concentrated in the soil as a result of evapotranspiration (E). Thus this solute can be used as a tracer to indicate downward moisture transport (Edmunds et al., 1988).

Chloride concentration in the upper unsaturated zone, above the root zone, fluctuates seasonally due to wetting and drying cycle. However, below the root zone a steady state often exists with slow downward transport of moisture and without further increase in chloride concentration.

Assuming a steady state is attained between total chloride deposition at surface and the concentration of chloride below the root zone, it can be shown that recharge rate q_w is (Edmunds et al., 1988)

$$q_w = \frac{PCl_p + D}{Cl_w} \qquad (5.3)$$

where, Cl_p is concentration of chloride in precipitation and Cl_w is the chloride concentration in the deep soil moisture. If dry deposition of chloride is ignored, as it is commonly negligible in inland areas, recharge rate can be calculated as

$$q_w = \frac{PCl_p}{Cl_w} \qquad (5.4)$$

If no further moisture is removed from the soil before it reaches the water table, the recharge R, will be equal to q_w and chloride concentration in groundwater Cl_{gw}, should be equal to Cl_w (Gieske, 1992). Thus equation 5.4 can be rewritten as

$$R = \frac{PCl_p}{Cl_{gw}} \qquad (5.5)$$

It is very clear from this equation that the fraction of the rainfall contributing to direct recharge is simply given by the ratio Cl_p/Cl_{gw}.

5.5.2 Rainfall in the Study Area

As mentioned in Section 2.5.2, there are three rainfall-recording stations just outside the bounds of the study area. Of these stations, only one, Zhombe Central (QK4734) has rainfall records for more than 30 years; the other two have since been closed to enable 30-year (long-term) averages to be calculated. Rainfall records are available for Zhombe Central from 1966 to present day. Over the 30-year period between 1967 and 1997 the mean annual rainfall at the station was 651mm.

5.5.3 Chloride Concentration in Rainfall

Rainfall was sampled for chemical analysis during the rainy seasons for the first two years of the study, 1996 and 1997. Samples were obtained from a rain gauge at Dendera Secondary School (QK209309), located almost in the centre of the study area. Samples from this rain gauge were collected by the Head-Teacher of the school, who was provided with clean PVC bottles. The samples were added to bulk samples in the bottle after each rainfall event. The author collected the bottles twice during 1996/97 rainy season and once during 1997/98 rainy season. The three rain samples were sent to the Chemistry Department of the University of Zimbabwe for a chemical analysis; the primary objective was to determine the concentration of the chloride ion (Cl^-). Analyses were carried out by Dr S.D Sithole using Ion Chromatography.

The results for the analyses are given in Table 5.3. These values represent the bulk deposition during the rainy season and it is assumed that during the dry season there is no deposition of chloride.

.TABLE 5.3 - Results of the Determination of Chloride Content

Sample No	Period of Sampling	Sample Volume (ml)	Cl^- Content (mg/l)
1	Oct-Dec 1996	670	1.91
2	Jan-March 1997	1626	1.37
3	Oct 1997-Jan 1998	856	1.90
Volume Weighted Average Cl^- (Mg/l)			**1.63**

A mean chloride concentration in rainfall of 1.63 mg/l is rather higher than expected for the continental position of Zimbabwe. However, data on chloride deposition in Zimbabwe is rather scarce because countrywide chloride deposition has not been determined. Thus the accuracy of the mean chloride content in the samples could not be easily verified. The only figure for chloride content in rain in Zimbabwe was determined at Goetz Meteorological Observatory in Bulawayo for the 1991/92-rain season (Nyika et al., 1996). Mean chloride content in rain of 0.28 mg/l was reported. This value is far too low as compared to the longer-term averaged chloride content of Botswana rainfall (1 mg/l) (Gieske, 1991). In Botswana chloride deposition has been systematically measured over the entire country for more than ten years. Edmunds et al. (1988) determined chloride content for rainfall in central Sudan during each of the year between 1982 and 1985 and arrived at mean chloride content in rainwater of 4.9 mg/l. This figure is, however, much higher than the mean chloride content established in this present study.

A value of 1.63mg/l has therefore been adopted for chloride concentrations in rainfall (Cl_p) although, as discussed earlier, this may be relatively higher than expected. As care was taken during sampling to avoid contamination, the only most probable cause of the high chloride content is the evaporation from the rain gauge before sampling; a reduction in volume due to evaporation leads to an increase in concentration of chloride.

5.5.4 Chloride Content in Groundwater

The most important source of chloride in groundwater is from atmospheric sources. There is no indication of other sources such as evaporite minerals in Dendera area and there is unlikely to be any significant contribution from the Kalahari Sand and Karoo Sediments. Furthermore, there are little chances for the composition of groundwater in the saturated

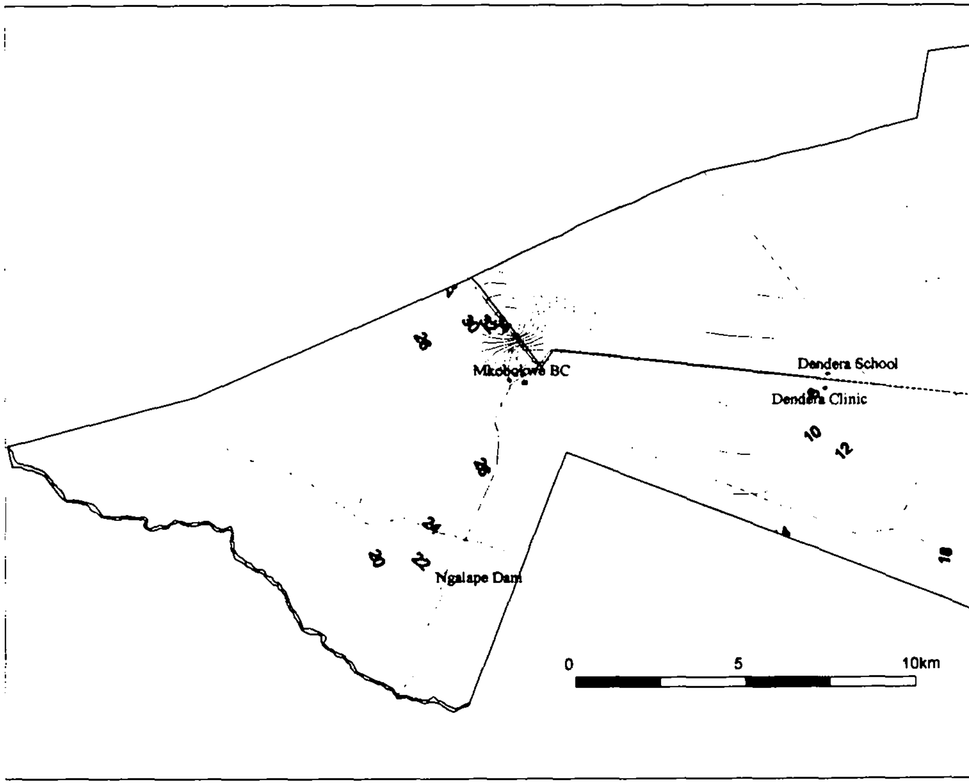
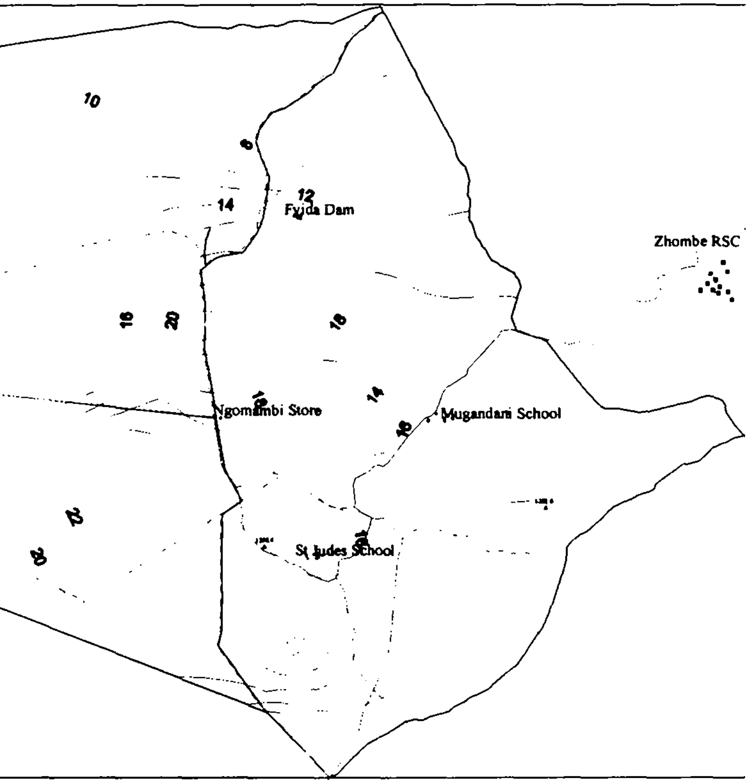


FIGURE 5.8 – Chloride Concentration in Groundwater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Zhombe RSC
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Ngomambi Store
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Mugandani School
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20
St Judes School

zone being modified by incoming lateral flow with higher salinity - it is evident from the potentiometric map (Figure5.2) that there is no sub-surface inflow into the area. It can thus be assumed that the chloride in ground waters of the area results from the infiltration of chloride bearing rainfall, which in turn originates from evaporation of seawater over the Indian Ocean.

While data on chloride deposition in Zimbabwe is scarce, determination of chloride content in groundwater is usually part of standard water analysis procedures, so much that many data is becoming available in recent years. As mentioned in Section 6.0, chemical analysis was undertaken for water samples obtained from 68 boreholes drilled recently in the study area. All the samples were analysed to determine 19 chemical parameters including the chloride concentration. The spatial variation of chloride concentrations in groundwater is illustrated in Figure 5.8 and a list of boreholes, with chloride concentration, is given in Appendix 5. Only chloride concentrations for analyses with balance error less than 10% were used in the estimation of the groundwater recharge. Noteworthy is the generally low chloride concentration in groundwater in the study area. In fact 29 out of 38 analyses (76%) have chloride concentrations less than 20 mg/l.

5.5.5 Estimation of Groundwater Recharge

Equation 5.5 presented in Section 5.1 was used in estimating the recharge at each borehole.The 30 year mean annual rainfall value for Zhombe Central (651 mm) and the chloride content of rainfall of 1.63 mg/l for the 1996/97 rainfall season (Section 6.4.3.) were used in the recharge estimation. At 38 boreholes with charge balance error less than 10%, the recharge was estimated to be in the range between 44.5 mm/y and 110mm/y, with an average of 67.4mm/y. The recharge estimates for the 38 boreholes are given in Table 5.4

5.6 CONCLUSION

Water table fluctuations indicate an average annual recharge value of 47.7mm, while chloride balance investigations show that annual recharge is in the order of 67.4mm. The results of recharge estimations agree reasonably well. It is important to note that water table fluctuation records were limited to only two climatologic years, although long periods are required to enable the calculation of statistically significant long-term mean annual recharge. As the chloride balance method provides long-term mean annual recharge, it seems reasonable to adopt an average recharge figure of 67.4mm/y for the study area.

TABLE 5.4 – Recharge estimates from chloride mass balance method

BH Identification	**Locality**	**Grid Ref.**	**Chloride (mg/l)**	**Recharge (mm)**
6-KWEK-165	Ntangwe 3	QK216267	14.28	74.25037941
6-KWEK-174	Stolo	QK124317	14.96	70.87536217
6-KWEK-183	Semisi	QK109279	28.28	37.49276584
6-KWEK-184	Bunywana	QK308260	21.17	50.08480954
6-KWEK-188	Munyamana 2	QK408302	18.00	58.905301
6-KWEK-189	Mbangwa	QK403282	20.57	51.54571794
6-KWEK-190	Mafusini	QK409232	14.78	71.73852625
6-KWEK-193	Hube	QK293282	26.35	40.23891529
6-KWEK-194	Phakana Line	QK387263	17.35	61.11212784
6-KWEK-196	Penduka	QK409261	19.67	53.90419004
6-KWEK-197	Mavule School	QK433245	17.35	61.11212784
6-KWEK-198	Bulunga	QK409232	15.17	69.89422663
6-KWEK-199	Donsimoyo	QK365222	18.00	58.905301
6-KWEK-204	Intandokazulu	QK354261	10.92	97.09665
6-KWEK-205	Kuhleloku	QK360273	17.35	61.11212784
6-KWEK-206	Khangelani	QK363305	12.85	82.5132621
6-KWEK-207	Thabani	QK365315	19.28	54.99457562
6-KWEK-208	Jabulani	QK362306	9.64	109.9891512
6-KWEK-209	Zimasko 2	QK369314	12.85	82.5132621
6-KWEK-211	Zimasko 1	QK367332	18.43	57.53095052
6-KWEK-213	Zenzeleni	QK334314	19.28	54.99457562
6-KWEK-214	Bambazonke	QK322323	23.78	44.5876963
6-KWEK-216	Madabu	QK341293	18.00	58.905301
6-KWEK-217	Siziba	QK342207	12.85	82.5132621
6-KWEK-218	Mancemeza	QK351226	23.14	45.82089101
6-KWEK-219	Zanke	QK352238	19.92	53.22768163
6-KWEK-221	Sinangeni	QK322309	16.71	63.45274794
6-KWEK-223	Kuwirirana	QK335287	20.57	51.54571794
6-KWEK-234	Refuse	QK195338	10.70	99.09302972
6-KWEK-235	Chitawara	QK286313	11.80	89.8555439
6-KWEK-236	Sakululwa	QK318369	11.80	89.8555439
6-KWEK-237	Godweni	QK311307	19.70	53.82210244
6-KWEK-238	Munyamana	QK283324	21.4	49.54651486
6-KWEK-239	Luka	QK252324	11.8	89.8555439
6-KWEK-244	Gwarazimba	QK338352	17.7	59.90369593
6-KWEK-251	Makombo	QK223316	11.8	89.8555439
6-KWEK-253	Budiriro 2	QK190569	11.9	89.10045529
6-KWEK-258	Zvakaitika	QK214377	11.8	89.8555439
Average				**67.41056**

6.0 HYDROCHEMISTRY

6.1 CHEMISTRY OF NATURAL GROUNDWATER

6.1.1 Introduction

In any evaluation of groundwater resources the quality of water is of almost equal importance to the quantity available. The chemical constituents of groundwater determine its usefulness for drinking, industry and agriculture. Furthermore, the dissolved chemical constituents provide clues on the mode of origin of the water and the geochemical processes associated with the evolution of groundwater.

Nearly all groundwater originates as precipitation that infiltrates through soil into the underlying geologic materials. Rainwater is never pure as it contains chemicals derived from the sea and industrial pollution. In Europe and North America dissolved solids in rain range from several milligrams per litre in continental non-industrial areas to several tens of milligrams in coastal and industrial areas. In Zimbabwe, rainfall analyses are rarely performed but because of the distance from the sea and relatively low levels of industrial pollution it can be assumed that the dissolved constituents of rainwater is negligible in comparison to that of groundwater.

Groundwater contains a wide variety of dissolved chemical constituents mainly because of chemical and biochemical interactions between groundwater and geological material occurring in the soil and saturated zones. In most groundwater, dissolved chemical constituents mainly occur in ionic forms of positively charged ions (cations) and negatively charged ions (anions); thus groundwater can be viewed as an electrolyte solution. The predominant cations are Ca^{2+}, Mg^{2+}, Na^{+}, and $K,^{+}$ while anions are CO_3^{2-}, HCO^-_3, Cl^- and SO_4^{2-}. The concentrations of the chemical constituents in groundwater is controlled by, among other things, the distribution, solubility, exchange capacity and exchange selectivity of the minerals involved in reactions, the porosity and permeability of the rocks, recharge to the groundwater system, and the flow path of the water. Of critical importance in this context is the residence time of the water, since this determines whether there is sufficient time for dissolution of minerals to proceed to the point where the solution is in equilibrium with the reaction. Stagnant water underground reacts with minerals of the host rock until its dissolved chemical composition is in equilibrium with the surroundings. On the other hand, non-stagnant water moving through varying geological formations does not attain chemical equilibrium, but continually dissolves and precipitates material in an effort to do so; thus the chemistry of groundwater may provide a clue to its history.

6.1.2 Chemical Reactions Within the Ground

Considering that subsurface geochemical processes control the composition of groundwater to a very large extent, there is need to identify the chemical reactions important in the evolution of groundwater. In this section, chemical reactions in unsaturated zone, and in saturated zone are dealt with.

Chemical Reactions in the Unsaturated Zone

(i) Gas Dissolution and Redistribution

The dissolution of carbon dioxide, $CO_2(g)$ is an important soil zone process. Rainwater contains some carbonic acid (H_2CO_3) and thus it is somewhat acidic. As this water moves downward, it rapidly dissolves CO_2, which occurs in soil at partial pressure larger than the atmospheric value: CO_2 tend to be more soluble at higher partial pressure. Additional CO_2 in the soil zone is generated by the decay of organic matter and plant roots and microbiological respiration. Carbon dioxide-charged water is a weak acid and as illustrated in equation 6.1 and 6.2, HCO^{3-} and H^+ are the dominant anions and cations respectively;

$$CO_2(g) + H_2O = H_2CO_3 \qquad (6.1)$$
$$H_2CO_3 = HCO_3^- + H^+ \qquad (6.2)$$

(ii) Weak acid-Strong Base Reactions

The formation of carbolic acid (H_2CO_3) results in the dissolution of carbonate, silicate and aluminosilicate minerals for example,

$$\text{Calcite: } CaCO_3(s) + H^+ = Ca^{2+} + HCO_3^- \qquad (6.3)$$
$$\text{Anorthite: } CaAl_2S{:}_3O_8(s) + 2H^+ + H_2O = Ca^{2+} + \text{Kaolinite} \qquad (6.4)$$

(iii) Sulphide Oxidation

Sulphide oxidation is one of the most important redox reactions within the unsaturated zone. Minerals such as pyrite (FeS_2) are oxidised to produce sulphuric acid:

$$FeS_2\,(s) + 15O_2\,(g) + 14H_2O = 4Fe\,(OH)_3 + 16H^+ + 8SO_4^{2-} \qquad (6.5)$$

This is a typical redox reaction in which dissolved oxygen (O_2) is consumed. Because the solubility of O_2 is low and because O_2 replenishment in subsurface environment is limited, this oxidation reaction is only a widespread process in the very shallow part of the subsurface. In this reaction H^+ ions are produced. In many groundwater systems the H^+ ions are consumed by reaction with carbonates, which promotes dissolution of these minerals (eqn. 6.3 and 6.4).

(iv) Gypsum Precipitation and Dissolution

The dissolution reaction of gypsum can be represented by the following equation;

$$CaSO_4.\,2H_2O(s) = Ca^{2+} + SO_4^{2-} + 2H_2O \qquad (6.6)$$

The cyclical precipitation and dissolution of gypsum occurs in cases where the solute load in soil water, with respect to this component, is much higher than normal. Evaporation, if it is high, causes deposition of small amounts of gypsum and with repeated similar process over the years, gypsum accumulates on the upper part of the soil horizon. Exceptional recharge from rain can dissolve some of this soluble material and transport it down to the groundwater system.

(v) Cation Exchange

An important process affecting the chemical composition of groundwater is cation exchange. Cation exchange involves the replacement of ions adsorbed on the surface of clay minerals, and organic compounds by ions in solution. The most important cation exchange reactions are the water softening reactions where sorbed Na_+ replaces Ca_{2+} and Mg_{2+} in the water as groundwater moves through clayey material. This is because the divalent ions, being more strongly bonded, have stronger adsorption affinity than monovalent ions, although this depends to some extent on nature of changer and the concentration of the solution. Examples of cation exchange are as follows;

$$Ca^{2+} + 2Na\text{-clay} = 2Na^{+} + Ca\text{-clay} \quad (6.7)$$

$$Mg^{2+} + 2Na\text{-clay} = 2Na^{+} + Mg\text{-clay} \quad (6.8)$$

Reactions in the Saturated Zone

The chemistry of groundwater not only depends upon the chemistry of the recharge but also the reactions operating within the flow system. While the processes in the saturated zone are complex because of the diverse hydrogeological and geochemical settings, most of the same processes influencing the chemical composition in the unsaturated zone are also operative in the saturated zone.

(i) Weak acid-strong Base Reaction

If the carbon dioxide-charged groundwater is not yet in equilibrium with carbonate, silicate and alumino-silicate minerals, by the time it reaches the saturated zone, it remains chemically aggressive and dissolution of these minerals will continue. Because of the relative abundance of these minerals, and their reasonable solubilities in the weak acid, these reactions increase the TDS concentrations, alkalinity and pH. Equations 6.3 and 6.4 give examples of these reactions: the reactions are much the same with those occurring in the unsaturated zone.

(ii) Dissolution of Soluble Salts

As groundwater moves along its flow path in the saturated zone, particularly in sedimentary basins, it may come into contact with mineral salts. Mineral salts are highly soluble and dissolve to produce brines whose composition depends upon the particular minerals present; for example halite ($NaCl$), anhydrite ($CaSO_4$) gypsum, ($CaSO_4$. $2H_2O$), Kieserite ($MgSO_4$. $2H_2O$) and Sylvite (KCl). This process may lead to formation of saline brines in the shallow groundwater if the mineral salts are encountered at shallow depth. Examples of some of the dissolution reactions are

$$\text{Halite: } NaCl\,(s) = Na^{+} + Cl^{-} \quad (6.9)$$

$$\text{Anhydrite: } CaSO_4(s) = Ca^{2+} + SO^{2-}{}_4 \quad (6.10)$$

$$\text{Kieserite: } MgSO_4.\ 2H_2O\,(s) = Mg^{2+} + SO^{2-}{}_4 + 2H_2O \quad (6.11)$$

(iii) Reduction - Oxidation (Redox) Reactions

In the majority of the groundwater systems dissolved oxygen is low. This is because the oxidation of organic matter, generally very active in the organic - rich layers of the soil zone, commonly removes most of the dissolved oxygen, for example

$$CH_2O + O_2 = CO_2 + H_2O. \qquad (6.12)$$

Nevertheless, even after dissolved oxygen is consumed to levels below detection by normal means, the redox potential can still be very high. This implies that other oxidation reactions such as of ferrous iron, ammonia, manganese and sulphide may still occur within the saturated zone. These processes consume only a small portion of oxygen relative to the oxidation of organic matter. This may result in both concentrations of Fe^{2+} and Mn^{2+} being low and undetectable. Examples of the oxidation reactions are

$$4Fe^{2+} + O_2 + 4H^+ = 4Fe^{3+} + 2H_2O \qquad (6.13)$$

$$2Mn^{2+} + O_2 + 2H_2O = 2MnO_2 + 4H^+ \qquad (6.14)$$

When the oxygen is depleted concentrations of Fe^{2+} and Mn^{2+} increase because MnO_2 and $Fe\ (OH)_3$, which are oxidised solids are not stable in more reducing environment. These reactions are

$$CH_2O - 8H^+ + 4Fe\ (OH)_{3\ (s)} = 4Fe^{2+} + 11\ H_2O + CO_2 \qquad (6.15)$$

$$CH_2O + 4H^+ + 2MnO_{2\ (s)} = 2Mn^{2+} + 3H_2O + CO_2 \qquad (6.16)$$

As the oxidising agents are consumed the groundwater environment becomes more and more reduced; redox potential being highly negative. Once sufficiently negative redox levels have been reached, the reduction of sulphate ($SO^{2-}{}_4$) to sulphide (H_2S) may occur as follows;

$$2CH_2O + SO^{2-}{}_4 + H^+ = HS^- + 2H_2O + 2CO_2 \qquad (6.17)$$

The reduction of organic matter by dissolved gaseous species CO_2 to CH_4 may occur also in these highly reducing conditions.

(iv) Cation Exchange

The most important cation exchange reactions are the natural water softening reactions, which take Ca^{2+} and Mg^{2+} from water and replace them with Na^+. These reactions are the same as those operative in the unsaturated zone, above-described. Another notable cation, which may be involved in cation exchange, is Fe^{2+} and the reaction is represented by the following equation;

$$Fe^{2+} + Na^{+} - clay = Na^{+} + Fe^{2+} - clay. \qquad (6.18)$$

6.1.3 Changes in Ionic Content of Groundwater with time and Distance of Travel

Groundwater chemistry changes as water moves along its flow paths, increasing the dissolved solids and major ions concentrations. Chebotarev (1955) observed that the longer water remains underground, and the further it travels, the more its molar ratio resembles sea water. These changes occur as the water moves from shallow zones of active flushing through intermediate zones into zones where flow is very sluggish and the water is old. In this regard Domenico (1972) noted that groundwater chemistry changes with depth particularly in large sedimentary basins and thus three main zones were distinguished. While the distance of travel and age tend to increase from upper zone to lower zone, the three zones cannot be correlated specifically with travel distance or time.

1. Upper Zone: Characterised by active groundwater flushing through the relatively well-leached rocks. Water in this zone is low in dissolved solids, while calcium (Ca^{2+}) and bicarbonate (HCO^-_3) are the dominant ions.
2. Intermediate Zone: Water move slowly and has high dissolved solids; the sulphate ion (SO^{2-}_4) becomes dominant.
3. Lower Zone: Very sluggish flow, thus so little water moves through this zone. Highly soluble minerals are commonly present because very little groundwater flushing has occurred. Sodium (Na^+) and chloride (Cl^-) are dominant ions and high dissolved solids are characteristic of this zone.

From a geochemical viewpoint the zonal analysis described above can be explained in terms of anion-evolution that, depends on two main variables; mineral availability and mineral solubility. The HCO^-_3 content in groundwater is normally derived from soil zone CO_2^- and dissolution of calcite and dolomite. Because calcite or dolomite occurs in significant amounts in nearly all sedimentary basins and because these minerals dissolve rapidly when in contact with CO_2 charged groundwater, HCO^-_3 is almost invariably the dominant anion in recharge areas or where groundwater has not travelled far in the flow system.

The most common of the sulphate - bearing minerals are gypsum ($Ca\ SO_4.\ 2H_2O$) and anhydrite ($CaSO_4$). These dissolve readily when in contact water. They are much more soluble than calcite and dolomite, but much less soluble than chloride minerals such as NaCl (halite). The reason that in most sedimentary terrains groundwater travels a considerable distance before SO^{2-}_4 becomes a dominant anion is that gypsum and anhydrite are rarely present in more than trace amounts. In many shallow zones these minerals have never been present or have been previously removed by groundwater flushing.

In deep groundwater flow systems in sedimentary basins, where recharge is low and at times in shallow systems, the Cl^- becomes the dominant anion. This occurs if groundwater comes in contact with chloride minerals such as halite or sylvite, which in deep sedimentary basins can occur as salt strata i.e. evaporites deposits. Chloride minerals of sedimentary origin dissolve rapidly in water and their solubilities are magnitudes higher than the solubilities of calcite, dolomite gypsum and anhydrite. Thus the general occurrence of Cl^- as a dominant anion only in deep groundwater or groundwater that has moved long distances can generally be accounted for by the scarcity of these minerals along the flow path.

Although zonal analysis and anion evolution sequence, above-described and the tendency of dissolved solids to increase along the paths of groundwater flow are somewhat generalised, it can provide important information on the flow history of the water.

6.1.4 Groundwater Constituents

Total Dissolved Solids (TDS)

The total concentration of dissolved minerals in water is generally an indication of its suitability for any particular use. It generally varies with aquifer lithology, source area, distance from recharge area and quantity of recharge and the age and flow rate of the water. Table 6.1 presents a classification scheme for groundwater based on the total dissolved solids (Fetter, 1994).

TABLE: 6.1 – Classification of Water Based on Total Dissolved Solids (Fetter, 1994, Pg434)

Class	TDS (mg/l)
Fresh	0 - 1 000
Brackish	1 000 - 10 000
Saline	10 000 - 100 000
Brine	> 100 000

Major Dissolved Constituents in Water

More than 90% of the dissolved chemical constituents in groundwater can be attributed to six ions; Na^+, Ca^{2+}, Mg^{2+}, SO^{2-}, Cl^- and HCO^{3-}. These are commonly referred to as the major ions and are usually present at concentrations greater than 1mg/*l*. Silica (SiO_2), a non-ionic constituent, is also typically present at concentrations greater than 1mg/*l*.

The predominant cation in groundwater is often calcium ion (Ca^{2+}) as it is derived from calcium containing minerals common in most types of rock. Calcium present in groundwater in sedimentary rocks is mainly derived from calcite or dolomite, minerals which are easily dissolved by carbon-charged water. Anhydrite and gypsum are only minor sources of Ca^{2+} as these minerals are commonly present in trace amounts in most sedimentary basins. In igneous and metamorphic rocks Ca^{2+} is supplied into solution by the weathering of plagioclase feldspars, pyroxene and amphiboles, as these minerals decompose chemically.

Mg^{2+}, despite being more soluble in water, is generally subordinate to Ca^{2+} because it is much less abundant in most source rocks. Dolomite is the main source of Mg^{2+} in sedimentary rocks. The rare evaporite minerals such as kierserite, kainite and carnallite are not significant contributors to the Mg^{2+} content. As Mg^{2+} cannot occur in the feldspar crystal structure, in the igneous and metamorphic rocks it is only derived from mafic minerals such as pyroxenes, olivines, hornblende, talc and tremolite.

Na^+, does not occur as an essential constituent of many of the principal rock forming minerals, plagioclase feldspar being an exception. Consequently its main source is chemical decomposition of plagioclase feldspar. Under certain conditions, some clay minerals may release exchangeable sodium ions, for example from clays of marine origin. Thus, Na^+ may be dominant in groundwater due to preferential adsorption of $Ca^{2+}$and Mg^{2+} on clay. Where the water has flowed through evaporitic deposits, such as halite (NaCl), significant amounts of Na^+ are contributed to the groundwater.

While Cl^- is a minor constituent in the earth's crust, it occurs in most groundwaters due to its extremely high solubility. Halite, an evaporitic deposit, is one of the principal mineral sources. The atmosphere probably makes a significant contribution to Cl^- content of surface waters, and in turn these contribute to groundwaters. The chloride ion is conservative and is not taken up in significant quantities by vegetation or evaporation. Thus it undergoes concentration in the soil and upper unsaturated zone as a result of evapotransipiration before being transported to the zone of saturation. Leaching of chlorides that have been deposited in the upper layers of the soil may be significant a source of chloride in dry climates.

Most $SO^{2-}{}_4$ is probably derived from dissolution of sulphate minerals found in evaporitic sequences, gypsum and anhydrite being most common; sulphur containing minerals such as pyrite or marcasite, are not abundant in rocks and thus make little contribution to $SO^{2-}{}_4$ content. Unlike Cl^- the concentration of $SO^{2-}{}_4$ in water can be reduced by chemical reactions and precipitation and is also affected by sulphate reducing bacteria in redox reactions.

Most $HCO^-{}_3$ and $CO^{2-}{}_3$ in groundwater is derived from CO_2 and solution of carbonate rocks. The $HCO^-{}_3$ content is usually much greater than $CO^{2-}{}_3$ content in the water because $HCO^-{}_3$ ions only give $CO^{2-}{}_3$ at $pH > 8.2$.

Although silicon is the second most abundant element in Earth's crust and is present in most of the principal rock-forming minerals, it is not abundant in groundwater. This is because silica (SiO_2) is only slightly soluble in water. The principal dissolved silicon species in groundwater at typical pH value of 6-9 is the molecules of silicic acid (H_4S0_4); while at pH value>9 silicate ions are found in solution because of the dissociation of the acid.

Minor Dissolved Constituents in Water

Most groundwaters contain some Fe^{2+}, because iron is common in many igneous and metamorphic rocks and is present in trace amounts in sedimentary rocks. The specific form iron takes (Fe^{2+} or Fe^{3+}) in water depends on the amount of oxygen in water and pH. In natural groundwater systems where oxygen concentrations are low and pH is below 7, the ferrous ions (Fe^{2+}) dominates and concentrations of iron in groundwater of 1mg/l or above are possible. When such groundwater is exposed to air., Fe^{2+} being unstable in contact with oxygen is oxidised to ferric ions (Fe^{3+}) and precipitates as ferric hydroxide. Ferric iron is almost insoluble in alkaline or weakly acid water.

Boron occurs in tourmaline and is produced as boron fluoride and boric acid during volcanic eruptions. Hence boron may be found in high concentration from water in volcanic areas.

Fluorite, which is the principal fluoride mineral in igneous rocks, and the mineral apatite and some amphiboles act as the source of fluoride (F^-) in groundwater. While F^- concentration at times exceed 10mg/l, water with a high content of Ca^{2+} does not contain more than 1mg/l of F^-.

The concentration of strontium in groundwater is generally low, not exceeding lmg/l, probably because of cation exchange with Ca-rich clays.

Common sources of potassium ions (K^+) in groundwater are the feldspars and micas of the igneous and metamorphic rocks. Potash minerals such as sylvite occur in some evaporitic sequences but their contribution is not important. Although highly soluble and abundant in the Earth's crust as sodium, its concentration is usually very low, less than one tenth that of sodium.

Unlike most other constituents in groundwater, nitrate (NO_3^-) is not derived primarily from the rocks. NO^{3-} is derived form the oxidation of decaying organic material, particularly that with a high protein content. The presence of NO_3^- in large amounts may be indicative of a source of pollution. Other sources of NO_3^- are animal waste and nitrate fertilisers.

6.1.5 Methods of Presenting Chemical Data

An important task in groundwater investigations is the description of the concentration or relative abundance of various chemical constituents dissolved in water. Five techniques are commonly used to portray the chemical analysis of natural groundwater. Data tables are the most common form in which the results of an analysis of water chemistry are reported. The data can be tabulated to give tables indicating the specific ions present and their relative or absolute abundance. For many purposes, the data may be also displayed in graphical form; thus four of these methods are graphical.

The simplest of these graphical methods is the Collins bar graph. Figure 6.1 shows the Collins bar graph that is commonly used in water-chemistry; in fact this method is still used by the US Geological Survey (Driscoll, 1989). The graph can represent the major-ion composition in milliequivalents per litre or in percentage of total equivalents. The chemical analysis of groundwater can also be represented by a circular diagram, commonly known as a pie diagram (Fig. 6.2). The radial axis is proportional to the total milliequivalents, whereas subdivisions of the circle represent the proportions for individual ions.

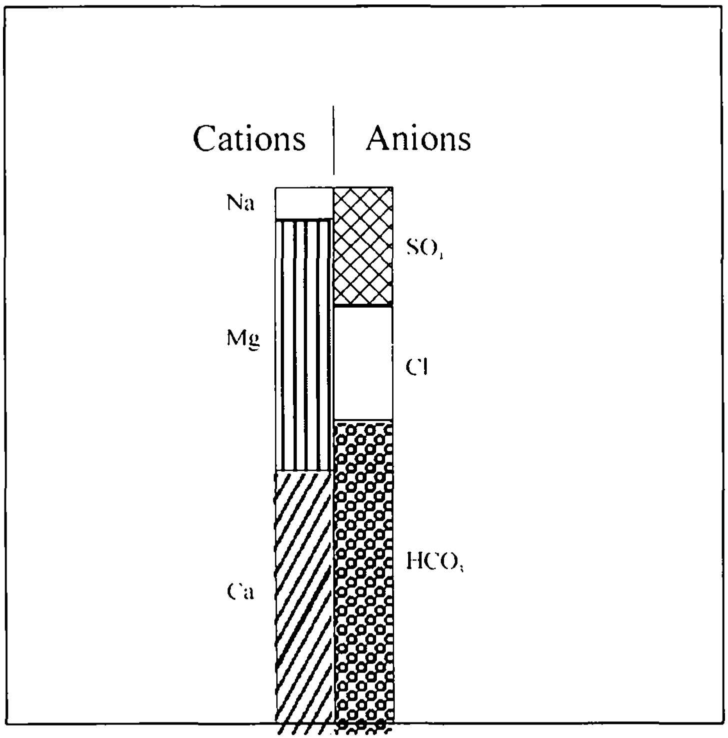

FIGURE 6.1 – A chemical analysis of groundwater using a bar graph

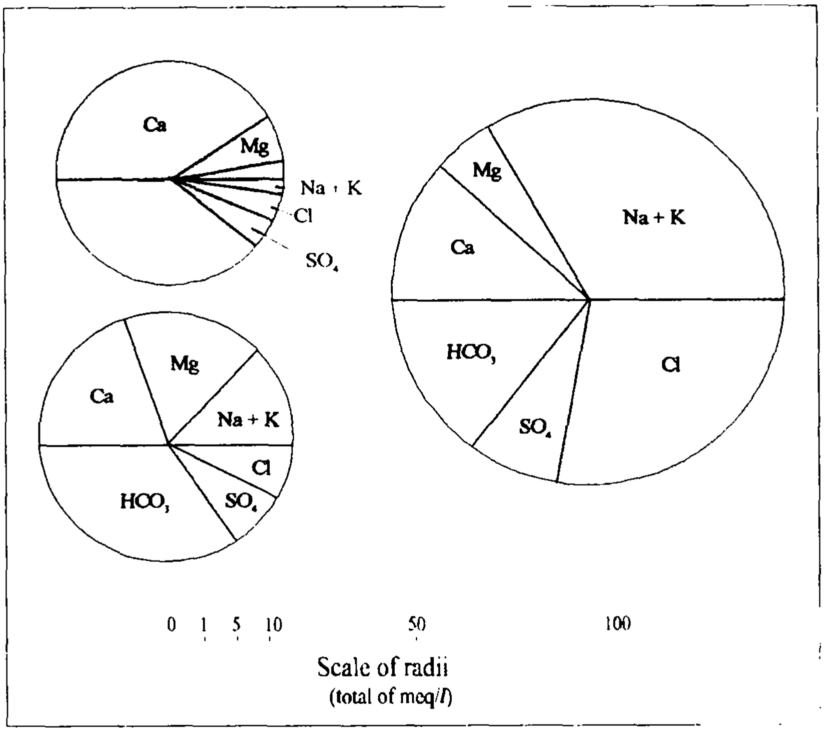

FIGURE 6.2 – Chemical analyses of groundwater presented as circular diagrams

Currently trilinear diagrams are the most widely used method to depict the chemical data. The trilinear diagram was developed by Piper in 1944 (Fetter, 1994). Figure 6.3 shows the form of a trilinear diagram that is commonly used in water chemistry studies. The diagram permits cation and anion composition of many samples to be represented on a single graph in which major groupings or trends in data can be observed. The Piper trilinear diagram combines three distinct fields for plotting; two triangular fields at the left and right respectively; and an intervening diamond shaped field. The fields have scale readings in 100 parts. The relative abundance of cations, with the % meq/l of major cations ($Na^+ + K^+$, Ca^{2+} and Mg^{2+}) assumed to be 100%, is plotted on the cation triangle. Similarly the right (anion) triangle displays the relative abundance of major anions (Cl^- SO^{2-}_4 and $HCO^-_3 + CO^{2-}_3$). Na^+ and K^+ and HCO^-_3 and CO^{2-}_3 are combined because to use this method three anions or cations are required. The central diamond shaped field of the trilinear diagram is used to show the overall chemical character of the groundwater by a third single point located at the intersection of rays projected from the plotting of the cations and anions. The plotting indicate the relative composition of the groundwater in terms of the cation-anion pairs and shows the chemical character of the groundwater according to relative concentration of its composition. The trilinear diagrams are,

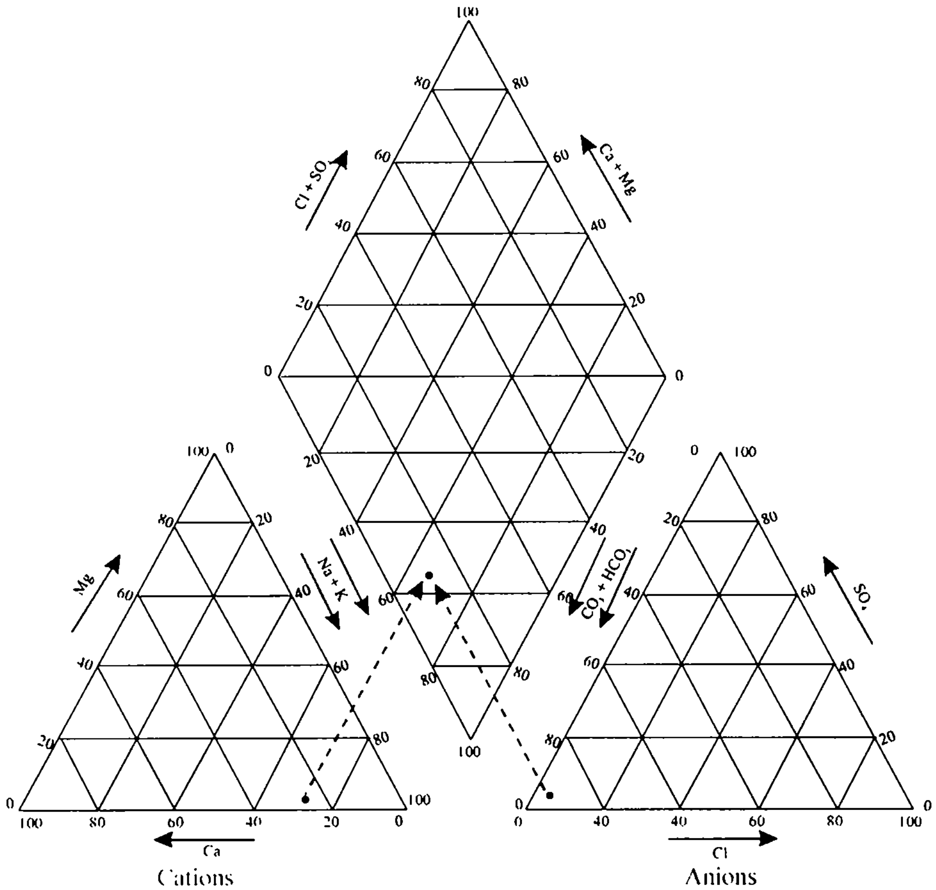

FIGURE 6.3 – Trilinear diagram used to display the results of chemistry studies

therefore, useful for visually describing differences in major ion chemistry in groundwater flow systems. Distinct groundwater quality types can be identified by their plotting in certain sub-areas of the diamond - shaped field. The term hydrochemical facies is used to describe distinct bodies of groundwater in an aquifer that have cation and anion concentrations describable within defined composition categories. The composition categories are commonly based on sub-divisions of the trilinear diagram in a manner shown in Figure 6.4.

One other graphical procedure has been developed to depict water chemistry and this is known as stiff diagram. It was named after the hydrogeologist who first used it in 1955. A polygonal shape is created from three parallel horizontal axes extending either side of a vertical axis. The concentration of each cation is plotted on the left of the axis, and the anions are similarly plotted on the right. Figure 6.5 shows stiff diagram for two typical samples (Fetter, 1994). The stiff diagrams are all easy to construct and are useful in making rapid visual comparison between water from different sources

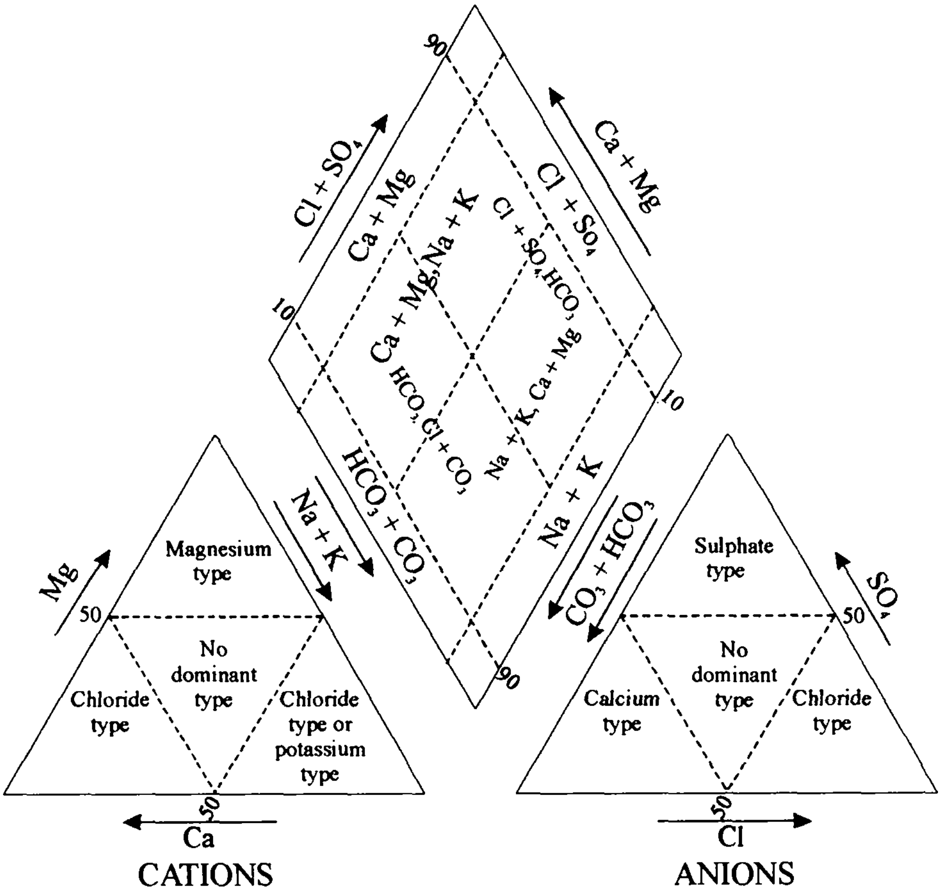

FIGURE 6.4 – Hydrochemical classification system for natural waters using the trilinear diagram

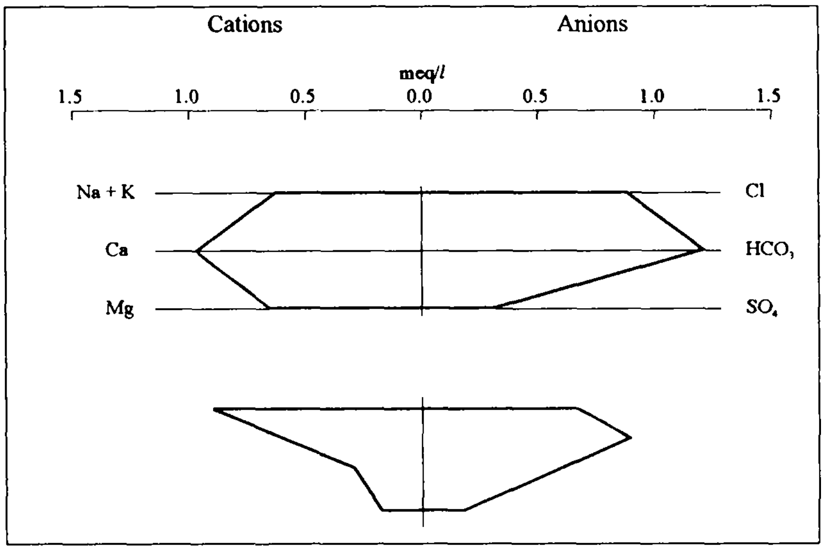

FIGURE 6.5 – Analysis represented by Stiff pattern

6.2 SAMPLING OF GROUNDWATER IN THE STUDY AREA

The author, on behalf of Groundwater Developments Consultants (GWDC), collected water samples from 48 boreholes soon after they were commissioned. The sampling procedure adopted at each borehole, in sequential order, is given below (GWDC, 1996).

i) The clean $2^1/_2$ litres plastic bottle was rinsed with the water from the borehole.
ii) The borehole was pumped for 10-15 minutes before collection to ensure the water is agitated and represent the rest of the water drawn from the aquifer.
iii) The $2^1/_2$ litre plastic bottles were filled and immediately tightly sealed with a screw cap.
iv) The sample bottle was properly labelled with the locality name before leaving the respective borehole.
v) The water sample bottles were carefully packed in boxes, ready for safe transportation.

Jeremy Prince and Associates, in 1997, during the implementation of the rural water supply programme in Ntabeni and Chaminuka Ward, collected further water samples from all new and rehabilitated boreholes; 20 of the boreholes occurring in the study area.

6.3 CHEMICAL ANALYSIS OF SAMPLES

The samples collected by the author were chemically analysed by the Chemistry Department of University of Zimbabwe. The Government Analyst Laboratory of the Ministry of Health carried out chemical analysis of water sampled by Jeremy Prince and Associates, on the other hand. In both cases, the samples were analysed to determine 19 chemical parameters listed in Table 6.2. The laboratory determinations were expressed in milligrams per litre (mg/l). However, in hydrogeological studies it is convenient if concentrations are expressed in chemical equivalents of the ionic components concerned because, by definition, cations and anions combine in proportion to their equivalent weight and charge. The equivalent, or combining weight of dissolved ionic species is the formula weight divided by the electrical charge. By dividing a concentration in milligrams per litre by the equivalent weight of the ion, the result is the concentration expressed in milliequivalents per litre (meq/l). For this thesis, the chemical concentrations were converted from mg/l to meq/l using the atomic weights given by CW Fetter (1994).

TABLE 6.2 - Guidelines for Drinking – Water Quality (WHO – Geneva, 1993)

PARAMETER	UNITS	GUIDELINE CRITERIA WHO*
PH	-	6.5 – 8.5
Colour	TCU	<15
Turbidity	NTU	<5
Specific Conductivity	mS/m	-
Approx. T.D.S	mg/l	<1000
Alkalinity	$CaCO_3$ mg/*l*	-
Total Hardness	$CaCO_3$ mg/*l*	<500
Line Hardness	$CaCO_3$ mg/*l*	-
Chloride	Cl^- mg/*l*	<250
Sulphate	SO_4^{2}- mg/*l*	<250
Nitrate	NO_3^-	<50
Bicarbonate	HCO_3^- mg/*l*	-
Sodium	Na mg/*l*	<200
Potassium	K mg/*l*	-
Calcium	Ca mg/*l*	<250
Manganese	Mn mg/*l*	<0.1
Magnesium	Mg mg/*l*	<150
Iron	Fe mg/*l*	<0.3
Fluoride	F mg/*l*	<1.5

6.4 RELIABILITY OF CHEMICAL ANALYSIS DATA

A long shelf life of the water samples, in some cases upto six months, between sampling and analysis means that some analyses are likely to be in error. This is particularly true for determinations of pH, conductivity and bicarbonate or alkalinity, since they are affected by the dissolution of oxygen.

It was the original intention that major ion analysis should be carried out on all samples. All the samples submitted to the University of Zimbabwe Chemistry Department had full major ion analysis. Of the samples sent to the Government Laboratories by Jeremy Prince and Associates, 80% had complete analysis. The reliability of these chemical analyses was checked by performing a cation-anion balance: the sum of positive ionic charges is expected to be equal to the sum of negative ionic charges in an electrolyte solution. This was accomplished by converting all ionic concentrations to units of milliequivalents per litre and comparing the sum of cations with the sum of the anions. The deviation from equality was determined by the charge-balance error, E, defined as:

$$E = \frac{\sum \text{cation concentration} - \sum \text{anion concentration}}{\sum \text{cation concentration} + \sum \text{anion concentration}} \times 100 \qquad (19)$$

where the concentration is expressed in milliequivalants per litre. According to Freeze and Cherry (1979, pg 79) the acceptable maximum error for water analysis is usually 5%.

The charge-balance error computations showed that only 44% of those samples with a major ion analysis fall within the bracket of an error of 5% or less. However, for the purpose of achieving a detailed hydrochemical analysis in this thesis the limit was relaxed to 10%. This limit contained 66% of the samples with complete analysis; 45 analyses had charge-balance error less than 10%. While the significant deviation from equality of the larger amount of analyses may have been caused by analytical errors in the concentration determination, the presence, in significant amounts, of ionic species that were not included in the analysis may contribute to these errors.

In order to calculate concentration of $CO^{2-}{}_3$ from alkalinity, a laboratory determined parameter, one needs to accurately determine the pH: field measurements on collection of samples are required. Unfortunately, field measurements of pH were not conducted and as such concentration of $CO^{2-}{}_3$ could not be accurately determined. Nonetheless, the laboratory analysis showed that groundwaters of the study area have pH ranging between 6.5 and 8.5 and therefore, the dissolved carbon exists almost entirely as $HCO^{-}{}_3$: in natural water $CO^{2-}{}_3$ is only found in appreciable amounts at pH >9.0. (Freeze and Cherry, 1994, pg 403).

Several analyses show zero value for concentrations of minor components included in the chemical analysis (Fe^{2+}, Mn^{2+}, F^-, NO_3^-, $SO^{2-}{}_4$). It was assumed that these are below detection limit of the determination techniques.

6.5 CHEMICAL CHARECTERISTIC OF GROUNDWATER OF THE STUDY AREA

6.5.1 Major Ions Characteristics

Chemical analyses of 68 samples are tabulated in Appendix 5. The total concentration of dissolved solids in the samples ranges from 75.5 to 706 mg/l with an average of 260 mg/l. Most samples (96%) have TDS less than 500mg\l; of the 68 samples with full analyses, in only three does the TDS exceed 500 mg/l. However, all samples are under 1000 mg/l and may therefore be classified as fresh water (Fetter, 1994).

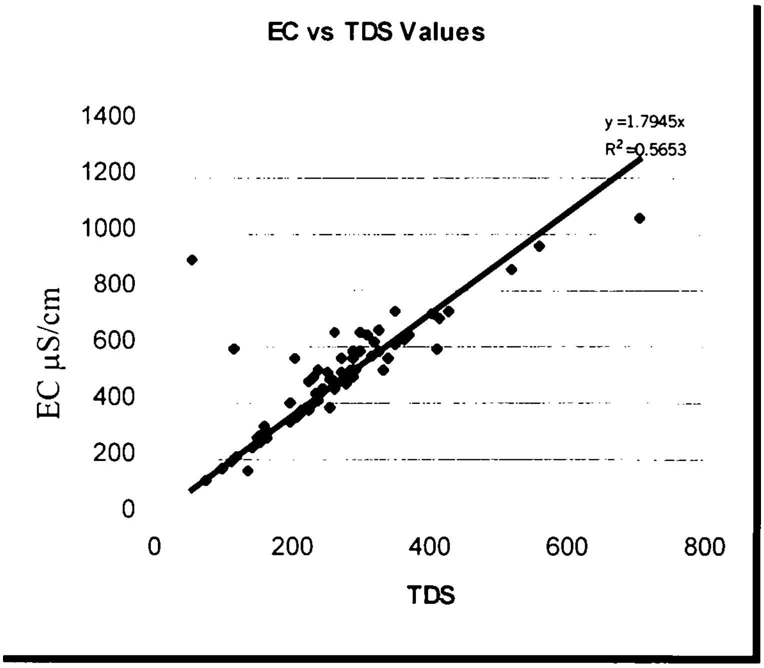

FIGURE 6.6 – Electrical conductivity values compared with TDS

Values of electrical conductivity plotted against TDS are shown in Figure 6.6. The TDS appears to be linearly related to the electrical conductivity within the tolerance of a very small scatter. Such a linear relationship shows a constant ratio between conductance and mineral content of the groundwater. The major ion chemistry for the 45 analyses with ion balance error less than 10% are shown plotted on the Piper Trilinear Diagrams in Figure 6.7. The anion field is dominated by HCO_3^-, while the cation field shows Ca^{2+} to be dominant ion.

6.5.2 Hydrochemical Facies

By making reference to the classification diagram for the designation of hydrochemical facies (Figure 6.4), it is apparent that all the samples are of the bicarbonate-type; HCO_3^- form more than 70% of the major anions in all the analyses. In contrast, the cations show much greater variation, although calcium-type of groundwater is predominant; more than 75% of the samples contain Ca^{2+} exceeding 50% of the total cations. Noteworthy is the generally low Na^+ in all samples; only two samples contain more than 30% of sodium. It is therefore, very clear from the classification scheme suggested by Black (1966) that in the study area calcium-bicarbonate-type groundwater is predominant. This is indicative of recently recharged water.

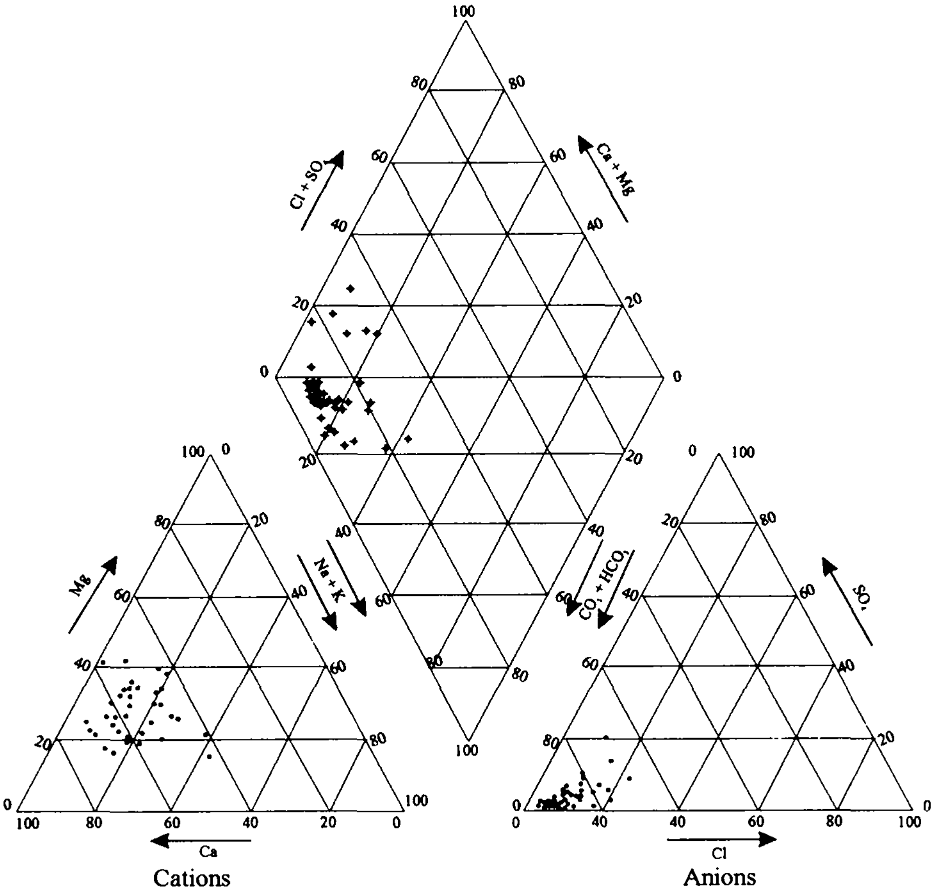

FIGURE 6.7 – Trilinear Diagrams of major Cations and Anions

6.6 GROUNDWATER QUALITY IN RELATION TO USE

The primary purpose of a water analysis is to determine the suitability of water for a proposed use (Driscoll, 1989). There are three principal classes of use namely, domestic (household), agricultural, and industrial. As this study seeks to determine the suitability of the water for domestic and agricultural use, only these are discussed further in this section.

6.6.1 Domestic Use and Groundwater Potability

Water for human consumption must be free from organisms and chemical substances in concentration high enough, to affect health adversely (Hamill and Bell, 1986). Furthermore, drinking water should be aesthetically acceptable, that is to say it should not have objectionable or unpleasant taste, odour, colour or turbidity. Standards for drinking water have been published by several organisations. The World Health Organisation (WHO) standards are shown in Table 6.2 (WHO, 1993). These standards serve as a basis of appraisal of the results of chemical analysis of water in terms of suitability for human consumption.

While all six major ionic species found in most natural water (Section 6.1.4) are commonly included in water-chemistry studies, five have recommended permissible limits specified: Cl^-, SO^{2-}_4, Ca^{2+}, Mg^{2+} and Na^+. Consumption by humans of waters with concentrations somewhat above these limits (Table 6.2) is generally not harmful. However, if Cl^- and SO^{2-}_4 are present in excessive amounts, the water will have disagreeable taste.

Hardness of water is the chemical property, which produces scum by reactions with soap, and cause encrustation in kettles and boilers. Hardness is normally expressed as the total concentration of Ca^{2+} and Mg^{2+} as mg/l equivalent $CaCO_3$. It is calculated from the equation;

$$\text{Total hardness} = 2.5\,(Ca^{2+}) + 4.1\,(Mg^{2+}) \qquad (6.20)$$

where the Ca^{2+} and Mg^{2+} concentrations are expressed in mg/l (Freeze and Cherry, 1979). Water for domestic purpose should not contain more than 80-100 mg/l total hardness. The degree of hardness in water has been described in Table 6.3 (Hamill and Bell, 1986).

TABLE 6.3 - Degree of Hardness of Water (After Sawyer and McCarty, 1967)

Description	**Hardness (mg/l as CaCO3)**
Soft	<75
Moderately hard	75-150
Hard	150-300
Very hard	>300

Many of the recommended limits specified for minor and trace inorganic constituents in drinking water are for reasons other than direct hazard to human health. For example, while intake of water with high concentration of iron and manganese is not harmful, the maximum recommended concentration specified for these metals are for reasons of taste and also to avoid problems associated with precipitates and stains formed on their oxidation.

Fluorine in public drinking water is a contentious subject. Some fluorine is recognised as being beneficial because it reduces dental decay, but higher concentrations (>1.5 mg/l) cause molting of teeth (fluorosis) and borne deformities, especially in growing children.

The groundwaters from the aquifer are within acceptable limits with respect to TDS since all samples have values well under 1000 mg/*l*. In addition most of the samples are within acceptable concentrations for the major ionic constituents. Only one sample from Borehole 6kwek-210 (Bambanani) is above the acceptable limits with respect to the Cl^- constituent.

In accordance to the classification of water in terms of the degree of hardness (Table 6.3), only four samples may be classified as soft water. Hardness of all the samples ranges from 46 to 471.3 mg/l: four (6%) are classified as soft; 13 (19%) are moderately hard; 41 (60%) are hard, while the remaining 10 (15%) are very hard. Nevertheless, no samples have hardness above the limits recommended for rural water supplies, (500 mg/l).

Although adults can tolerate moderate concentration of nitrate, concentration of over 50 mg/l, measured as NO^-_3, can be very dangerous to infants if drunk regularly. The nitrate concentrations of all the samples are low; 92% of the samples have concentrations less than 10 mg/l and no sample exceeds 50 mg/l. The low nitrate concentrations clearly indicate that no organic or sewage pollution is currently present in groundwaters.

Fluoride concentration in the groundwaters varies between 0.08 and 1.8 mg/l. Five samples marginally exceed the maximum fluoride concentration (1.5 mg/l) recommended by the WHO. However, several national and International organisations have recommended fluoride concentrations as high as 2.5 mg/l; in fact a maximum concentration of 3.0 mg/l has been recommended for Zimbabwe in the National Master Water Plan (Interconsult, 1986). Thus the water from the five boreholes whose samples exceeded the WHO limits with regard to fluoride can safely be used for domestic consumption.

6.6.2 Suitability for Livestock Watering

Quality requirements for livestock watering are not as stringent as for drinking water of humans. Limits for the content of total dissolved solids (TDS) recommended for the Western Australia are given in Table 6.4 (Hamill and Bell, 1986). While a total dissolved solids content higher than 3000 mg\l is unsuitable for poultry, a content of 10 000 mg/l is acceptable for beef cattle. In addition recommended limits of individual constituents range from twice to twenty times the acceptable limits for potability.

TABLE 6.4 - Western Australia Standards for Livestock Water (after Hamill and Bell, 1988)

Livestock	TDS (Mg/l)
Poultry	2900
Pigs	4300
Horses	6400
Dairy Cows	7100
Beef Cattle	10 000
Sheep on dry feed	13 000

Though upper limits for TDS are as much 3000mg/l for small animals and 10 000mg/l for large animals, it was noted in Section 6.5.1 that all samples have TDS less than 1000 mgl/l. Groundwater in the study area is therefore suitable for all forms of livestock with regard to the chemical constituents determined in the analyses.

6.6.3 Suitability for Irrigation

The suitability of groundwater for irrigation depends on the effects that salt concentration contained therein has on soil and plants. The three main factors, which affect the suitability of water for irrigation, are total salinity, concentration of particular chemical constituents, and sodium content.

Excessive salinity occurs when there is accumulation of salts in the soils. Salts may harm plant growth in that they reduce the uptake of water and nutrients due to osmotic effects. Some waters contain high enough concentration of certain elements to retard or even eliminate the growth of some plants. Boron, sodium and chlorides are common toxic constituents (Driscoll, 1989, pg. 122).

However, plant species vary widely in their tolerance to overall salinity and to particular chemical constituents that cause toxicity. The effects salts have on some soils, notably the changes brought about in soil fabric, which in turn may reduce the permeability and aeration significantly, also influence plant growth, as sufficient water cannot reach the root zone. A measure of salinity hazard is given by the electrical conductivity of the water because there is a strong correlation between the concentration of dissolved salts and the electrical conductivity. In solutions as dilute as most groundwater the specific conductance varies directly with the amount of dissolved salts.

Sodium has far-reaching and harmful effects on soil. High sodium content in irrigation water can bring about a reduction in soil permeability and cause soil to harden. It may also result in reduction of nutrients available to plants. All these effects are attributable to cation exchange of calcium and magnesium ions by sodium ions on clay minerals and colloids. Notably, high concentration of sodium salts can produce alkali soils in which little or no vegetation can grow. Due to the importance of sodium effects, in 1954 the United States Salinity Laboratory (Driscoll, 1989, pg 114) derived a parameter, sodium absorption ratio (SAR), from which the amount of sodium absorbed by a soil can be estimated. The SAR is defined as;

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}} \tag{6.20}$$

where the cation concentrations are expressed in milli-equivalent/litre. For any particular value of SAR the actual hazard to soil increases with the total salinity. Classification of irrigation waters based on the SAR and Salinity Hazard (conductivity) is presented in Figure 6.8. This is according to the scheme developed by the United States Department of Agriculture (Driscoll, 1989, pg. 902).

The sodium hazard of water samples, with balance error better than 10%, is plotted in Figure 6.8. The figure shows that all samples plot in a compact group having a very low sodium hazard; such water can be used with little danger on nearly all soils. It is also noted from the same figure that, all but one of the samples have salinity hazard ranging from low to medium. Water from Borehole 6kwek-180 has high salinity hazard and thus cannot be used on soils with restricted drainage. All in all, groundwater in the study area is generally suitable for irrigation purposes.

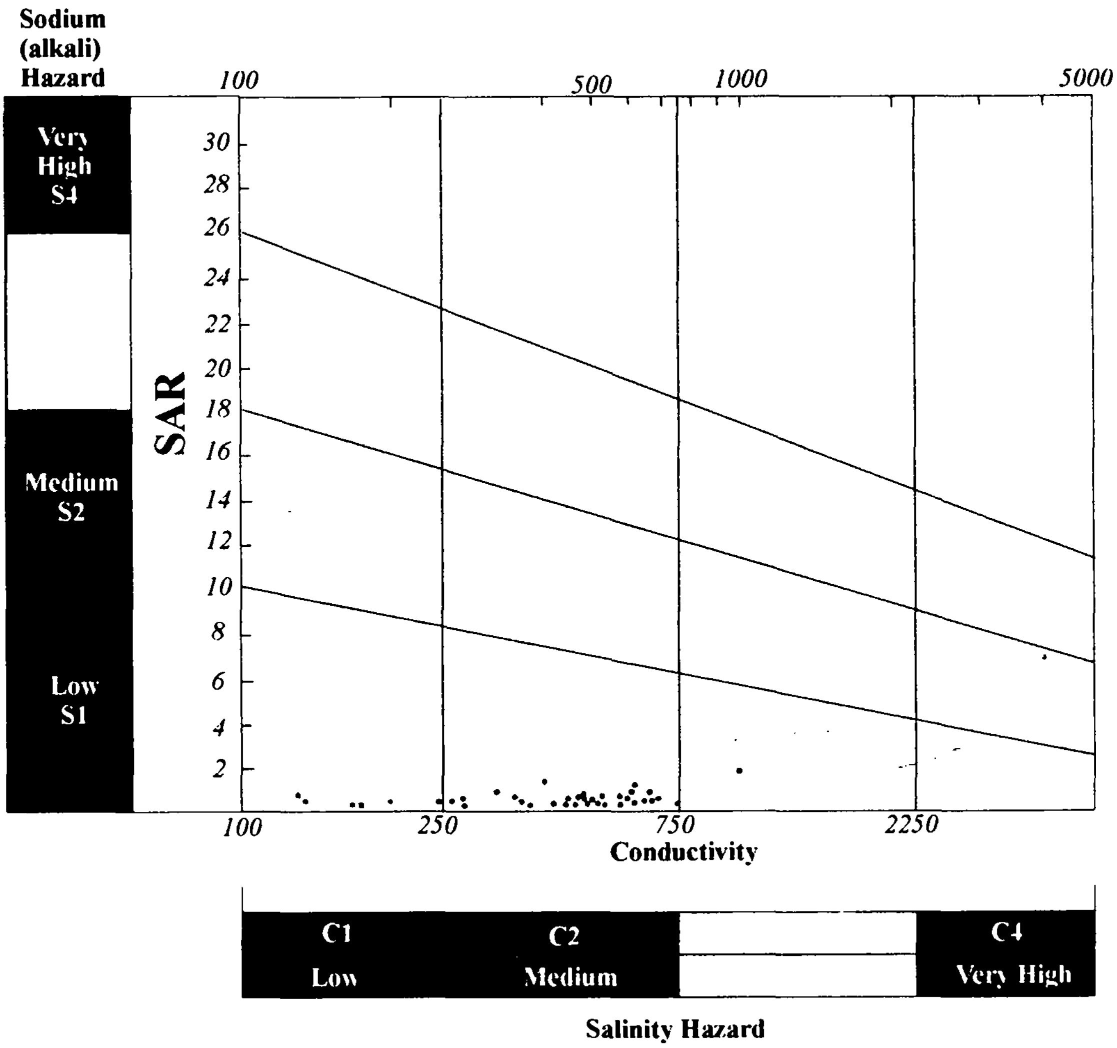

FIGURE 6.8 - Classification of irrigation waters based on SAR and conductivity.

Description of Salinity hazard.

Low-salinity water (Cl) can be used for most crops and soils with little likelihood that soil salinity will develop. Some leaching is required , but this occurs under normal irrigation on all but the tightest soils.

Medium-salinity water (C2) can be used where a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

High-salinity water (C3) cannot be used on soils that have restricted drainage. With adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected.

Very-high-salinity water (C4) is not suitable for irrigation under ordinary conditions. If used, the soils must be permeable, drainage must be adequate, considerable excess irrigation water must be applied, and very tolerant crops should be selected.

Description of Sodium hazard.

Low-sodium water (S1) can be used with little danger on nearly all soils. Sodium-sensitive crops such as stone-fruit trees and avocados may accumulate injurious concentrations of sodium.

Medium-sodium water (S2) is hazardous for use on fine-textured soils that have a high cation-exchange capacity. This water may be used on course-textured soils or organic soils with good permeability.

High-sodium water (S3) may be harmful to most soils and thus requires special soil management: good drainage, high leaching, and addition of organic matter. Chemical amendments may be necessary except for gypsiferous soils.

Very-high-sodium water (S4) is generally unsatisfactory for irrigation purposes , except at low salinity and where calcium from the soil or use of gypsum or other mineral additions may make these waters usable. (U.S. Department of Agriculture in Driscoll, 1989)

7.0 ASSESSMENT OF GROUNDWATER CONSUMPTION

7.1 GROUNDWATER USAGE IN RURAL AREAS IN GENERAL

Demand on the water resources of Zimbabwe is increasing annually as a result of economic development and population expansion. Surface water sources tend to be seasonal and are affected by droughts. Moreover, water stored on surface is exposed to the environmental hazards and prone to contamination; thus some sort of purification systems is required to ensure the delivery of safe and clean water for human consumption. Given the scattered nature of rural settlements, the high costs for supplying purified water inhibits the use of surface water sources in rural areas.

In recent years, groundwater has been playing an increasingly important role in meeting the current and future water demands of the country's rural population. In the rural areas of Zimbabwe. where about 69% of the country's population live, groundwater is the major source of reliable and portable water. Within a rural setting groundwater is usually obtained from hand-dug wells, boreholes equipped with handpumps or spring capture. Diesel and electrical driven and solar powered facilities are rarely installed in villages due to both high initial and maintenance costs. In the rural areas groundwater is used for domestic consumption, livestock watering and garden watering. The total annual groundwater abstraction for rural water supply is approximately 2.77 x $10^7 m^3$ (Lamont, 1995)

7.2 QUANTIFICATION OF CURRENT GROUNDWATER CONSUMPTION

The quantification of the current groundwater consumption in the study area was accomplished by following sequential steps indicated in Figure 7.1.

A quantitative survey method was employed to establish the types of use, the collection techniques and the pattern of use of groundwater in the study area. The survey entailed conducting field visits to sampled boreholes in order to gather a wide range of relevant socio-economic data. The social data gathering techniques used included the following;

- Interviews of the respective water-point committee members using a structured questionnaire.
- Water-point users interviews through administering of a structured questionnaire on three randomly selected borehole users.
- Direct field observations on groundwater usage practices.

Twelve borehole, representing 10% of the total 120 boreholes in the study area, were sampled for purpose of the survey. A systematic random sampling method was used to select the 12 boreholes. The surveys, however, excluded other groundwater sources, such as hand-dug wells, since less than 10% of the population draw water for drinking and domestic uses from these sources; these sources are usually unprotected.

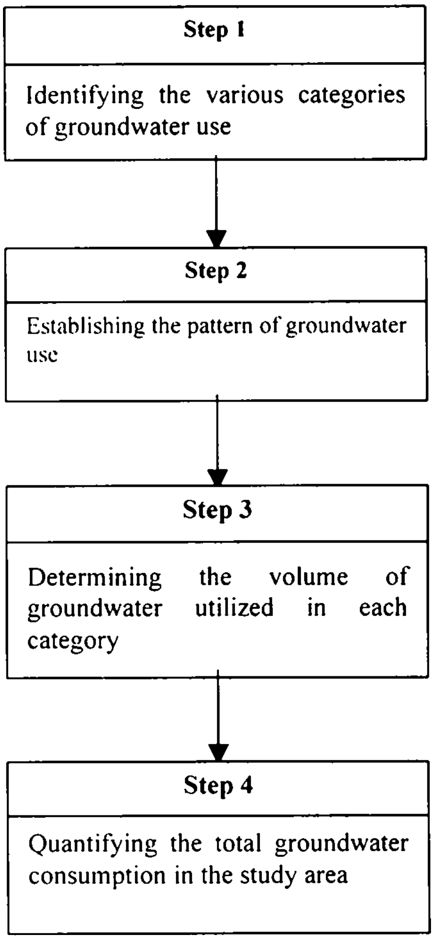

FIGURE 7.1 – Sequential stages for Estimation of groundwater Consumption.

Evidently, water demand satisfied by groundwater sources other than boreholes is insignificant and constitutes a very small percentage of the annual groundwater abstraction for rural water supply in the study area. The inadequate quantities of water from the wells particularly in the dry season, the poor potential for hand-dug well development and the undesirable quality of the water from the unprotected wells may have caused the greater dependence on boreholes noted in the area.

Besides the socio-economic data collection, the review of existing information was carried out so as to provide supplementary information and to verify and validate the survey results. This information was obtained from (i) several technical reports including the relevant volumes of National Master Water Plan – Volume 8 and 8.1 (Interconsult, 1985), (ii) the unpublished project activity work plans, annual progress reports, mid-term evaluation report and terminal evaluation report for the Kwekwe District IRWSS Programme supported by Plan International and (iii) Various relevant technical reports for previous work on rural development and rural water supply. Information concerning the population distribution, landuse patterns and livestock population, was obtained at district level from the relevant Government Departments such as Agritex and Veterinary Services.

7.3 POPULATIONS AND LIVESTOCK IN STUDY AREA

7.3.1 Population

The most recent population census in Zimbabwe was conducted in 1992 (Central Statistic Office – Zimbabwe Government, 1992). The Census (1992) results showed a population of 16 611 people in the study area. Thus 1992 has been taken as the base year for population projections in the present study. Using the 1992 population figures and a natural growth rate of 2.52% for Kwekwe Rural, the current (1997) population was projected. It is estimated that population in the study area should have reached approximately 18 812 people by 1997.

Registration of existing population in 1997 by Agritex (unpublished records) in each of the three wards comprising the study area, showed a total population of 19 353 people. This is consistent with the results of the population projection. Table 7.1 shows the estimated population by ward in accordance with the two sources of information. The population figures for 1992 as per the 1992 Census are also shown.

TABLE 7.1 – Estimated 1997 Population by Ward

Ward	1992 Population (from 1992 Census)	1997 Population	
		Population Projections (base population from 1992 Census)	Population Figures from Agritex records
Kwayedza	5905	6687	6989
Chitepo	5269	5967	6078
Chaminuka	5437	6157	6286
TOTAL	**16 611**	**18 812**	**19 353**

7.3.2 Livestock

The Department of Veterinary Services maintains registers of livestock holdings in the various wards of Kwekwe District at district level. These records are up-dated on an annual basis in order to assess the demand on services such as cattle dipping. Equally important, such records serve as tools for monitoring the levels of stocking so as to avoid overgrazing and potential degradation of the communal lands. Table 7.2 depicts the population for the different categories of livestock in the study area.

TABLE 7.2 – Livestock Population in Study Area

Livestock Category	Number of Livestock	Percent of Total Livestock
Cattle	17 864	75.0
Sheep	249	1.0
Goats	3438	14.4
Donkeys	2031	8.5
Pigs	270	1.1

7.4 GROUNDWATER USE PATTERN AND CURRENT CONSUMPTION

7.4.1 Groundwater Use Categories

The use of groundwater in the study area may be divided into four categories and these are;

- Domestic consumption
- Clothes washing
- Livestock watering
- Garden watering

Water collected from the sources to the homestead is primarily for domestic use. The water collected was used for personal and domestic hygiene, drinking, food preparation and cooking and clothes washing. Clothes washing at the boreholes were prevalent in the area. This may be attributed to the availability of washing slabs and drying lines at the boreholes. While water collected to homesteads was also used for clothes washing by a significant number of the households, the larger proportion of the households preferred to wash at the source. The reasons for this preference are: (i) each washing episode uses copious quantities of water and much labour is saved by washing at the source; (ii) the conviviality of mothers and children; and (iii) ease of drying. Therefore, clothes washing at the source have been considered as a groundwater use category on its own. However, clothes washing at the homesteads have been classified under domestic use as it was found extremely difficult to determine the specific proportion of water utilised for this purpose among the variety of domestic water usage.

7.4.2 Domestic Consumption

Water collected from the sources to the homestead is used for domestic purposes including the following;

- Drinking
- Food preparation and cooking
- Personal and domestic hygiene
- Clothes washing at home

Beer brewing and building are once of the activities which if being undertaken may double a household water usage.

The mean quantity of water collected from the boreholes and used for domestic purposes per household per day is 85 litres. Therefore assuming that the average household size is 6 people (CSO – Zimbabwe, 1992) the average per capita water consumption is 14.2 litres per day. Compared to the National Master Water Plan (Interconsult, 1985) and the WHO Rural Water Consumption Standards, this figure is quite realistic as these standard figures have a range of 10 to 30 litres per capita per day (lcd).

Worth noting is the fact that the population of the area is entirely dependent on groundwater sources; over 95% of households collect water for domestic uses from boreholes equipped with handpumps, while the remainder obtained water from unprotected hand-dug wells. Therefore, using a population for the study area of 18 812 and a consumption of 14.2 lcd, the total groundwater abstraction for domestic water uses is approximately $9.75 \times 10^4 m^3/y$

7.4.3 Clothes Washing

The surveys indicated that 75% of the households in the area washed clothes at the boreholes, while the remainder washed either at home or other sources such as perennial rivers and dams. The mean quantity of water used for each washing episode at the borehole is approximately 70 litres per households. On average, the frequency of the washing is twice per household per week.

Assuming that 2440 households – representing 75% of the total of 3211 households in the area - wash at the borehole, the weekly consumption of groundwater in this category is estimated to be $341 m^3$. Therefore, the total annual groundwater abstraction for washing clothes at the sources is approximately $1.7 \times 10^4 m^3$.

7.4.4 Livestock Watering

The dominance of cattle in the livestock holding in the study area was very apparent (Table 7.2). The water consumption of cattle is more than eight times as large as that of sheep and goats. Therefore, for the purpose of estimating livestock consumption, cattle watering alone was taken into account. This consumption consists of two parts;

- drinking water
- dipping services

Drinking Water

Nearly all households in the study area water their cattle at surface water sources for most of the year. This is largely because of the availability of reliable sources of surface water within the proximity of most settlements. In the dry season the perennial sources of surface water predominantly occur in the prominent vleis, such as those along Magwizi and Mkobokwe rivers (Fig.2). These vleis are discharge zones of the main aquifer of the area, the Karoo Sediment aquifer. The sources are mainly in the form of isolated stagnant pools of water. The use of boreholes for cattle watering is infrequent in the study area. This is because the people would rather use surface sources as long as they are within a walking distance of between 5 and 7km in order to avoid the labour required for operating the handpumps. The surveys showed that only 20% of the households relied on boreholes for cattle watering, but mainly as fallback systems in the dry season. If watered at the borehole each stock unit consumes 25 litres/day.

Assuming that cattle are watered at the boreholes for 5 months of the year, during the dry season between May and November, and accepting that 20% (3573) of the 17864 head of cattle found in the area are watered at the boreholes, then the groundwater abstracted for this purpose is approximately $1.34 \times 10^4 m^3/y$.

Dipping Services

A total of 7 dip tanks are operational throughout the study area. All the dip tanks depend on boreholes for their supply of water. The dipping is undertaken on weekly basis and $4m^3$ of water is pumped into each dip tank per week. Therefore, the total annual groundwater abstraction for dipping cattle is $1.46 \times 10^3 m^3$.

7.4.5 Garden Watering

While vegetable gardening is prevalent in the study area, all gardens used unimproved surface water as a source of their watering. The majority of the gardens are situated along the streams of vleis where perennial sources of surface water are available. Boreholes have not been used for garden watering in this area for different reasons that include the following;

- The problems of land access and availability in the localities of the boreholes
- The community management of communal property limits the use of water from boreholes for garden watering
- The groundwater extraction technology based on handpumps limits the output of the boreholes; indeed much labour is required to pump the water, moreso because the water levels are generally deep in this area.

The only households, which used groundwater sources for garden watering, were those with individual hand-dug wells at the homesteads. All the households with hand-dug wells practice gardening at the homesteads. The vegetable gardens are watered for about 7 months and this is during the dry season. The average garden size per household is about $50m^2$.

Using an application rate of $0.6m^3$ per garden per day (Interconsult, 1985) and taking into account that 43 households have gardens watered from hand-dug wells, the total groundwater utilised for garden watering is estimated to be $5.4 \times 10^3 m^3/y$.

7.4.6 Concluding Remarks

Table 7.3 summarises the current estimated groundwater consumption for the various categories of water usage and Figure 7.2 presents a picture of the groundwater usage by category. The total groundwater consumption in the study area is estimated to be $1.35 \times 10^5 m^3/y$.

TABLE 7.3- Current groundwater consumption in the study area

Category of Groundwater Usage	**Consumption (x $10^3 m^3/y$)**	**Proportion Used in each Category (%)**
Domestic Consumption	97.5	72.3
Clothes washing	17.0	12.6
Livestock watering	14.9	11.1
Garden watering	5.4	4.0
Totals	**134.8**	**100**

It is clear that the domestic water usage is the largest consumer of groundwater in the study area. More than half (73.3%) of all the groundwater abstracted was used for domestic purpose. The recent intervention by the government and NGOs which resulted in the provision of protected water sources, only in the form of boreholes fitted with handpumps, has evidently altered the practice of using unprotected surface water (rivers, springs, dams etc). The greater dependence on the boreholes has been due to the availability of these source within reasonable walking distance and communities' appreciation of the fact that use of good quality water leads to long term health benefits.

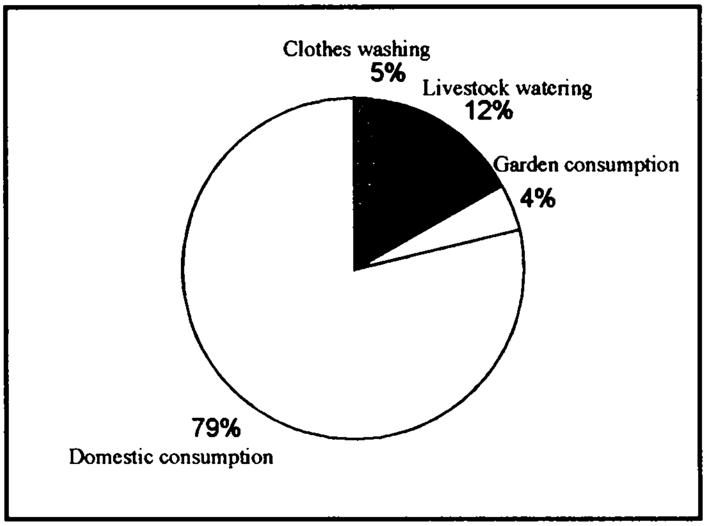

FIGURE 7.2- Proportion of groundwater consumed in the various usage categories

The use of groundwater in livestock and garden watering is very limited. The proportion of groundwater usage in these categories is just under one fifth of the total groundwater consumption of the area. The communities prefer to use surface water for livestock and garden watering as these are huge consumers of water and much labour, required for pumping the water from boreholes, is saved. Moreover, the quality of water for these water usages is less relevant.

The volume of groundwater used in the study area can also be estimated by using other crude values for comparison purposes. Assuming that each borehole in the study yields 0.1 l/s over a period of 8 hours per day and taking into account that 120 boreholes are in existence in the area, a total of 1.260 x $10^5 m^3/y$ are abstracted from boreholes. Assuming that each of the 43 households with hand-dug wells draws $1.0m^3/day$ for both domestic use and garden watering, an additional 1.57 x $10^4 m^3/y$ are abstracted. A combined total of 1.41 x $10^5 m^3/y$ is thus obtained from both facilities; this figure agrees well with estimates obtained from the more direct method of quantifying groundwater consumption according to the groundwater use categories (Table 7.3).

7.5 FUTURE DEMANDS ON GROUNDWATER

The sustainability and success of the small-scale irrigation schemes primarily depends on the availability of surplus water in the long-term. Of vital necessity is the assurance of availability of water for irrigation purposes, over and above the basic community water requirements, over the design life of the scheme; the groundwater resources should be able to cover the demand over the design life. The design life normally varies from 15 to 20 years (Interconsult, 1985-NMWP Vol. 8.1). During this period the demand for water is likely to increase substantially as a result of population expansion. Hence the surplus groundwater currently available may dwindle with time in response to the increase in demand for water to meet basic community requirements, in particular domestic usage and livestock watering. Forecasting the increase in population in the next 15 years and the projections of future water demands based on current practises and water use pattern are major determinants for assessing the long-term sustainability of the irrigation schemes.

7.5.1 Population and Livestock Size Projections

Based on the design life of the relevant infrastructure of 15 years the short -, medium-, and long-term plan periods for the schemes are 1997-2002, 1997-2007 and 1997-2012 respectively. An attempt has therefore been made to estimate the population in the study area at the end of each five years period as from present (1997) through to 2012. A growth rate of 2.52%, was used to estimate the population in the short-term (2002) medium-term (2007) and long-term (2012); these are given in Table 7.4.

TABLE 7.4 – Projected population and number of household in the study area for 2002, 2007 and 2012.

Year	Population Size	Number of Households
2002	21 305	3550
2007	24 128	4 021
2012	27 325	4 554

The study area, like all other communal lands of Kwekwe District, is under severe pressure for land (Whitsun Foundation, 1978). In recent times large tracts of pastures, have had to be converted to arable land to cater for the increasing population; the demand for arable land is closely tied to the growth of population.

The reduction of pastures directly affects the livestock carrying capacity of these communal lands. It is thus unlikely that the population of livestock in the study area will increase over the design life of the schemes; in fact a decrease in number of livestock may seem inevitable. In light of the foregoing discussion the present livestock population (Table 7.3) has been accepted as applicable for all the situations, that is for the short-term, medium-term, and long-term planning periods of the schemes.

7.5.2 Projected Water Demand

The projections of groundwater demand in the short-term, medium-term and long-term situations has been based on the current practises and pattern of groundwater use mentioned in Section 7.4.1. Table 7.5 depicts the projected consumption of groundwater in the four usage categories for each of the planning periods. These groundwater consumption figures are derived from the following assumptions;

(i) the population projections based on 1992 Census figures and growth rate (Table 7.4) are acceptable.

(ii) the whole population will continue utilising groundwater sources, particularly boreholes, for all their domestic requirements.

(iii) all households in the study area will wash clothes at the boreholes, especially if some of the borehole pumps are motorised on implementation of the irrigation schemes.

(iv) garden watering from family hand-dug wells is unlikely to increase – obviously the majority of the households will prefer to undertake their gardening activity under the irrigation schemes.

(v) the livestock population is unlikely to increase over the design period of the schemes due to factors mentioned earlier (Section 7.5.1).

TABLE 7.5 – Projected groundwater consumption for 2002, 2007 and 2012

Category of Groundwater Usage	**Groundwater Consumption (x 10^3m^3)**		
	2002	**2007**	**2012**
Domestic Uses	10.4	125.1	141.6
Clothes Washing	25.9	29.3	33.2
Livestock Watering	14.9	14.9	14.9
Garden Watering	5.4	5.4	5.4
Total Consumption	**156.6**	**174.7**	**195.1**

8.0 SUSTAINABLE AQUIFER EXPLOITATION POTENTIAL

8.1 CONCEPTS OF GROUNDWATER YIELD

The concept of safe yield warrants more than a mention in this thesis because one of the primary objectives of the present groundwater resource study is to determine the maximum possible abstraction rates that are compatible with the hydrogeological environment from which the water will be withdrawn. Safe yield is defined as the practical rate of withdrawal of naturally occurring groundwater for perennial use without undesirable effects (Freeze, 1971). However, this term is difficult and ambiguous to address and can vary greatly according to the scale considered. Thus the scope of a groundwater resource evaluation study to a great extent, depends on the definition chosen for the term, as well as whether a borehole or an entire aquifer is the unit of the study. If a single borehole is the focus of a study then a borehole yield needs to be established and if the study targets an entire aquifer then an aquifer yield should be determined.

Borehole yield represents pumpage from a borehole, and may be defined as the maximum pumping rate that can be supplied by a borehole without lowering the water level in the well below the pump-intake. The rate of pumping of a borehole is largely controlled by: (i) transmissivity (T) and storativity (S) of the water bearing formation – these hydraulic parameters are discussed in Section 4.1; (ii) the available drawdown, defined as the difference between the static water level and the lowest pumping level that can be imposed; (iii) the well/borehole efficiency; and (iv) The distance and nature of boundaries – recharge boundaries will reduce drawdown, while impermeable boundaries will result in increase of drawdown.

The term aquifer yield is defined as maximum rate of withdrawal that can be sustained by an aquifer without causing an unacceptable decline in hydraulic head in the aquifer. The maximum yield that can be obtained from an aquifer over a prolonged period should not exceed the average annual recharge otherwise this might result in the reduction in the amount of water stored in the aquifer and the fall of water levels. Indeed, the amounts of water abstracted from boreholes from an aquifer should be related to the long-term natural flow through the aquifer, that is the water transferred from recharge to discharge areas through natural processes. In addition to the recharge, the aquifer yield0Xalso controlled by the storativity, permeability and aquifer thickness and areal extent.

In this thesis the significant unit of study is an aquifer. Thus it is of critical importance that the long-term yield capability of the aquifer – the exploitation potential of the aquifer - be established. Because of the important role recharge plays in determining the aquifer yield, quantification of the rate of natural recharge is a basic prerequisite for accurate assessment of the aquifer's exploitation potential – the estimation of recharge was dealt with in Chapter 5 of this present study. While the exploitation potential of the aquifer is the main focus of the present study, it was also found necessary to determine the sustainable borehole yields in order establish the number of boreholes to be utilised for irrigation and their pumping rates; thus Section 8.2 deals with sustainable borehole yield assessments.

8.2 STAINABLE BOREHOLE YIELDS

As noted from Section 4.3.1, pumping test interpretations are used primarily to establish the hydraulic properties of an aquifer. However, sustainable yield of a borehole is not obtained from these conventional pumping test interpretations. Sami and Murray (1997) assessed the methods used in South Africa for recommending borehole abstraction rates. Based on the data requirements of these methods, a computer programme was developed for estimating sustainable yields of boreholes from pumping test data (Sami, 1999). This programme includes seven methods, which are based on constant discharge and recovery tests performed on the boreholes.

Methods for estimating sustainable borehole yields have been described in details by Sami and Murray (1997) and will not be discussed any further in this thesis.

Borehole yield assessments utilising the programme developed by Sami (1999), were conducted for the four boreholes pump tested in study area. The sustainable borehole yields estimated from the pumping test and recovery data are shown in Table 8.1, together with the transmissivity values that where derived from these assessments. In addition, the sustainable yield worksheets for the pump-tested boreholes are presented in Appendix 6.

TABLE 8.1 - Sustainable borehole yields from pump tested boreholes

BOREHOLE NAME AND NUMBER	TRANSMISSIVITES				SUSTAINABLE YIELDS		
	Early – Time T (m^2/d)	**Late – Time T (m^2/d)**	**Recovery T (m^2/d)**	**Average T (m^2/d)**	**Min (m^3/d)**	**Max (m^3/d)**	**Mean (m^3/d)**
Inthandokazulu 6 Kwek – 204	6.6	2.3	5.2	4.7	11	85	33
Chitwara 6 Kwek – 235	16.1	9.3	16.8	16.5	30	155	81
Rufuse 6 Kwek - 234	6.1	10.2	1.5	6.1	155	352	253
Gondweni 6 Kwek -237	15.7	18.0	12.0	13.85	29	383	138

Notes for Table 2.5 – the underlined T values are unreliable and thus have not been calculating the average T.

Average sustainable borehole yields range from 33 m^3/d (0.4 l/sec) to 253 m^3/d (2.9l/sec). These small sustainable borehole yields are consistent with the low transmissivity values obtained for the Karoo aquifer of Dendera area. It is, therefore, evident that the low transmissivity is a major limiting factor in the exploitation of groundwater resources of the Karoo aquifer. This is largely because the sandstone contains a high proportion of fine dust and is often interbedded with silts and clays, which give the aquifer materials a low permeability.

8.3 AQUIFER YIELD ESTIMATION BASED ON RECHARGE

The concept of aquifer yield was discussed in Section 8.1, where it was pointed out that recharge ultimately defines the long-term abstractable volume of water from an aquifer. The maximum volume of water extractable from an aquifer over a prolonged period is equal to the annual recharge, provided the annual discharge is stopped (Hamill and Bell, 1986). However, it is difficult or impossible to prevent some natural discharge from an aquifer in the form of river baseflow, springs and seepages. It is therefore important to emphasise that only a fraction of the annual recharge is abstractable from the aquifer. Department of Water Affairs Forestry South Africa uses between 0.5 and 0.7 as the exploitable fraction of recharge (DWAF, 1993). Unfortunately, in Zimbabwe there is no documented literature on this subject.

The volume of groundwater sustainably abstractable from an aquifer on annual basis (Q_{sus}) based on recharge is calculated using the following formula (Sami and Murray 1997).

$$Q_{sus} = A.R.D$$

where

A is the area over which recharge to the aquifer occurs (m^2).
R is the recharge to the aquifer (m).
D is abstractable proportion of recharge.

From Section 5.6 it was shown that the average annual recharge is 67.4mm (0.0674m). If an abstractable fraction of recharge of 0.5 is assumed, this annual recharge rate on the 7.92×10^8 m^2 of Dendera area gives an exploitable volume of groundwater of 2.68×10^7 m^3/y. This annual exploitable volume of groundwater is a conservative estimate considering that only 50% of the recharge is considered for abstraction. Nevertheless, the current demand for groundwater, estimated as 135 000 m^3/y (Sec. 7.5.2), is less than 1% of this exploitable aquifer potential. It can therefore be concluded that recharge is unlikely to be a limiting factor in resource development for small-scale irrigation projects.

8.4 NUMBER, LOCATION AND PUMPING RATES OF BOREHOLES FOR IRRIGATION

From the foregoing (Sec. 8.1 and Sec.8.2) it can be noted that while the recharge can consistently supply water for high yielding boreholes, the low transmissivity is the major limiting factor controlling the borehole abstraction rates; that is, only low yielding boreholes are feasible. This tends to suggest that large number of boreholes would be required to fully exploit the aquifer yield - 2.68×10^7 m^3/y

Assuming that the highest average sustainable borehole yield of 250 m^3/d, estimated from pumping tests (Sec. 8.1), is feasible over much of the area, approximately 420 boreholes would be required if the aquifer is to be exploited to its full potential (2.68×10^7 m^3/y). This translates to a density of one 250m^3/d capacity borehole per 2 km^2 of the 800 km^2 Dendera area. However, because of the costs of drilling and equipping boreholes, and pumping costs, simple economics dictate that installation of such large number of boreholes on sustained basis is not possible.

Irrigation requirements for Dendera area have been estimated to be 6mm/d (Interconsult, 1986); this is equivalent to 0.006m/d. If maximum sustainable borehole yield from a properly located borehole is taken as 250m^3/d, then an area of 42 166m^2 (4.2ha) can be irrigated by each borehole at the water application rate of 0.006m/d. Assuming that only 10 boreholes can be put to use for the irrigation projects, which is not unreasonable considering the inhibiting economic factors, the irrigation of 42ha of land would be feasible. The volume abstractable from the 10 boreholes is 2 500m^3/d and this constitutes a very small fraction of the exploitable proportion of recharge. This tends to imply that the number of boreholes for irrigation purposes can always be increased even by a five-fold factor or greater, provided social and economic factors are permitting.

Although the aquifer yield, based on the abstractable proportion of recharge, is considerably high, hydraulic conductivity values derived from pumping tests and slug tests show that permeability of aquifer material is in fact significantly low for the location of high yielding boreholes. It is also evident that boreholes supplying the maximum sustainable yield (250 m^3/d) are by no means ubiquitous in the Karoo aquifer. Therefore, it is of critical importance that boreholes for irrigation abstractions be properly sited so that highest possible yields are extractable from each borehole. Because the aquifer materials have small variations in permeability as reflected by the hydraulic conductivity values (Sec. 4.5), transmissivity will only increase with increasing saturated thickness. This suggests that boreholes for irrigation abstractions should be located in the regions of the study area where saturated thickness is greatest. It appears the most favourable target for irrigation abstractions would be the region that coincides with the local watershed, where the thickness of Karoo sediments is greatest. (Fig.3.10). It is worth noting that the potentiometric surface map (Fig.5.2) reflect more widely spaced equipotential lines on this local watershed region, which also confirms a greater saturated thickness and possibly an increase of the hydraulic conductivity.

It is also important to emphasise that, large diameter, properly gravel packed and well-developed boreholes may facilitate larger abstractions from the Karoo aquifer. This tends to suggest that the drilling of new boreholes for irrigation purposes is preferable to the utilisation of existing boreholes. Although higher yields may be obtained from properly constructed boreholes, generally a sustained yield of the order of 250m^3/d appears to be the best that can be expected.

9.0 MAIN CONCLUSION

Sustainable aquifer yield, deduced from the abstractable proportion of recharge, is 2.68 x 10^7 m^3/y. This sustainably abstractable volume of groundwater represents 50% of the annual rate of groundwater recharge and thus can be considered a conservative estimate. It is therefore, considered very probable that the volume of water abstractable from the aquifer is much greater

The estimated volume of water exploitable on sustained basis (3.83 x 10^7 m^3/y) is more than 100 times the estimated current demand for groundwater, implying that there are large volumes of surplus water, which can be utilised for irrigation. Even the groundwater consumption projected for 2012 ($1.95x10^5/y$) is negligible in comparison to the sustainable aquifer yield and in fact groundwater volume in the order of 2.67 x 10^7 m^3 may remain unexploited annually.

The average total concentration of dissolved solids of 68 samples being 260 mg/l, the groundwater is chemically of good quality. The groundwater is suitable for both human and livestock consumption. In addition, the low sodium and salinity hazards imply that the groundwater is also suitable for irrigation.

Transmissivity derived from pumping tests ranges from 4.9 m^2/d to 13.6 m^2/d, while hydraulic conductivity ranges from 0.187m/d to 0.649 m/d. Slug test gave slightly lower values of transmissivity and hydraulic conductivity. The generally low transmissivity values show that only small sustainable boreholes yields are feasible and thus large number of boreholes – as much as 420 boreholes – may be required to fully exploit the sustainably abstractable groundwater. However, socio-economic factors, such as drilling, installation and pumping costs, inhibit such an unrealistic resource development. It is in fact not unreasonable to expect that only 10 boreholes can be utilised for the community irrigation projects on sustained basis. If properly sited, these (10 boreholes) can support irrigation of 42 ha of land.

The most favourable location of boreholes for maximum sustainable yields appears to be the region along the local watershed, where saturated thickness is greatest. Although occasionally higher yields may be obtainable, particularly from gravel packed and well-developed boreholes, sustainable pumping rates of the order of $250m^3/d$ appear to be the best which can be expected.

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INVESTIGATIONS TO DETERMINE THE LONG-TERM SUSTAINABLE YIELD OF THE KAROO AQUIFER AND THE SUSTAINED AVAILABILITY OF GROUNDWATER FOR SMALL-SCALE IRRIGATION PROJECTS, IN DENDERA AREA, KWEKWE DISTRICT - ZIMBABWE

A thesis submitted in fulfilment of the
Requirement of the degree

of

MASTER OF SCIENCE IN THE DEPARTMENT OF
EXPLORATION GEOLOGY, OF RHODES UNIVERSITY

VOLUME 2: APPENDICES

BY: JOSEPH TENDAYI NJANIKE

January 2001

APPENDIX 1

BOREHOLE DRILLING AND GEOLOGICAL LOGS

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

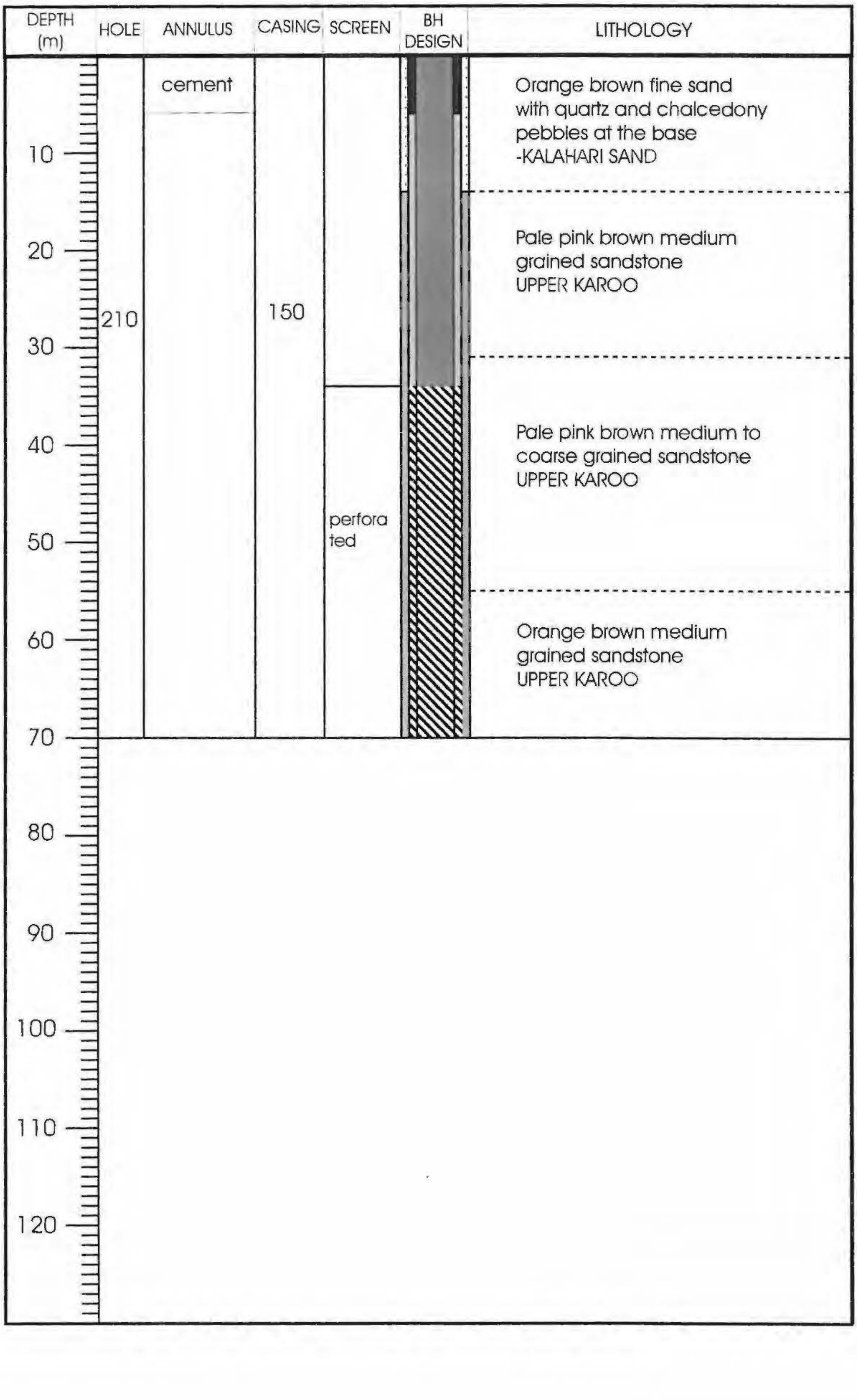
BH ID: 6-KWEK-165

LOCALITY: Ngatwe 3

GRID REF: QK 216267

DRILLING METHOD: Percussion

DATE DRILLED: 27.02.95



Orange brown fine sand with quartz and chalcedony pebbles at the base -KALAHARI SAND

Pale pink brown medium grained sandstone UPPER KAROO

Pale pink brown medium to coarse grained sandstone UPPER KAROO

Orange brown medium grained sandstone UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

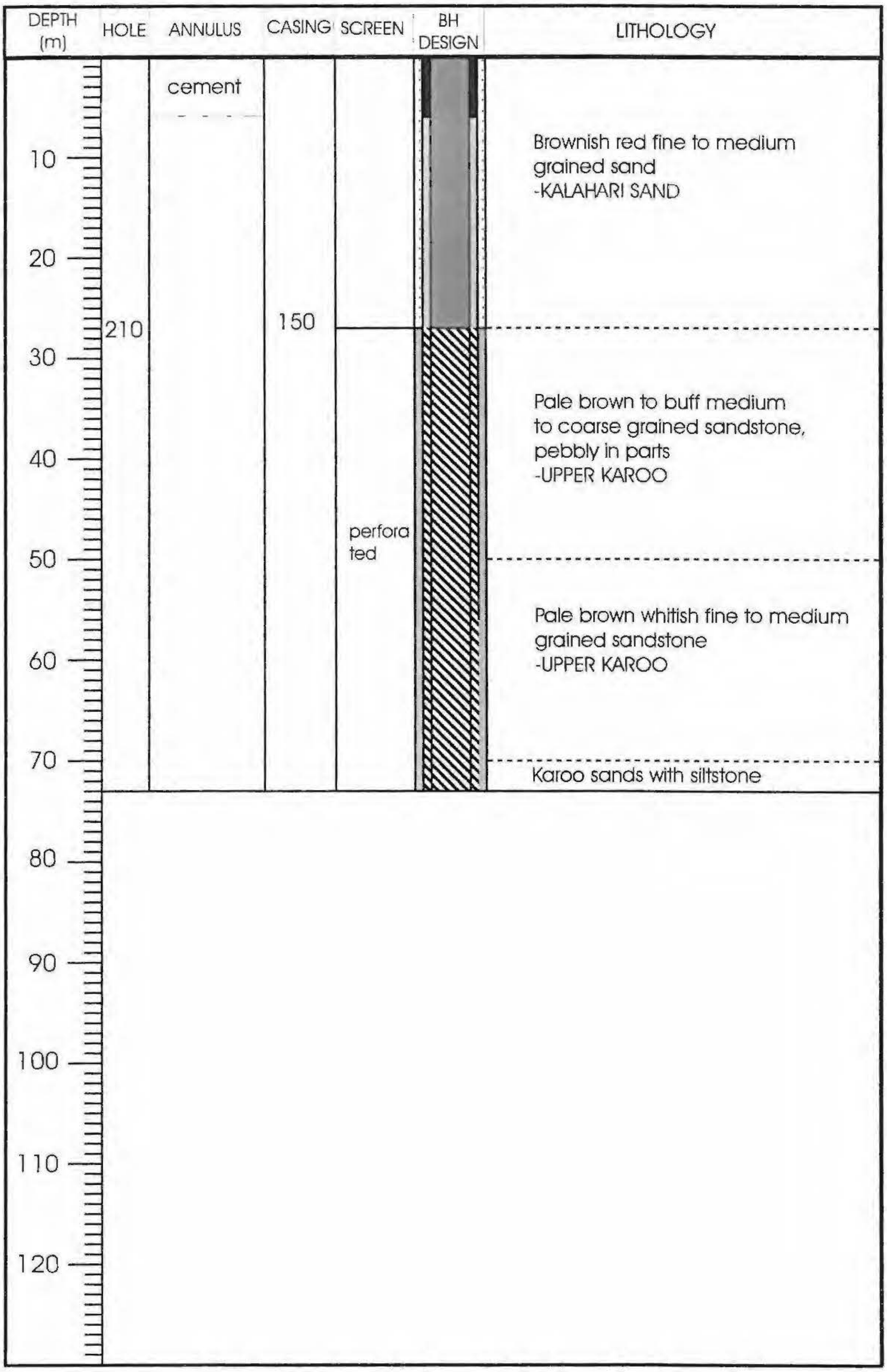
BH ID: 6-KWEK-166

LOCALITY: Mudzingwa

GRID REF: QK 169290

DRILLING METHOD: Percusion

DATE DRILLED: 07.03.95



Brownish red fine to medium grained sand
-KALAHARI SAND

Pale brown to buff medium to coarse grained sandstone, pebbly in parts
-UPPER KAROO

Pale brown whitish fine to medium grained sandstone
-UPPER KAROO

Karoo sands with siltstone

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

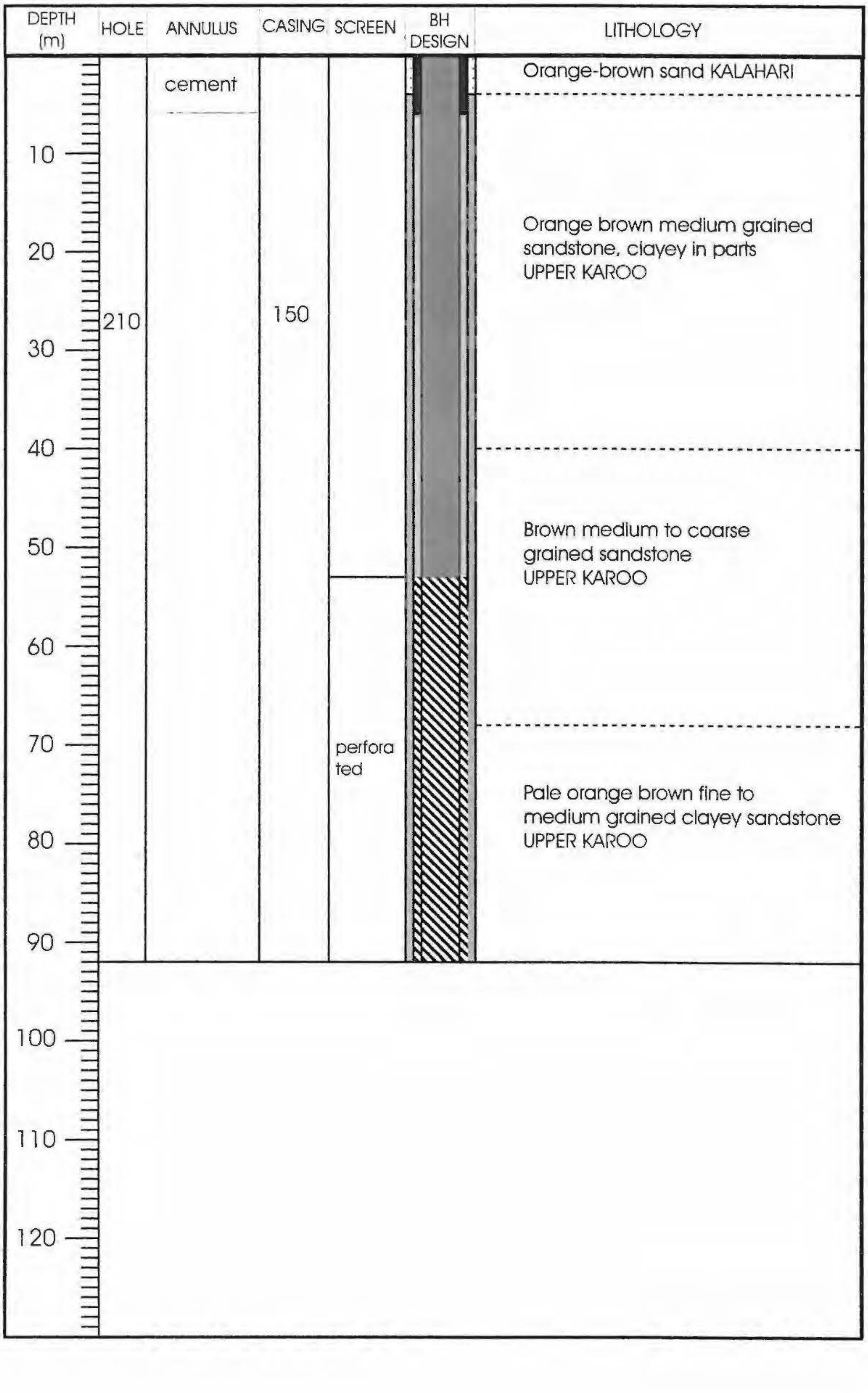
BH ID: 6-KWEK-167

LOCALITY: Ngatwe 2

GRID REF: QK 236265

DRILLING METHOD: Percussion

DATE DRILLED: 18.12.94



WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

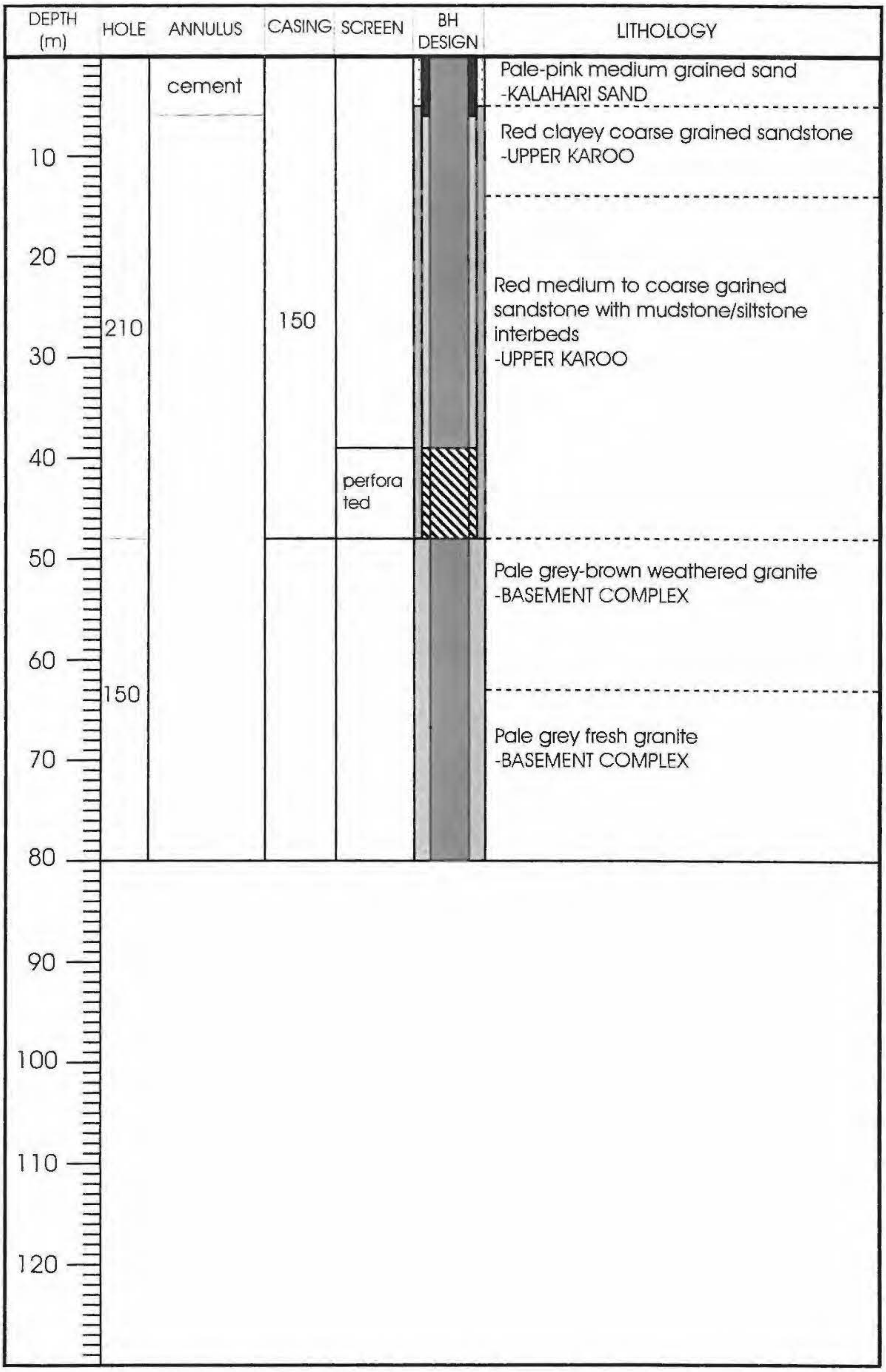
BH ID: 6-KWEK-171

LOCALITY: Notice

GRID REF: QK 066293

DRILLING METHOD: Percusion

DATE DRILLED: 14.06.96



Pale-pink medium grained sand
-KALAHARI SAND

Red clayey coarse grained sandstone
-UPPER KAROO

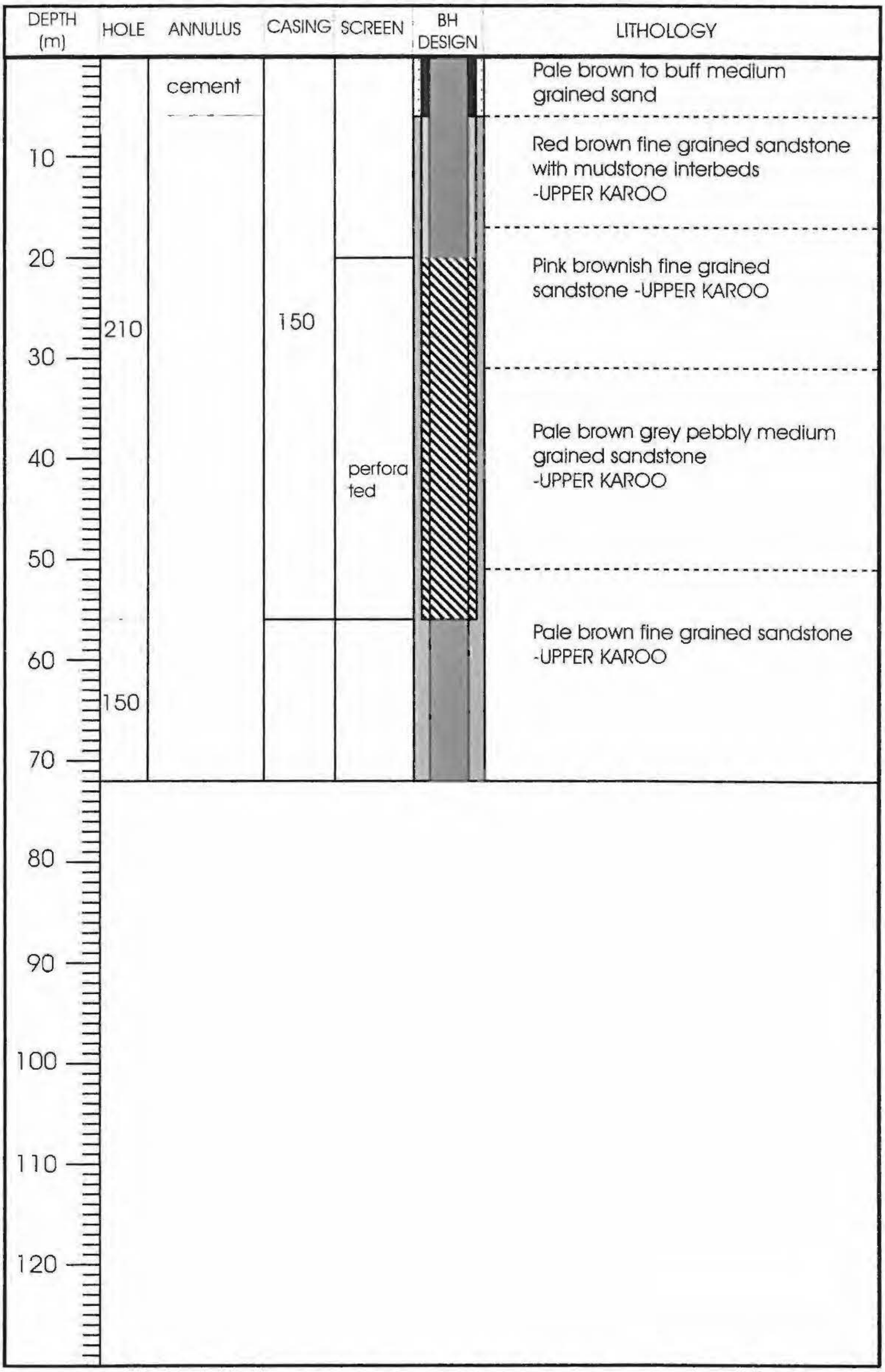
Red medium to coarse garined sandstone with mudstone/siltstone interbeds
-UPPER KAROO

Pale grey-brown weathered granite
-BASEMENT COMPLEX

Pale grey fresh granite
-BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT	KWEKWE
BH ID	6-KWEK-172
LOCALITY	Mkambeni
GRID REF	QK 062279
DRILLING METHOD	Percusion
DATE DRILLED	20.02.95



Pale brown to buff medium grained sand

Red brown fine grained sandstone with mudstone interbeds -UPPER KAROO

Pink brownish fine grained sandstone -UPPER KAROO

Pale brown grey pebbly medium grained sandstone -UPPER KAROO

Pale brown fine grained sandstone -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

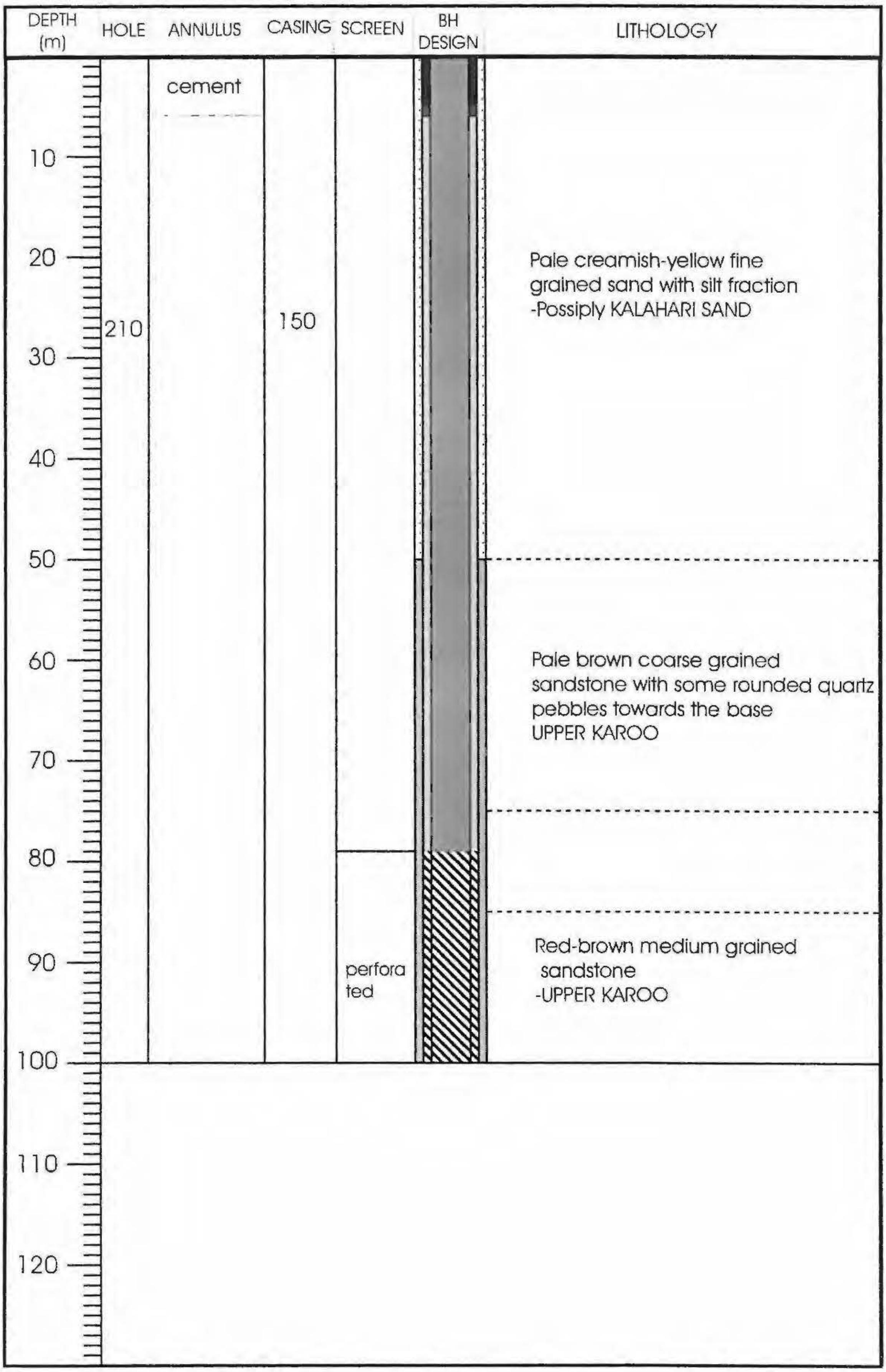
BH ID: 6-KWEK-173

LOCALITY: Thuthuko

GRID REF: Qk166310

DRILLING METHOD: Percusion

DATE DRILLED: 13.11.94



Pale creamish-yellow fine grained sand with silt fraction -Possiply KALAHARI SAND

Pale brown coarse grained sandstone with some rounded quartz pebbles towards the base UPPER KAROO

Red-brown medium grained sandstone -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

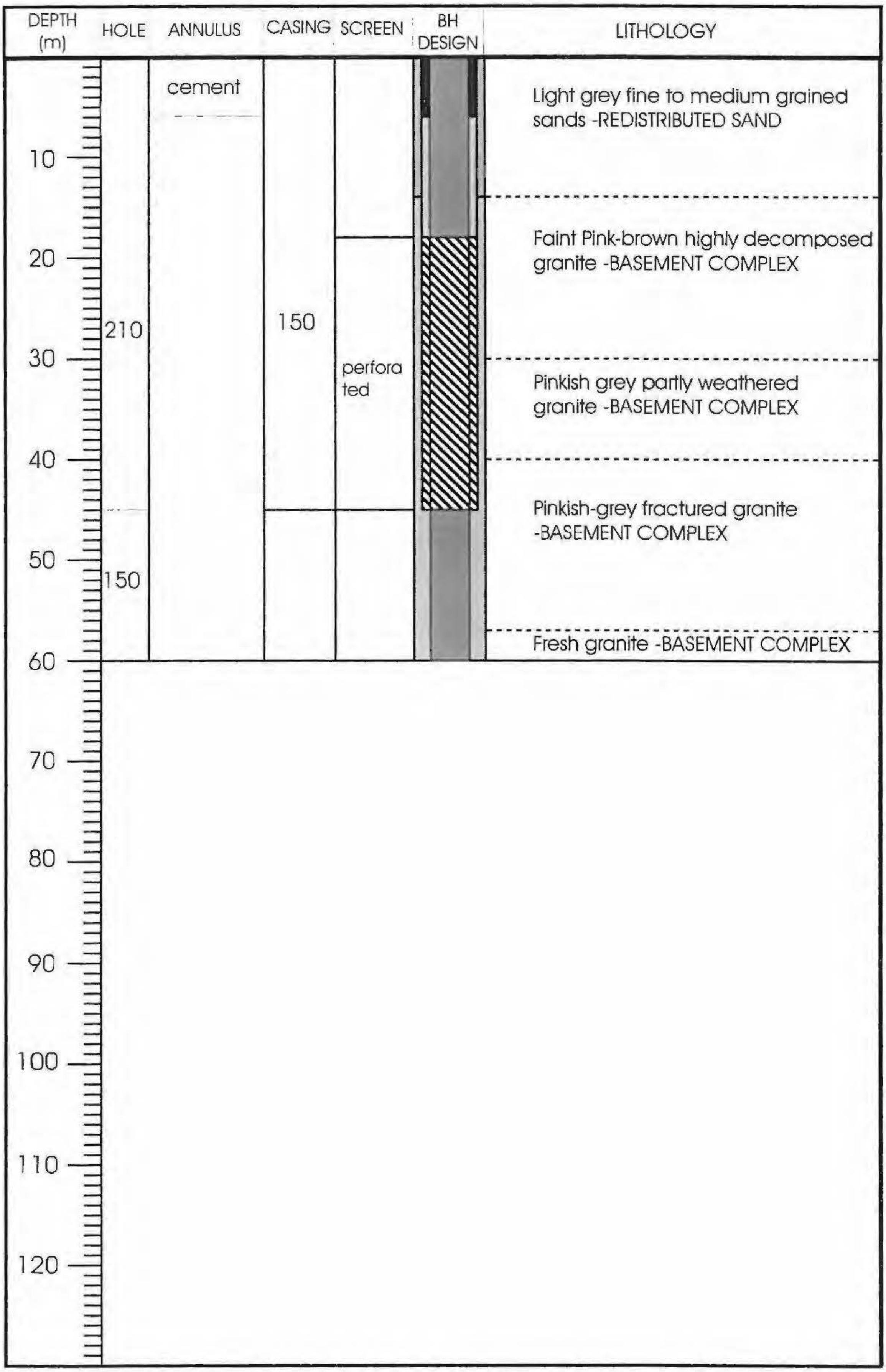
BH ID: 6-KWEK-174

LOCALITY: Tsolo

GRID REF: QK 124317

DRILLING METHOD: Percusion

DATE DRILLED: 27.01.95



Light grey fine to medium grained sands -REDISTRIBUTED SAND

Faint Pink-brown highly decomposed granite -BASEMENT COMPLEX

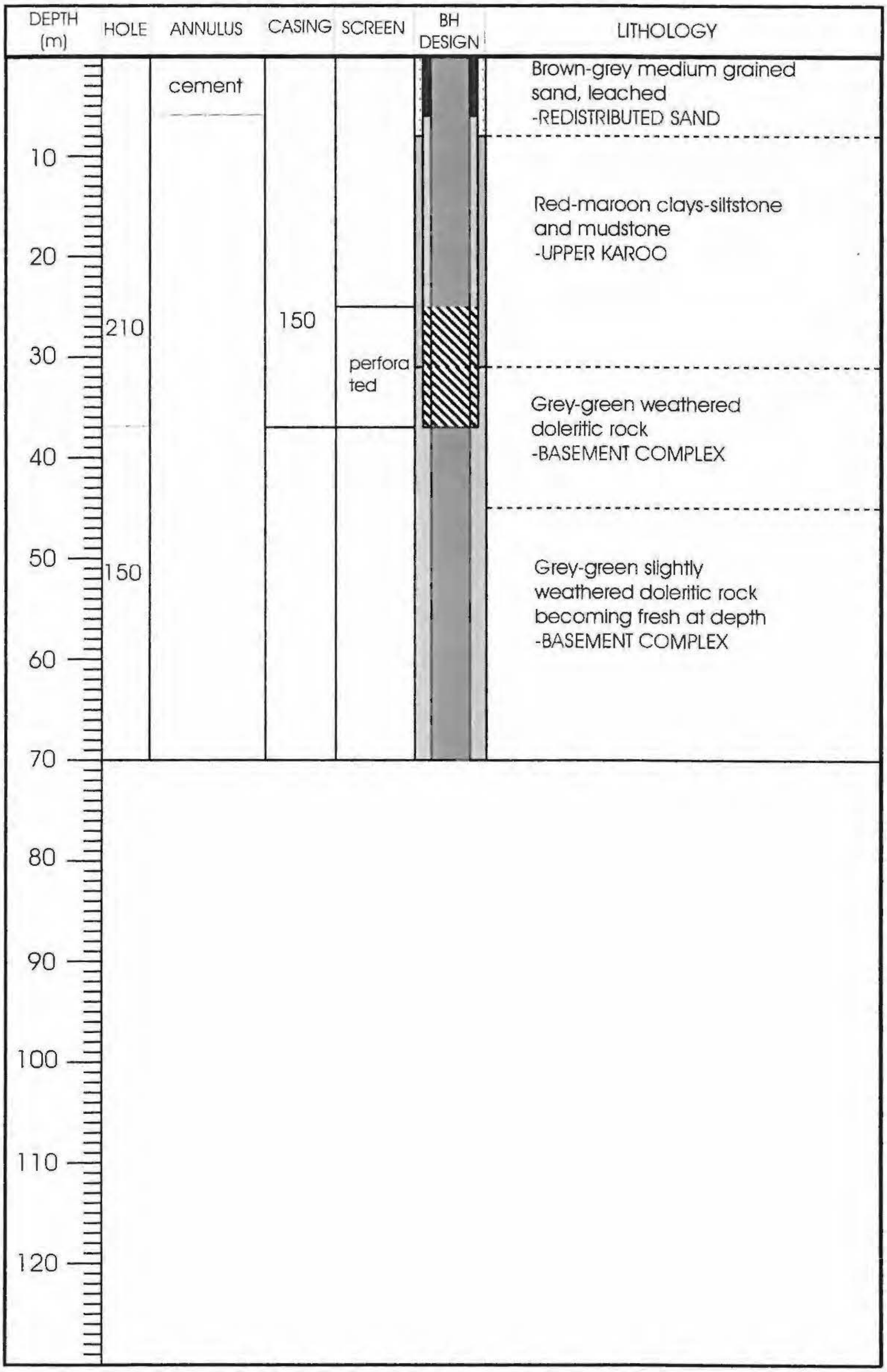
Pinkish grey partly weathered granite -BASEMENT COMPLEX

Pinkish-grey fractured granite -BASEMENT COMPLEX

Fresh granite -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT	KWEKWE
BH ID	6-KWEK-175
LOCALITY	Matamba
GRID REF	Qk104334
DRILLING METHOD	AIR/DTH
DATE DRILLED	30.01.95



Brown-grey medium grained sand, leached
-REDISTRIBUTED SAND

Red-maroon clays-siltstone and mudstone
-UPPER KAROO

Grey-green weathered doleritic rock
-BASEMENT COMPLEX

Grey-green slightly weathered doleritic rock becoming fresh at depth
-BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

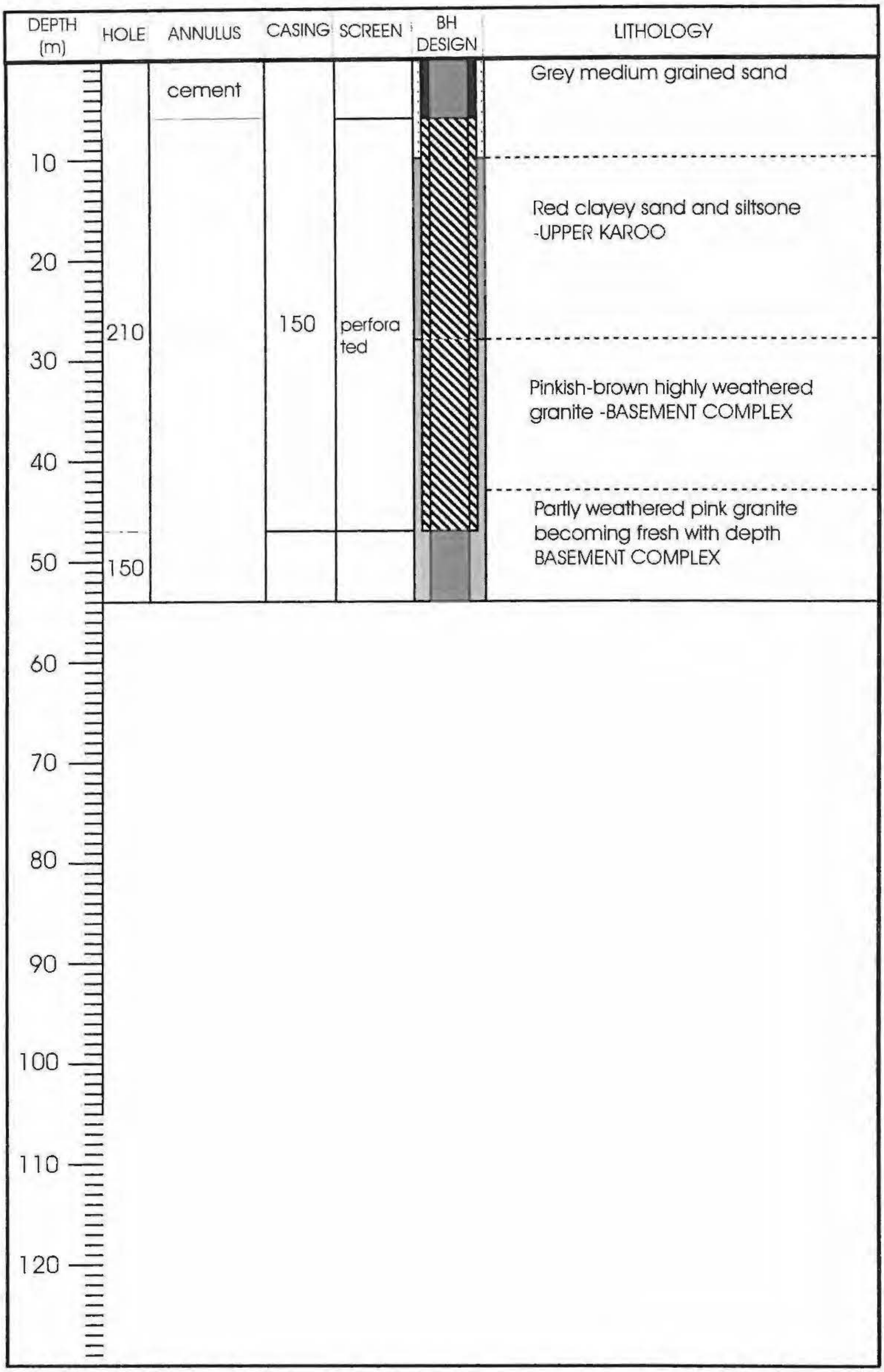
BH ID: 6-KWEK-176

LOCALITY: Njini

GRID REF: QK 085327

DRILLING METHOD: AIR/DTH

DATE DRILLED: 02.02.95



Grey medium grained sand

Red clayey sand and siltsone -UPPER KAROO

Pinkish-brown highly weathered granite -BASEMENT COMPLEX

Partly weathered pink granite becoming fresh with depth BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

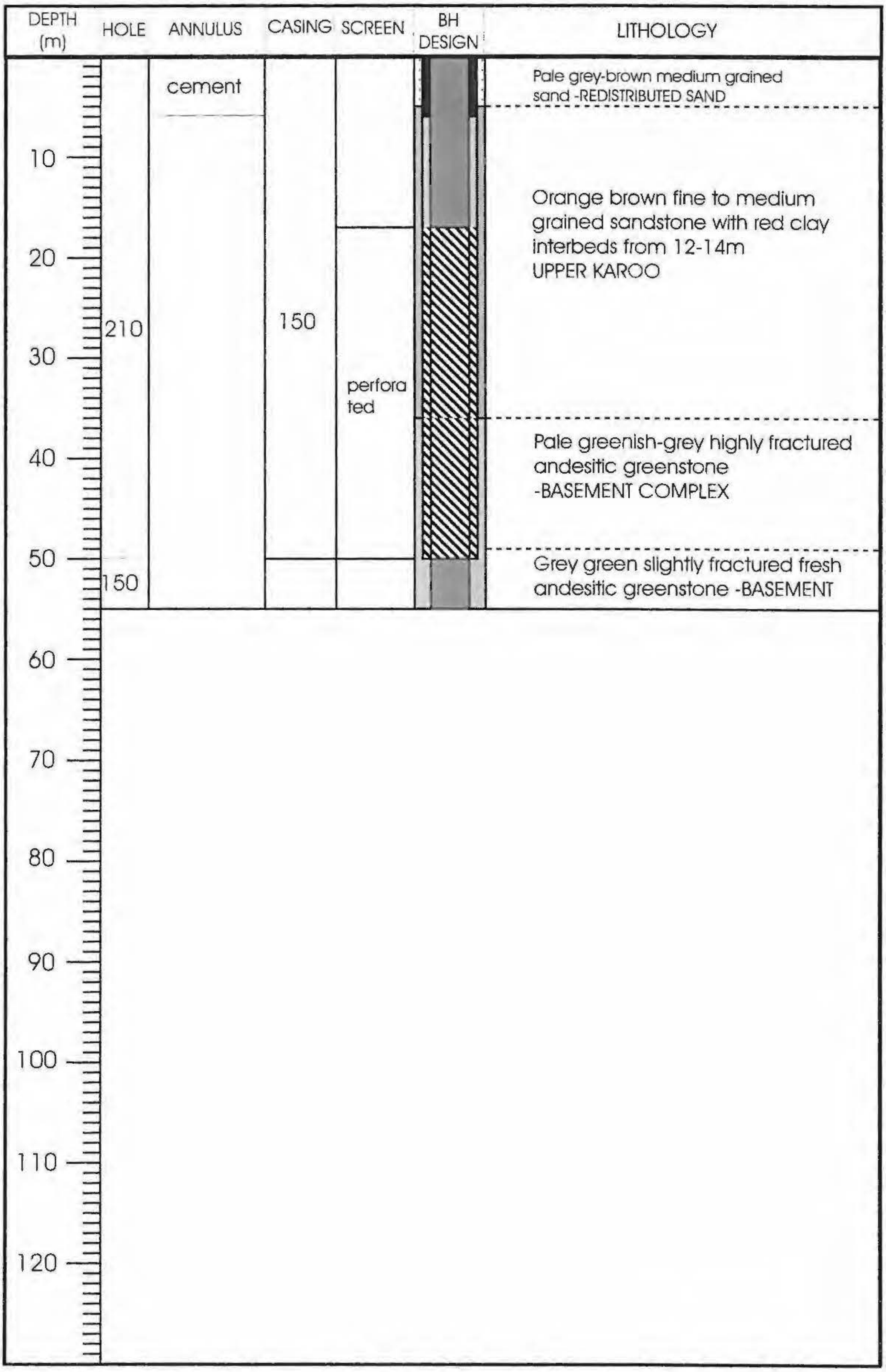
BH ID: 6-KWEK-178

LOCALITY: Mkobogwe East

GRID REF: QK 146292

DRILLING METHOD: AIR/DTH

DATE DRILLED: 26.01.95



Pale grey-brown medium grained sand -REDISTRIBUTED SAND

Orange brown fine to medium grained sandstone with red clay interbeds from 12-14m UPPER KAROO

Pale greenish-grey highly fractured andesitic greenstone -BASEMENT COMPLEX

Grey green slightly fractured fresh andesitic greenstone -BASEMENT

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

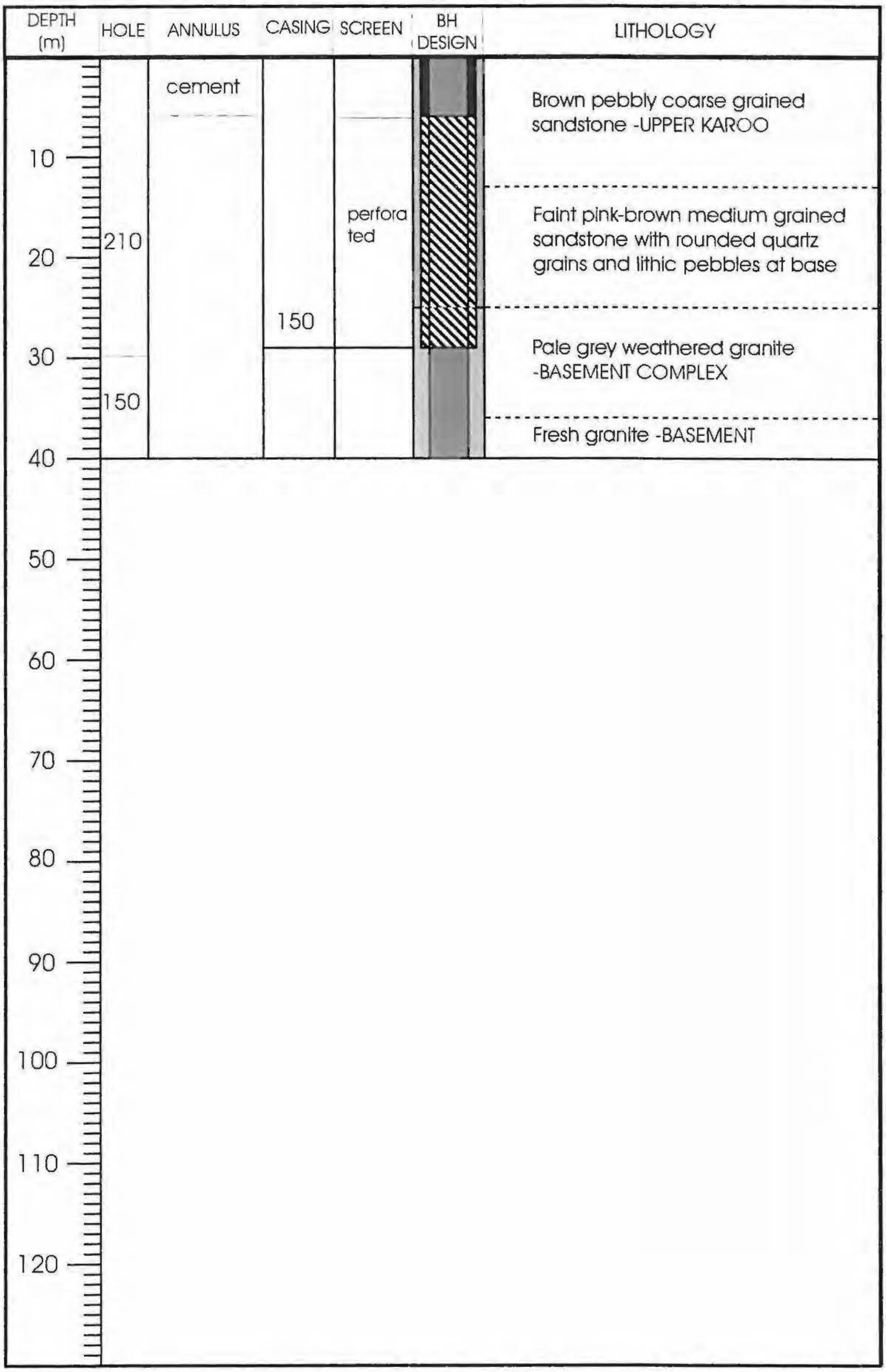
BH ID: 6-KWEK-179

LOCALITY: Short Line

GRID REF: QK 035286

DRILLING METHOD: Percusion

DATE DRILLED: 20.02.95



Brown pebbly coarse grained sandstone -UPPER KAROO

Faint pink-brown medium grained sandstone with rounded quartz grains and lithic pebbles at base

Pale grey weathered granite -BASEMENT COMPLEX

Fresh granite -BASEMENT

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

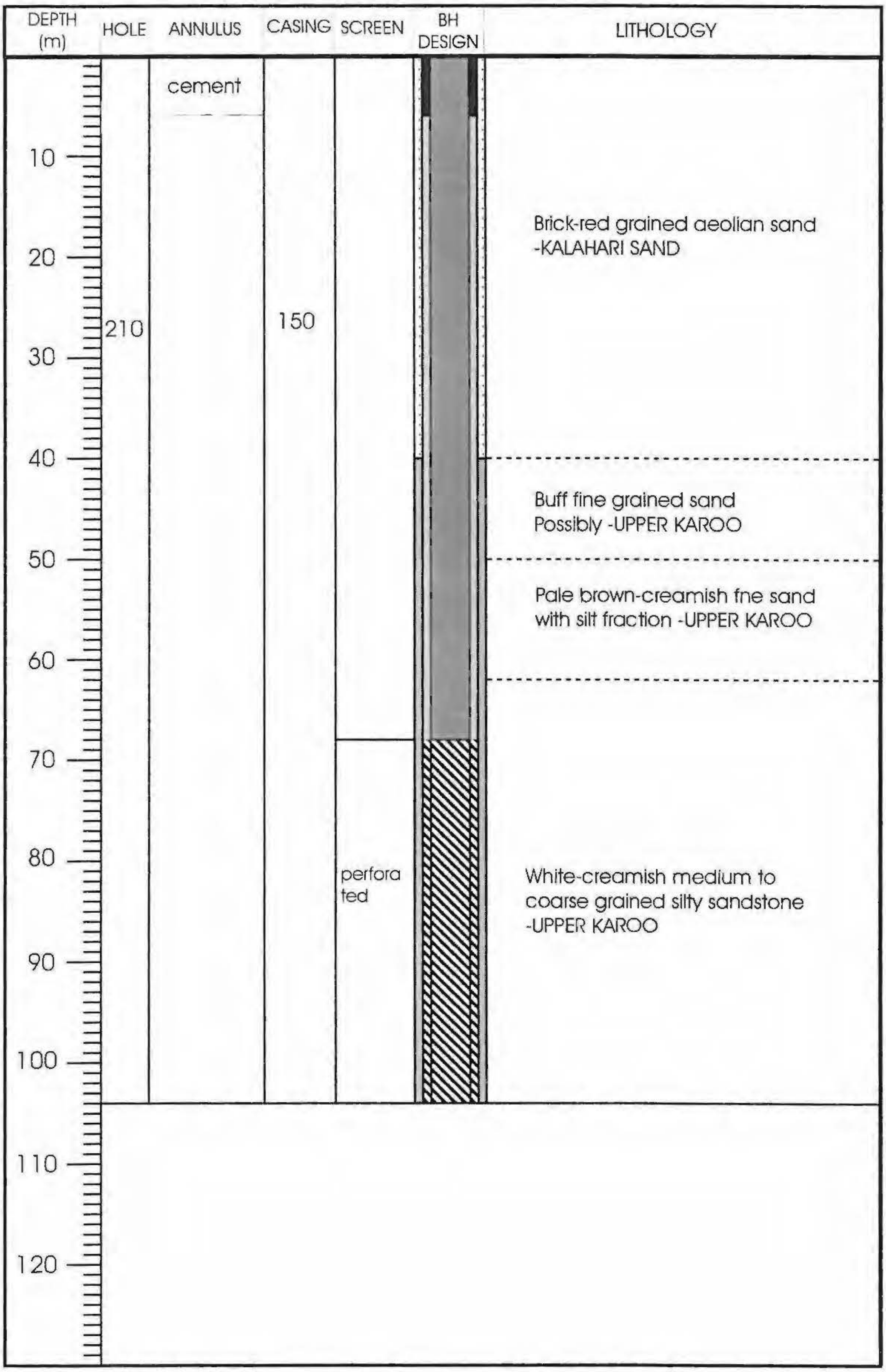
BH ID: 6-KWEK-180

LOCALITY: Zororo

GRID REF: QK 235304

DRILLING METHOD: Percusion

DATE DRILLED: 12.12.94



Brick-red grained aeolian sand -KALAHARI SAND

Buff fine grained sand Possibly -UPPER KAROO

Pale brown-creamish fne sand with silt fraction -UPPER KAROO

White-creamish medium to coarse grained silty sandstone -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

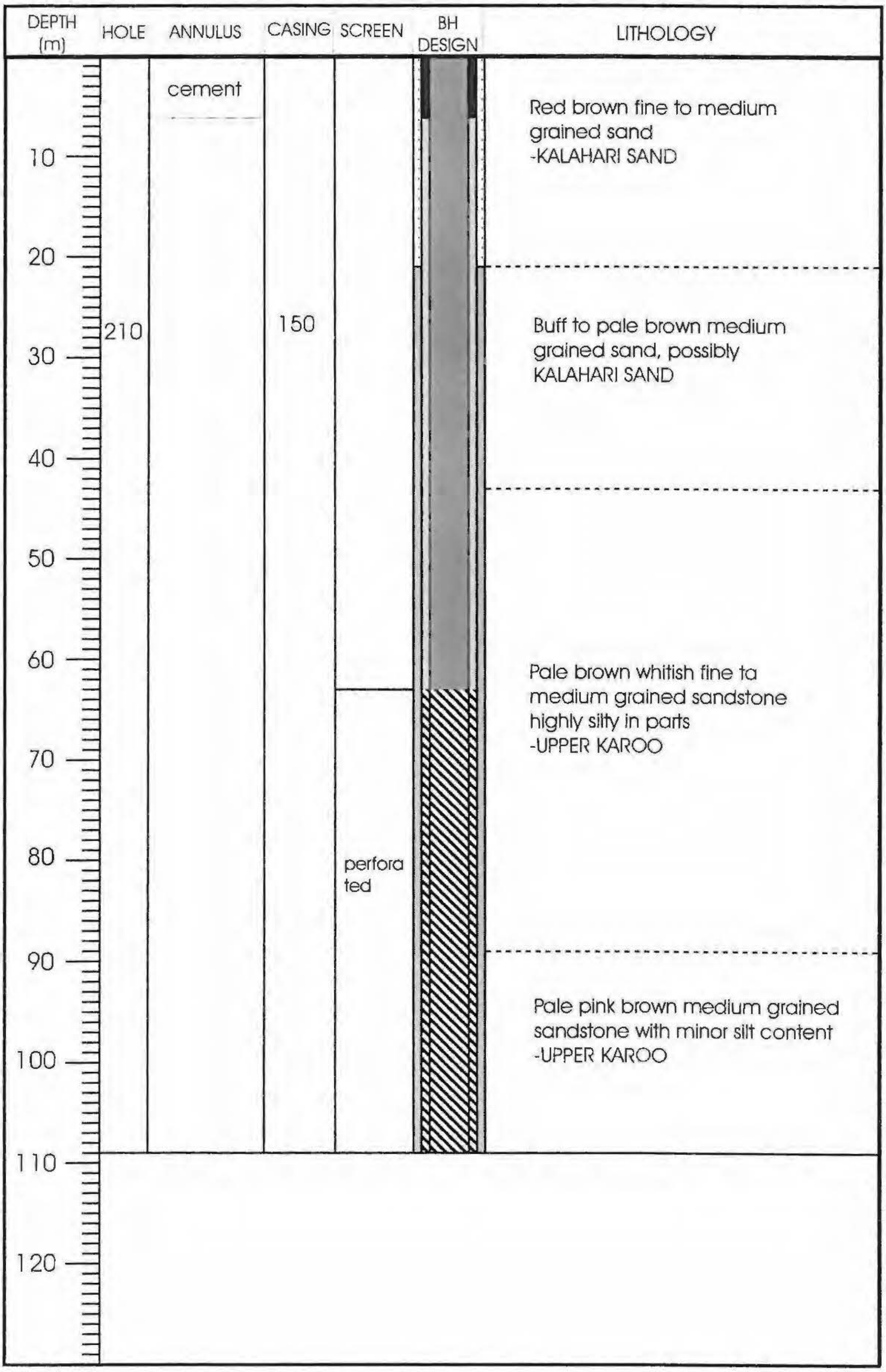
BH ID: 6-KWEK-182

LOCALITY: Mashakadzwa

GRID REF: Qk307292

DRILLING METHOD: Percusion

DATE DRILLED: 18.11.94



Red brown fine to medium grained sand
-KALAHARI SAND

Buff to pale brown medium grained sand, possibly KALAHARI SAND

Pale brown whitish fine to medium grained sandstone highly silty in parts
-UPPER KAROO

Pale pink brown medium grained sandstone with minor silt content
-UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT
KWEKWE

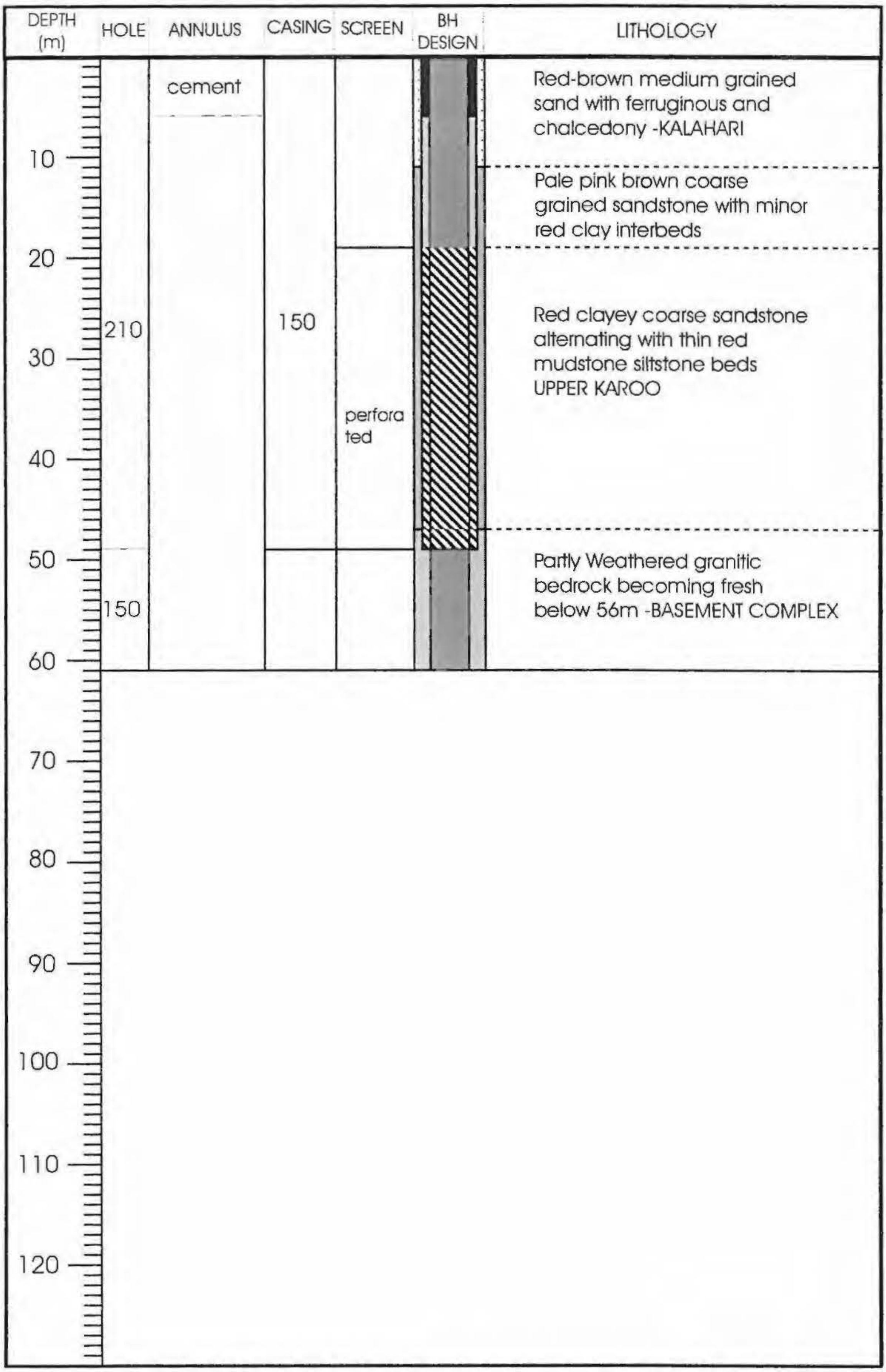
BH ID
6-KWEK-183

LOCALITY
Semisi

GRID REF
Qk110264

DRILLING METHOD
Percusion

DATE DRILLED
27.05.96



Red-brown medium grained sand with ferruginous and chalcedony -KALAHARI

Pale pink brown coarse grained sandstone with minor red clay interbeds

Red clayey coarse sandstone alternating with thin red mudstone siltstone beds UPPER KAROO

Partly Weathered granitic bedrock becoming fresh below 56m -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

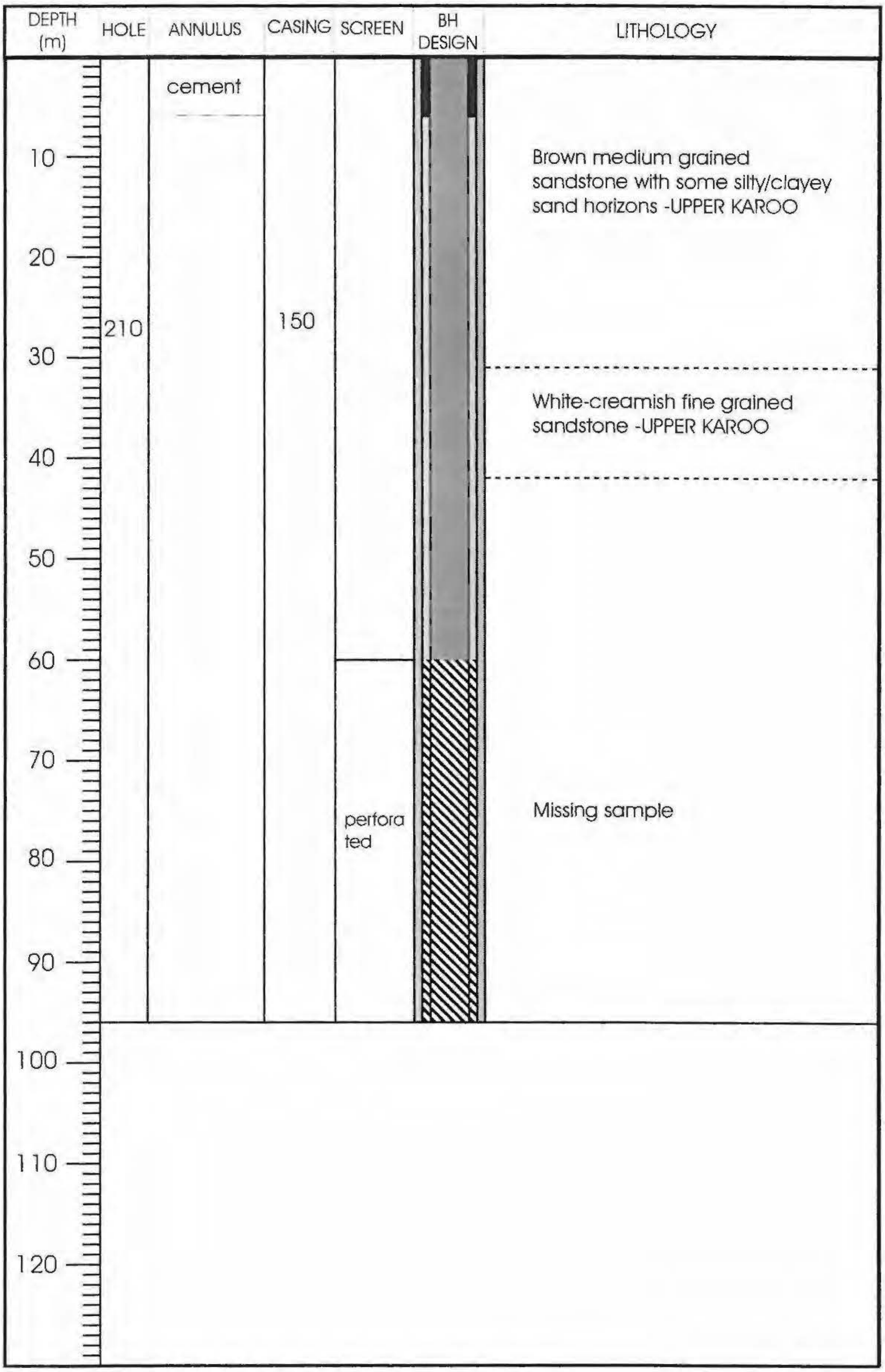
BH ID: 6-KWEK-184

LOCALITY: Bunywana

GRID REF: Qk308260

DRILLING METHOD: Percusion

DATE DRILLED: 31.01.95



Brown medium grained sandstone with some silty/clayey sand horizons -UPPER KAROO

White-creamish fine grained sandstone -UPPER KAROO

Missing sample

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

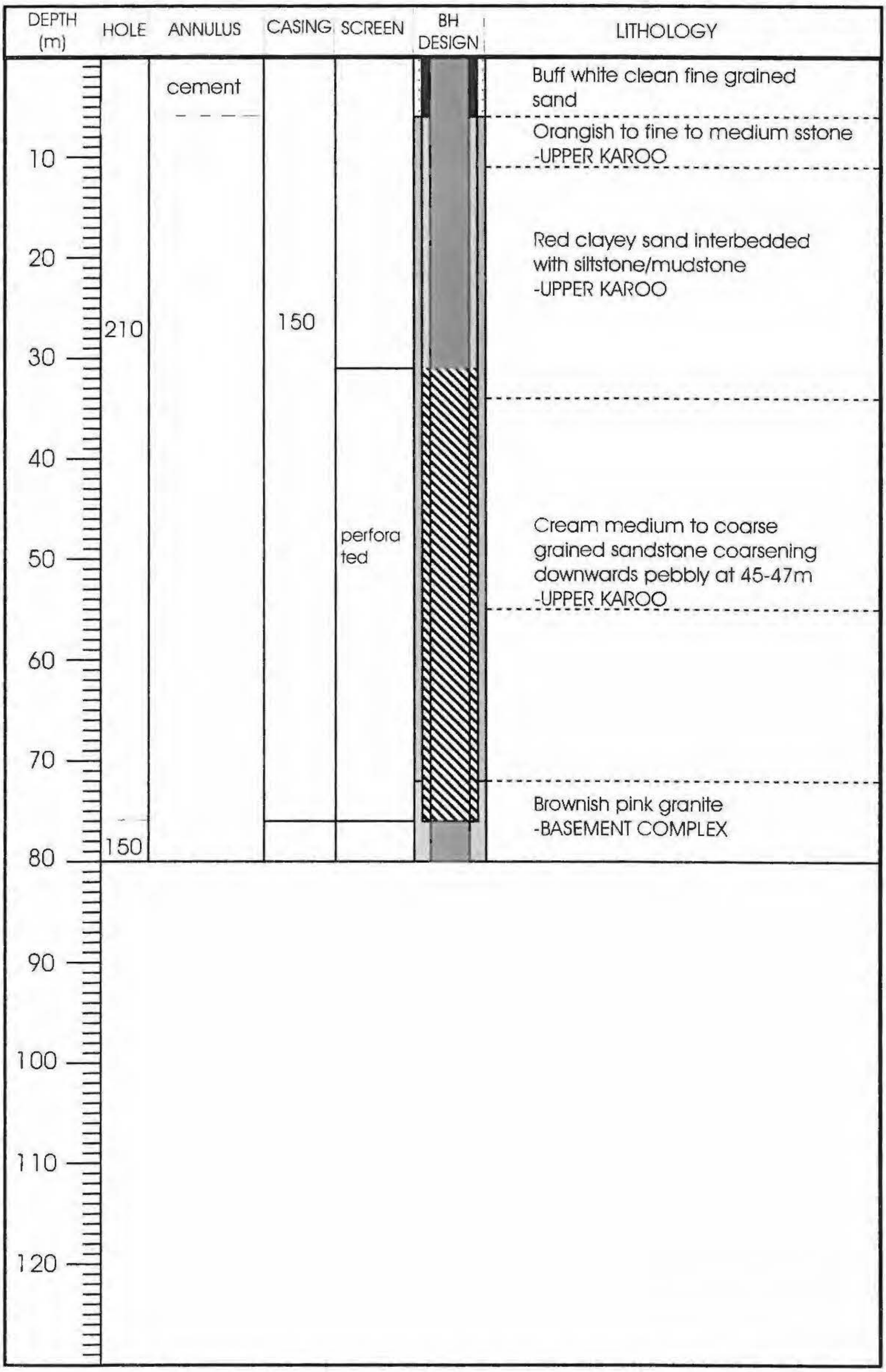
BH ID: 6-KWEK-187

LOCALITY: Munyamana

GRID REF: Qk403307

DRILLING METHOD: Percusion

DATE DRILLED: 10.06.96



Buff white clean fine grained sand

Orangish to fine to medium sstone -UPPER KAROO

Red clayey sand interbedded with siltstone/mudstone -UPPER KAROO

Cream medium to coarse grained sandstone coarsening downwards pebbly at 45-47m -UPPER KAROO

Brownish pink granite -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

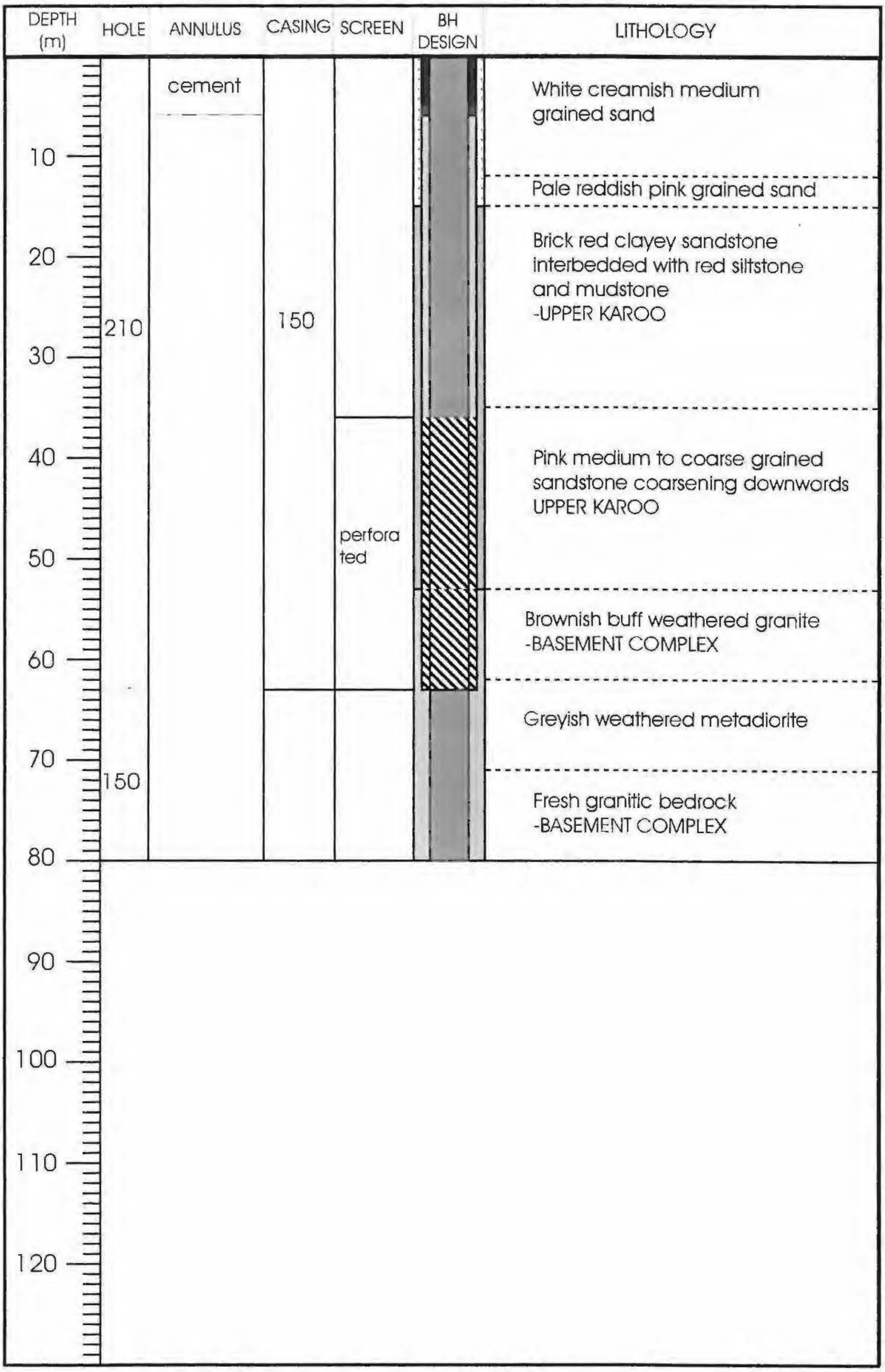
BH ID: 6-KWEK-189

LOCALITY: Mbangwa

GRID REF: Qk103296

DRILLING METHOD: Percusion

DATE DRILLED: 17.05.96



White creamish medium grained sand

Pale reddish pink grained sand

Brick red clayey sandstone interbedded with red siltstone and mudstone
-UPPER KAROO

Pink medium to coarse grained sandstone coarsening downwords
UPPER KAROO

Brownish buff weathered granite
-BASEMENT COMPLEX

Greyish weathered metadiorite

Fresh granitic bedrock
-BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

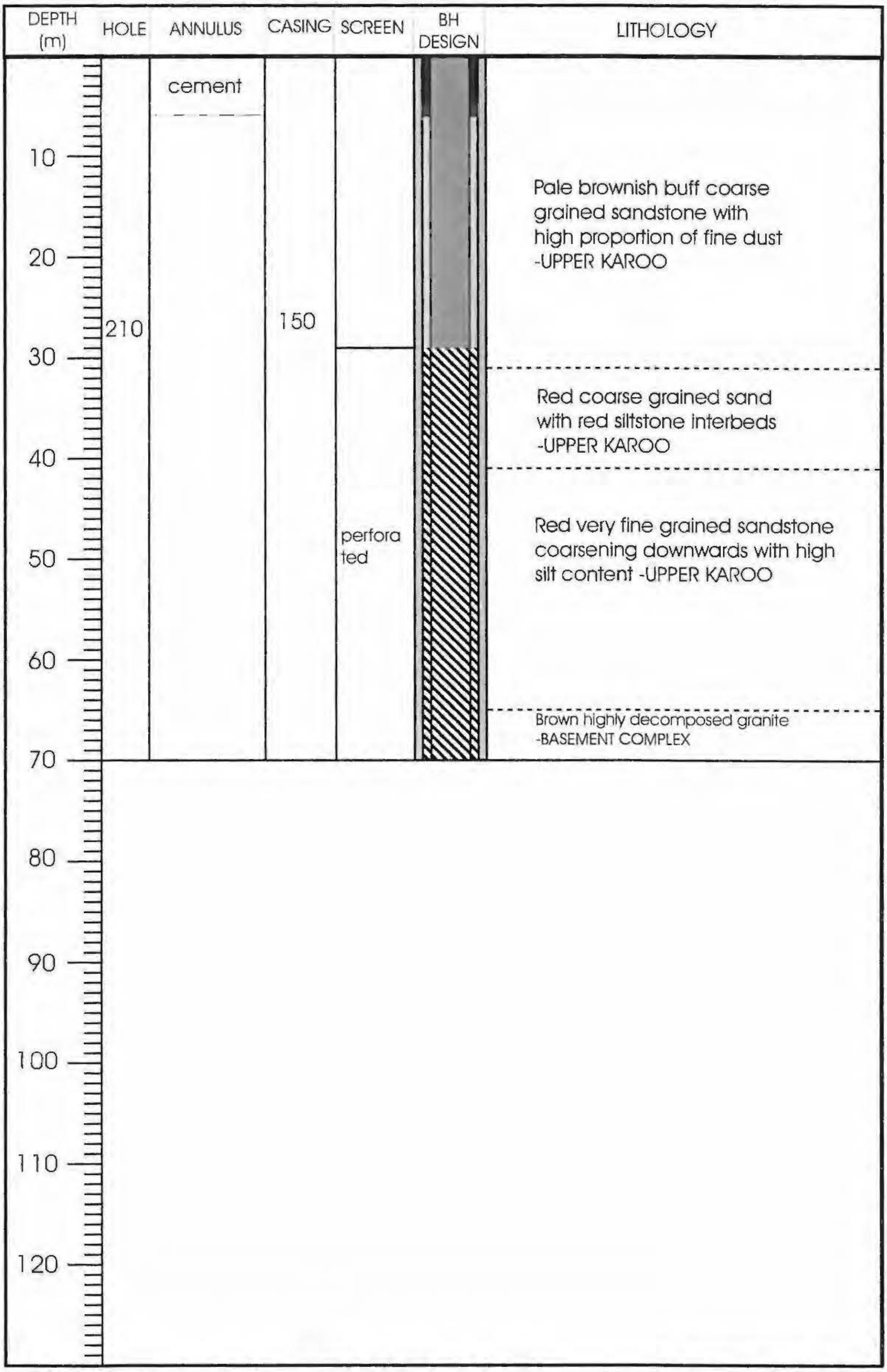
BH ID: 6-KWEK-190

LOCALITY: Mafusini

GRID REF: Qk403282

DRILLING METHOD: Percusion

DATE DRILLED: 12.05.96



Pale brownish buff coarse grained sandstone with high proportion of fine dust -UPPER KAROO

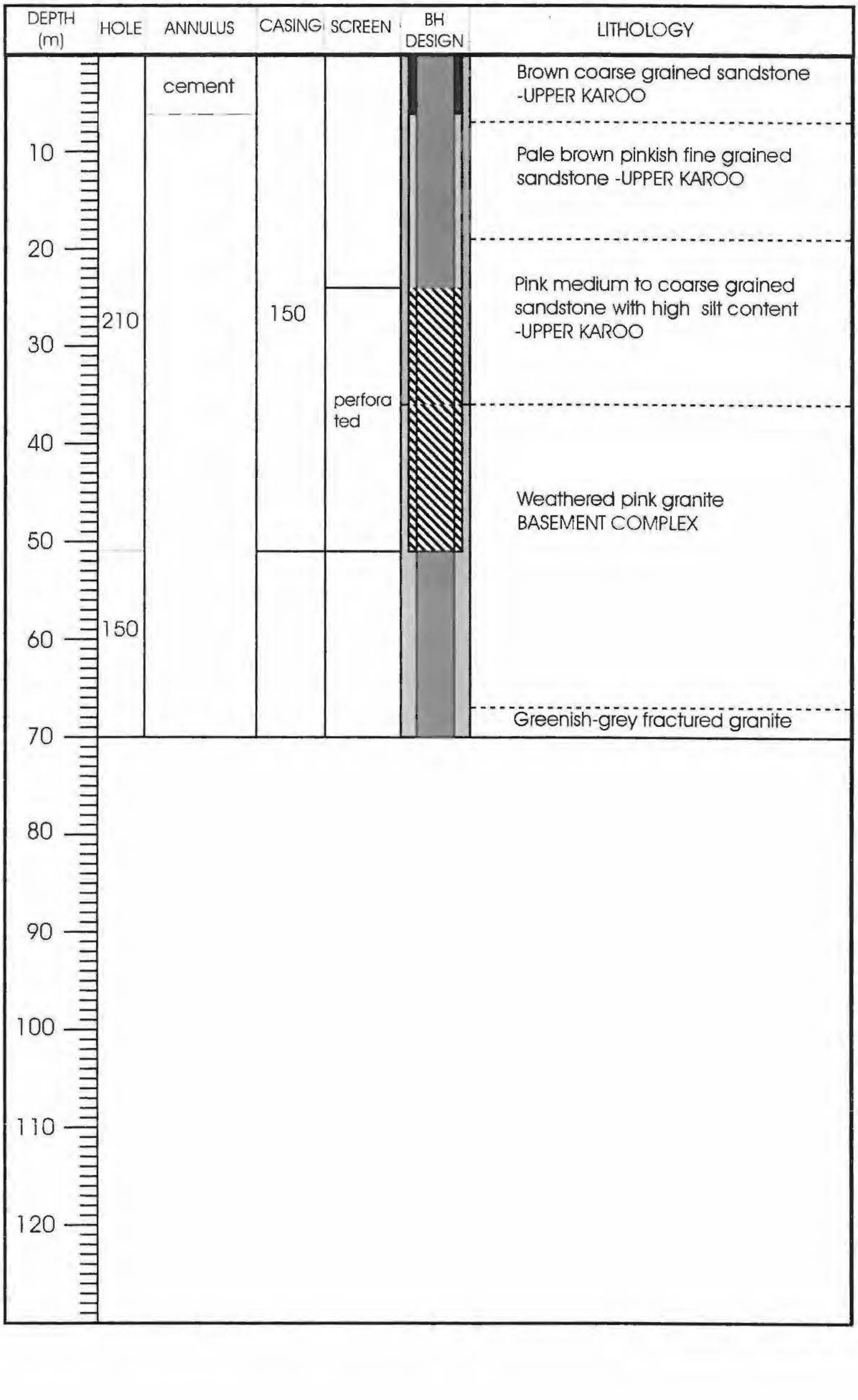
Red coarse grained sand with red siltstone interbeds -UPPER KAROO

Red very fine grained sandstone coarsening downwards with high silt content -UPPER KAROO

Brown highly decomposed granite -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT	KWEKWE
BH ID	6-KWEK-193
LOCALITY	Hube
GRID REF	QK 393282
DRILLING METHOD	Percussion
DATE DRILLED	07.05.96



Brown coarse grained sandstone -UPPER KAROO

Pale brown pinkish fine grained sandstone -UPPER KAROO

Pink medium to coarse grained sandstone with high silt content -UPPER KAROO

Weathered pink granite BASEMENT COMPLEX

Greenish-grey fractured granite

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

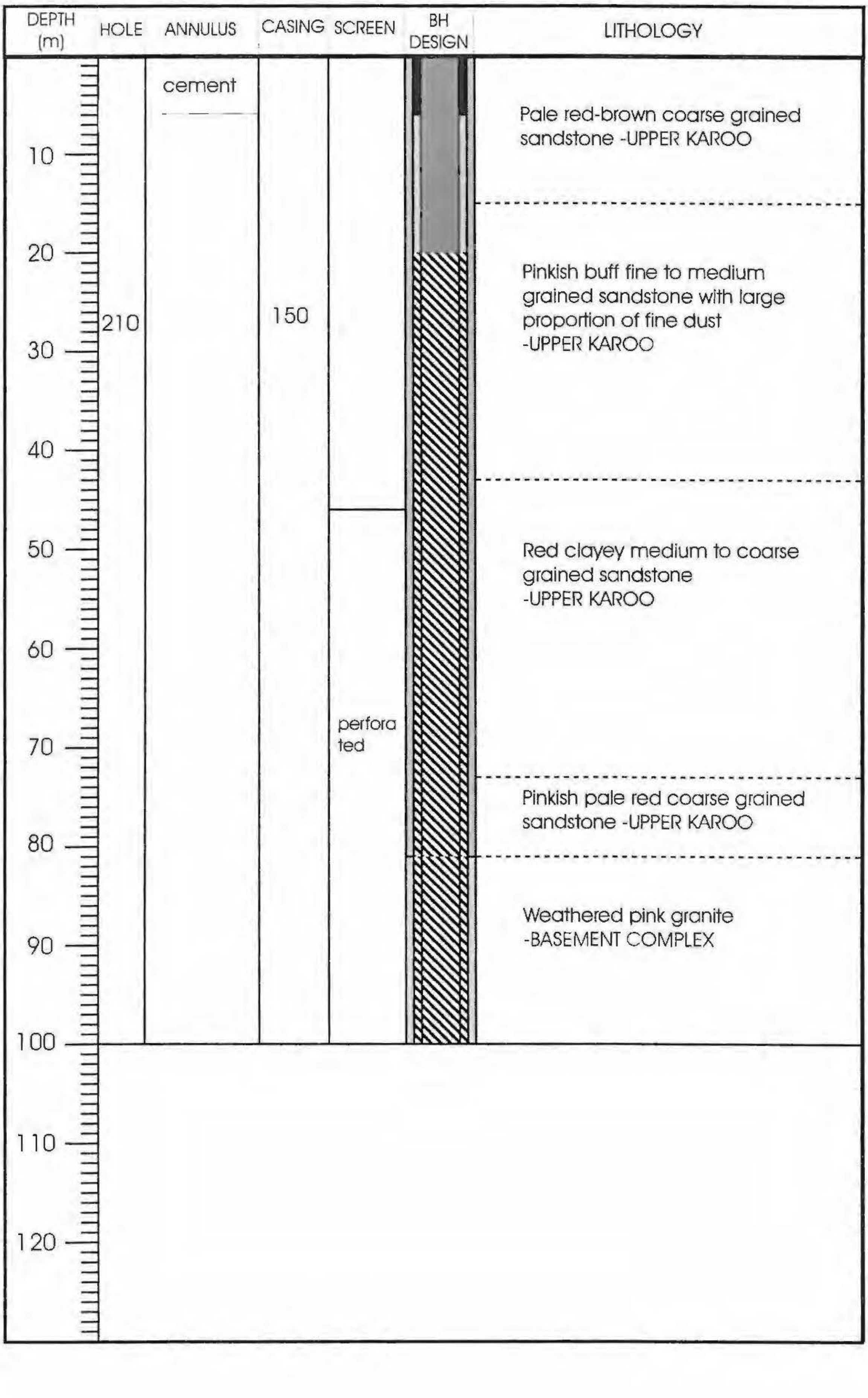
BH ID: 6-KWEK-194

LOCALITY: Pakhama Line

GRID REF: Qk378263

DRILLING METHOD: Percusion

DATE DRILLED: 01.04.96



Pale red-brown coarse grained sandstone -UPPER KAROO

Pinkish buff fine to medium grained sandstone with large proportion of fine dust -UPPER KAROO

Red clayey medium to coarse grained sandstone -UPPER KAROO

Pinkish pale red coarse grained sandstone -UPPER KAROO

Weathered pink granite -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

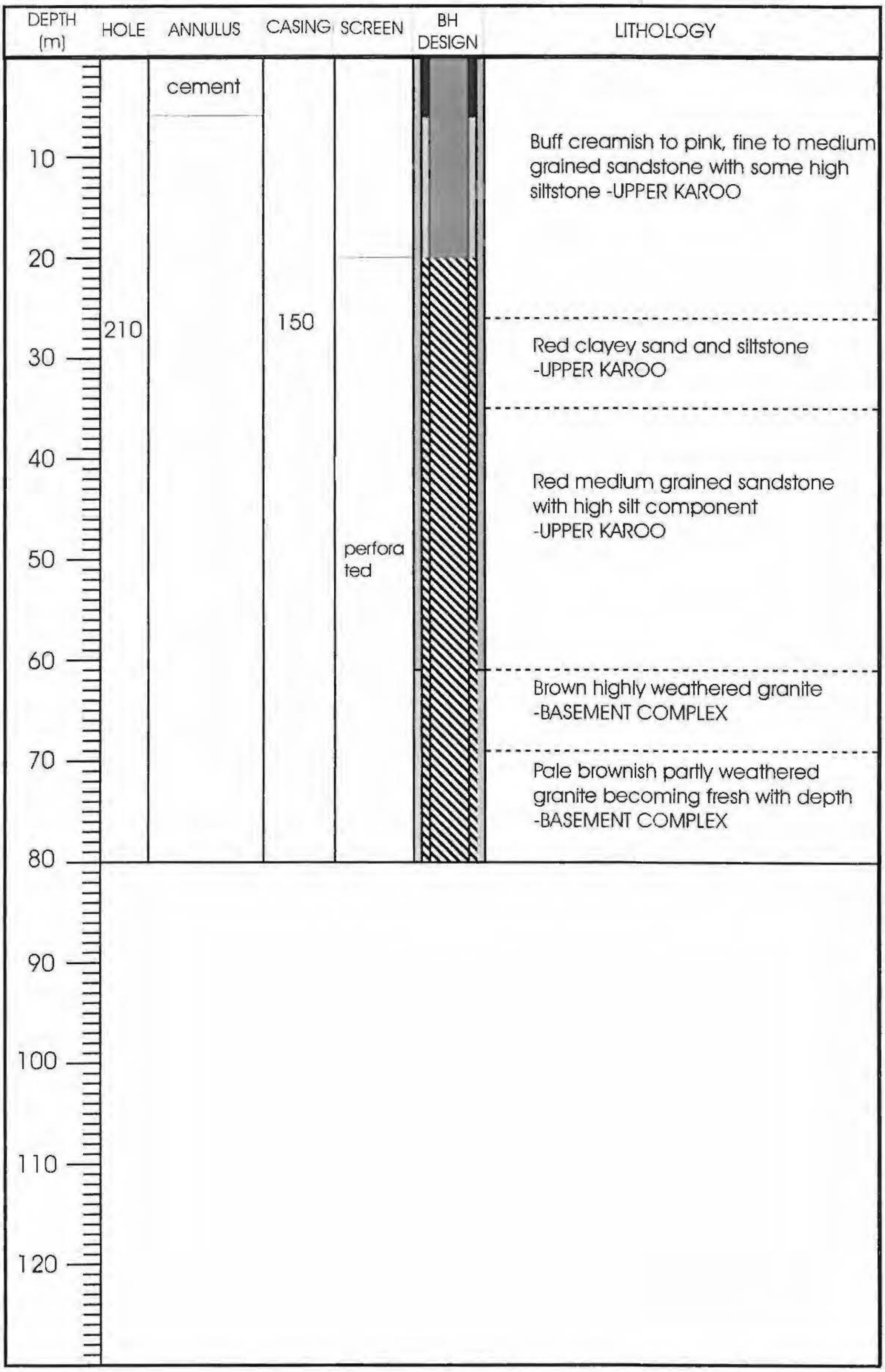
BH ID: 6-KWEK-195

LOCALITY: Lokhutheza

GRID REF: QK 396269

DRILLING METHOD: Percusion

DATE DRILLED: 15.04.96



Buff creamish to pink, fine to medium grained sandstone with some high siltstone -UPPER KAROO

Red clayey sand and siltstone -UPPER KAROO

Red medium grained sandstone with high silt component -UPPER KAROO

Brown highly weathered granite -BASEMENT COMPLEX

Pale brownish partly weathered granite becoming fresh with depth -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

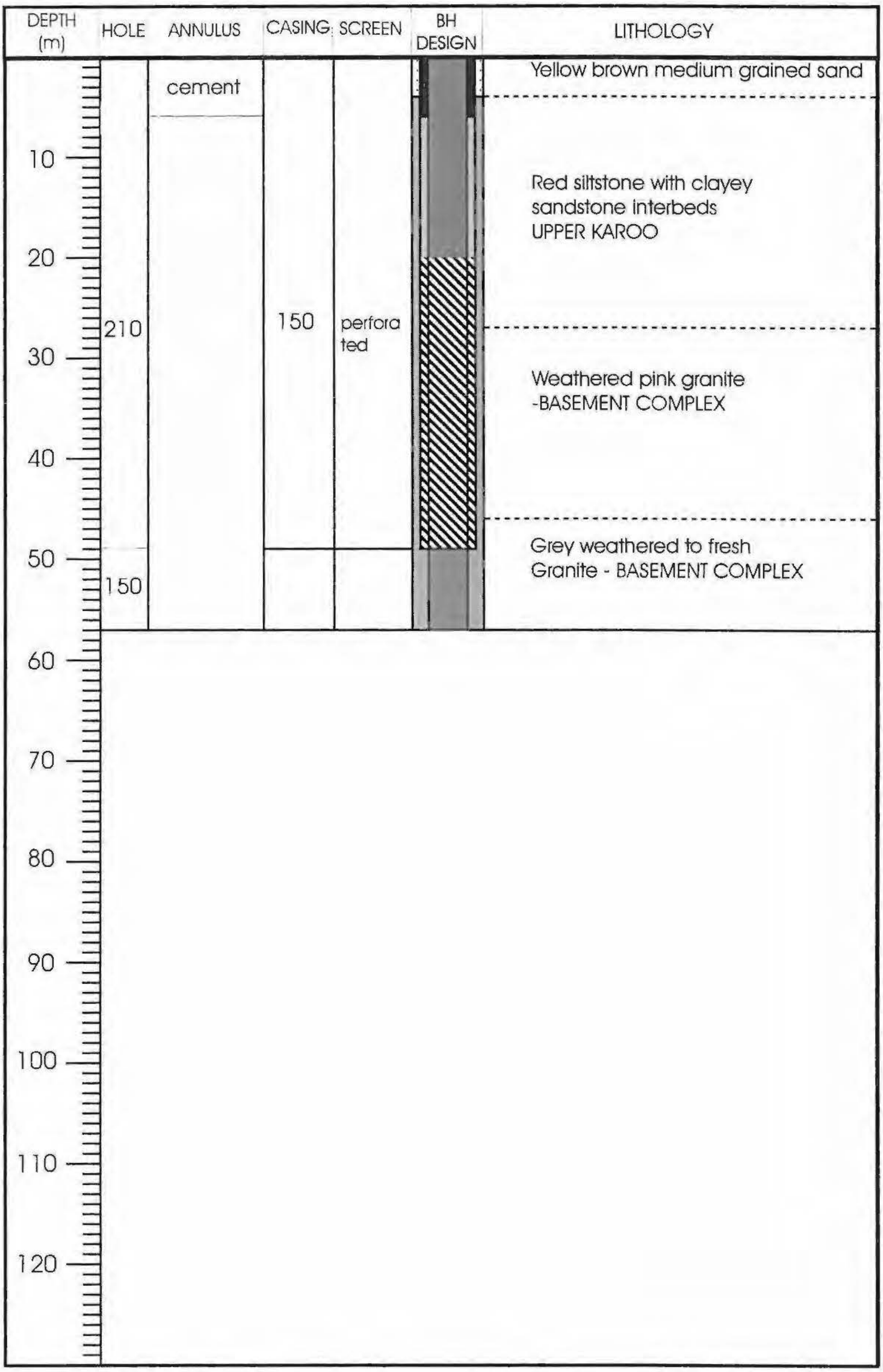
BH ID: 6-KWEK-198

LOCALITY: Bulungu

GRID REF: QK 409232

DRILLING METHOD: Percussion

DATE DRILLED: 17.04.96



Yellow brown medium grained sand

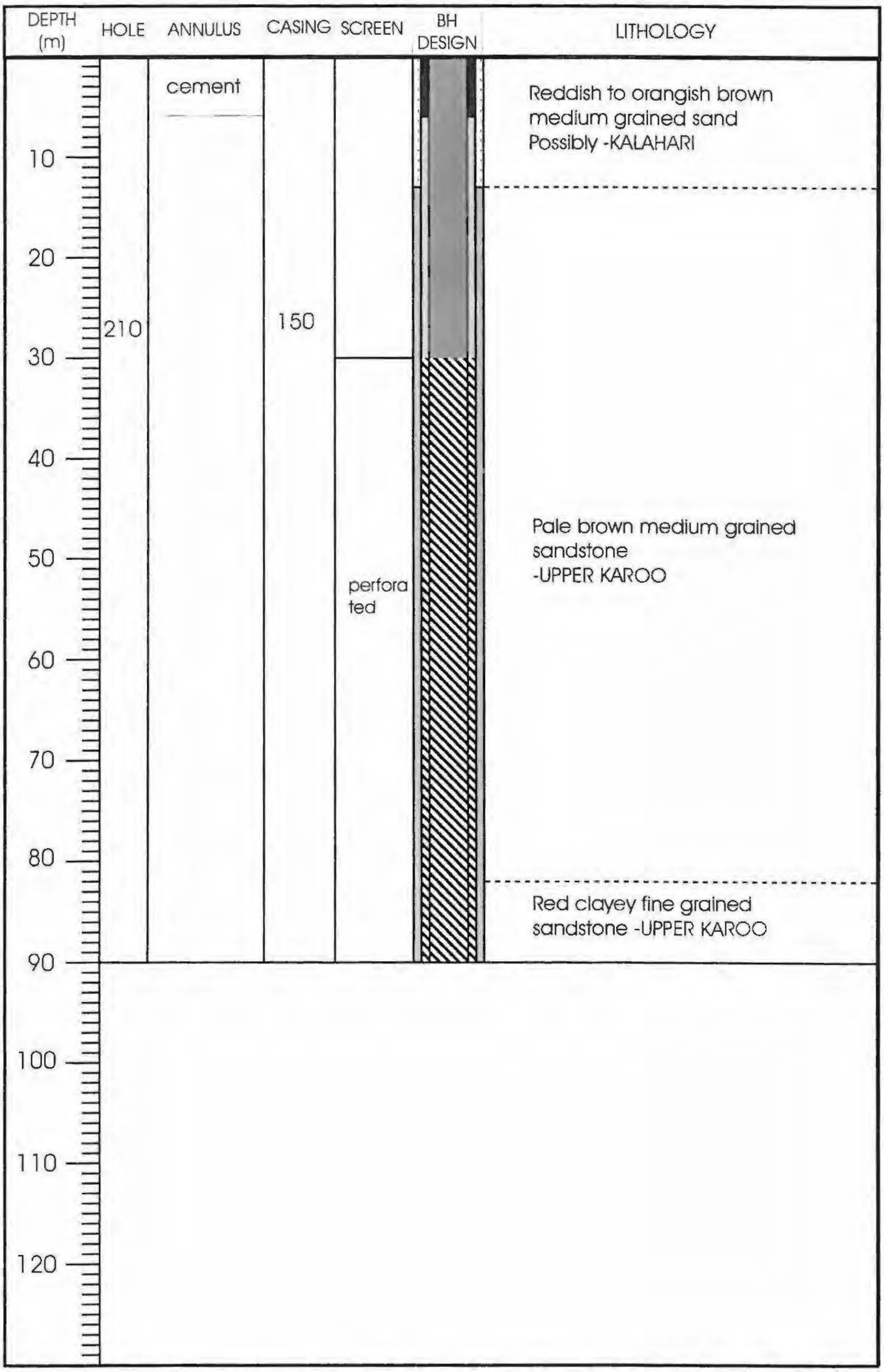
Red siltstone with clayey sandstone interbeds
UPPER KAROO

Weathered pink granite
-BASEMENT COMPLEX

Grey weathered to fresh
Granite - BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT	KWEKWE
BH ID	6-KWEK-205
LOCALITY	Khuhleloku
GRID REF	Qk360273
DRILLING METHOD	Percusion
DATE DRILLED	28.04.96



Reddish to orangish brown medium grained sand Possibly -KALAHARI

Pale brown medium grained sandstone -UPPER KAROO

Red clayey fine grained sandstone -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

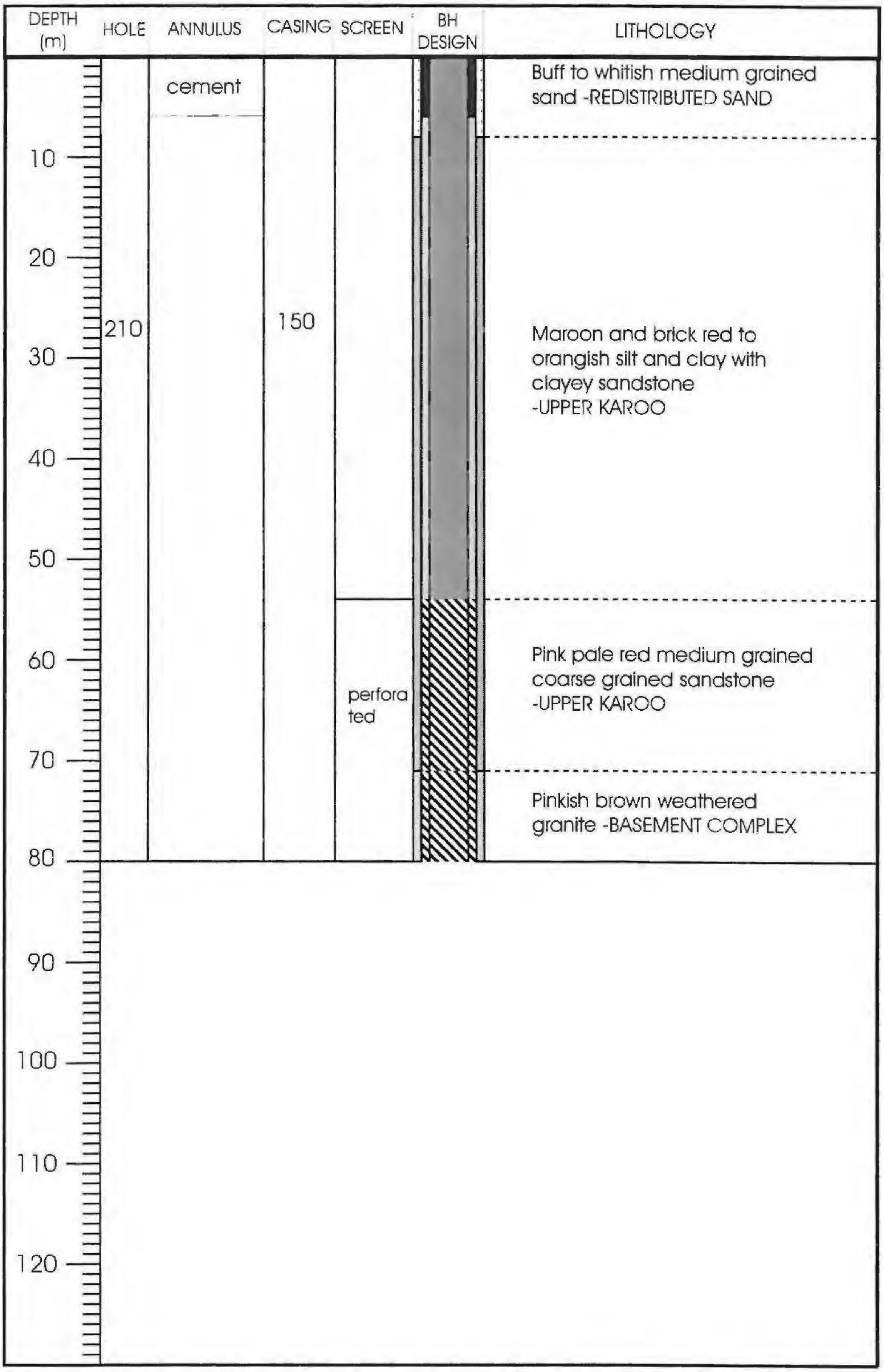
BH ID: 6-KWEK-206

LOCALITY: Khangelani

GRID REF: Qk363305

DRILLING METHOD: Percusion

DATE DRILLED: 15.04.96



Buff to whitish medium grained sand -REDISTRIBUTED SAND

Maroon and brick red to orangish silt and clay with clayey sandstone -UPPER KAROO

Pink pale red medium grained coarse grained sandstone -UPPER KAROO

Pinkish brown weathered granite -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

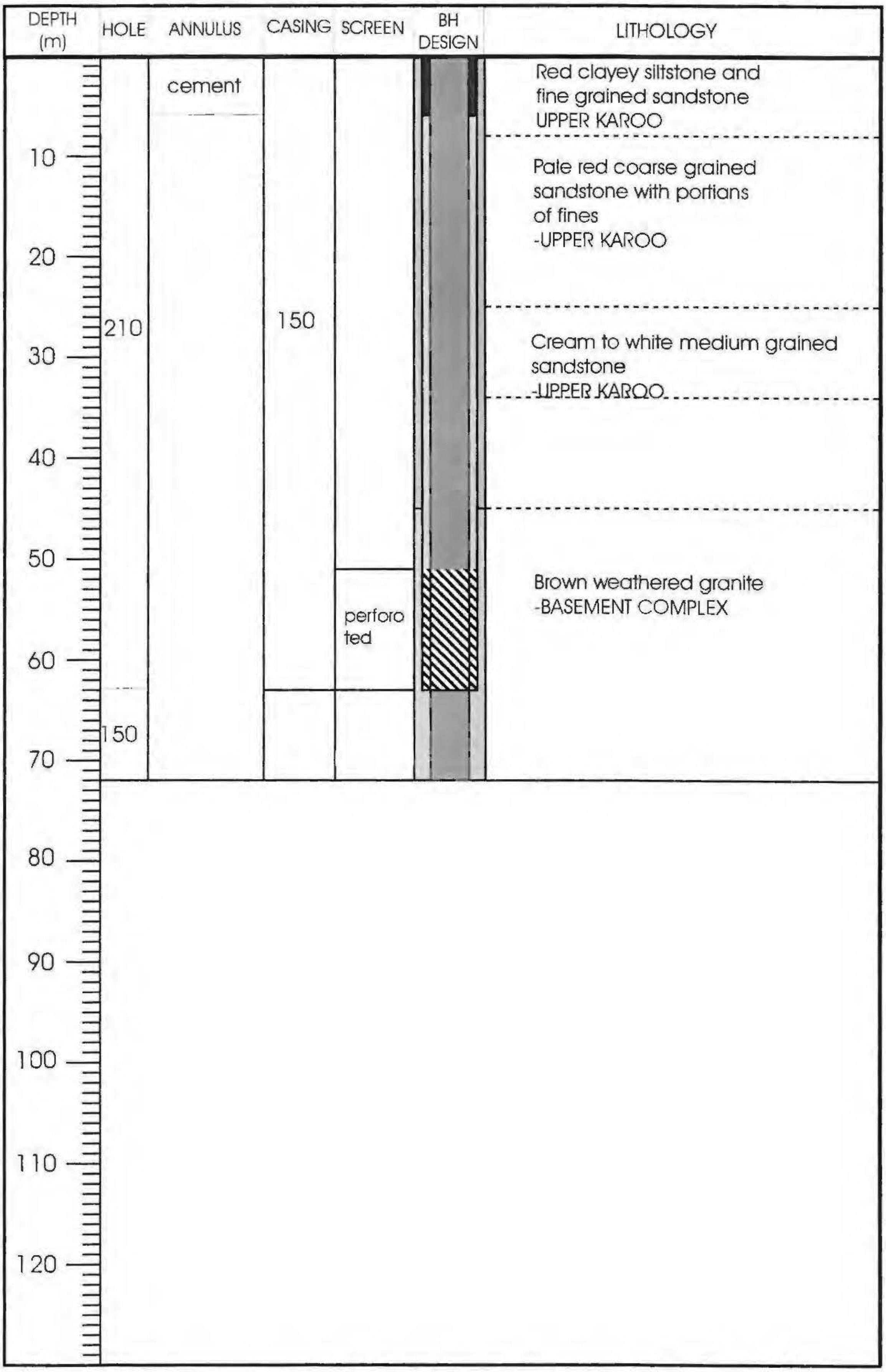
BH ID: 6-KWEK-208

LOCALITY: Jabulani

GRID REF: Qk362306

DRILLING METHOD: Percusion

DATE DRILLED: 20.04.96



Red clayey siltstone and fine grained sandstone UPPER KAROO

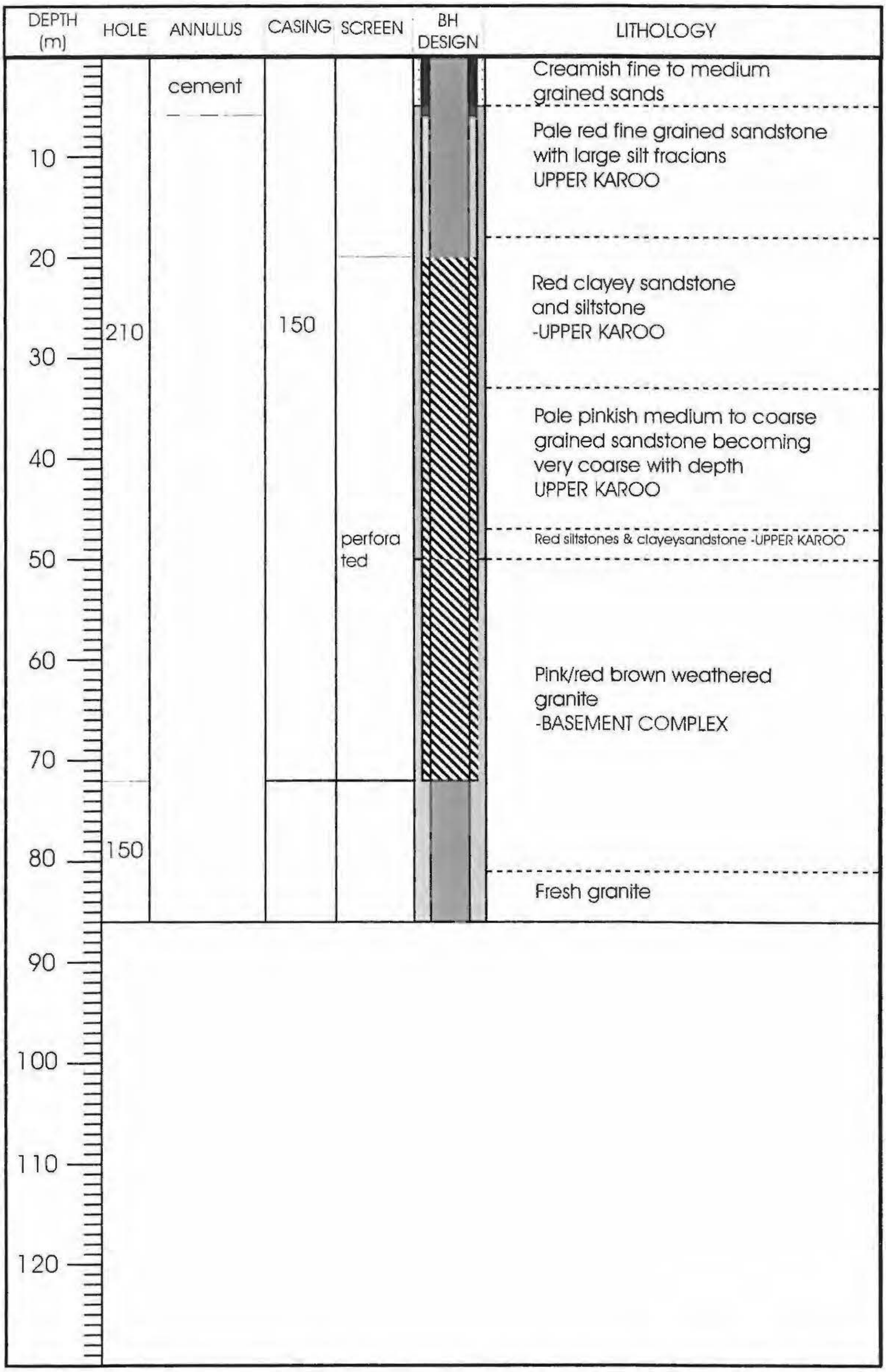
Pale red coarse grained sandstone with portians of fines -UPPER KAROO

Cream to white medium grained sandstone -UPPER KAROO

Brown weathered granite -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT	KWEKWE
BH ID	6-KWEK-209
LOCALITY	Zimasko 2
GRID REF	Qk369314
DRILLING METHOD	Percusion
DATE DRILLED	08.06.96



Creamish fine to medium grained sands

Pale red fine grained sandstone with large silt fracians
UPPER KAROO

Red clayey sandstone and siltstone
-UPPER KAROO

Pale pinkish medium to coarse grained sandstone becoming very coarse with depth
UPPER KAROO

Red siltstones & clayeysandstone -UPPER KAROO

Pink/red brown weathered granite
-BASEMENT COMPLEX

Fresh granite

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

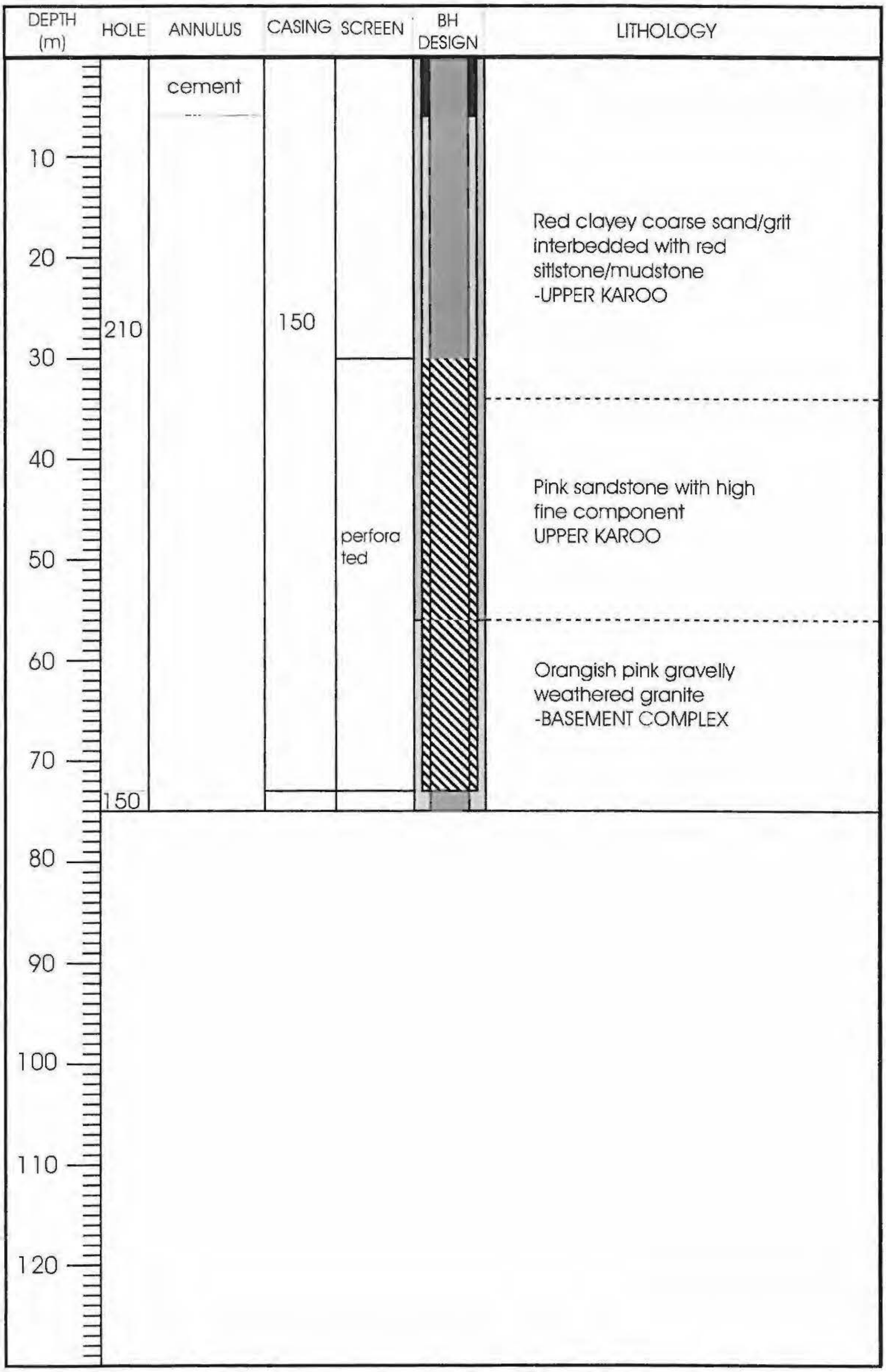
BH ID: 6-KWEK-210

LOCALITY: Bamambanani

GRID REF: Qk370318

DRILLING METHOD: Percusion

DATE DRILLED: 11.05.96



Red clayey coarse sand/grit interbedded with red siltstone/mudstone -UPPER KAROO

Pink sandstone with high fine component UPPER KAROO

Orangish pink gravelly weathered granite -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

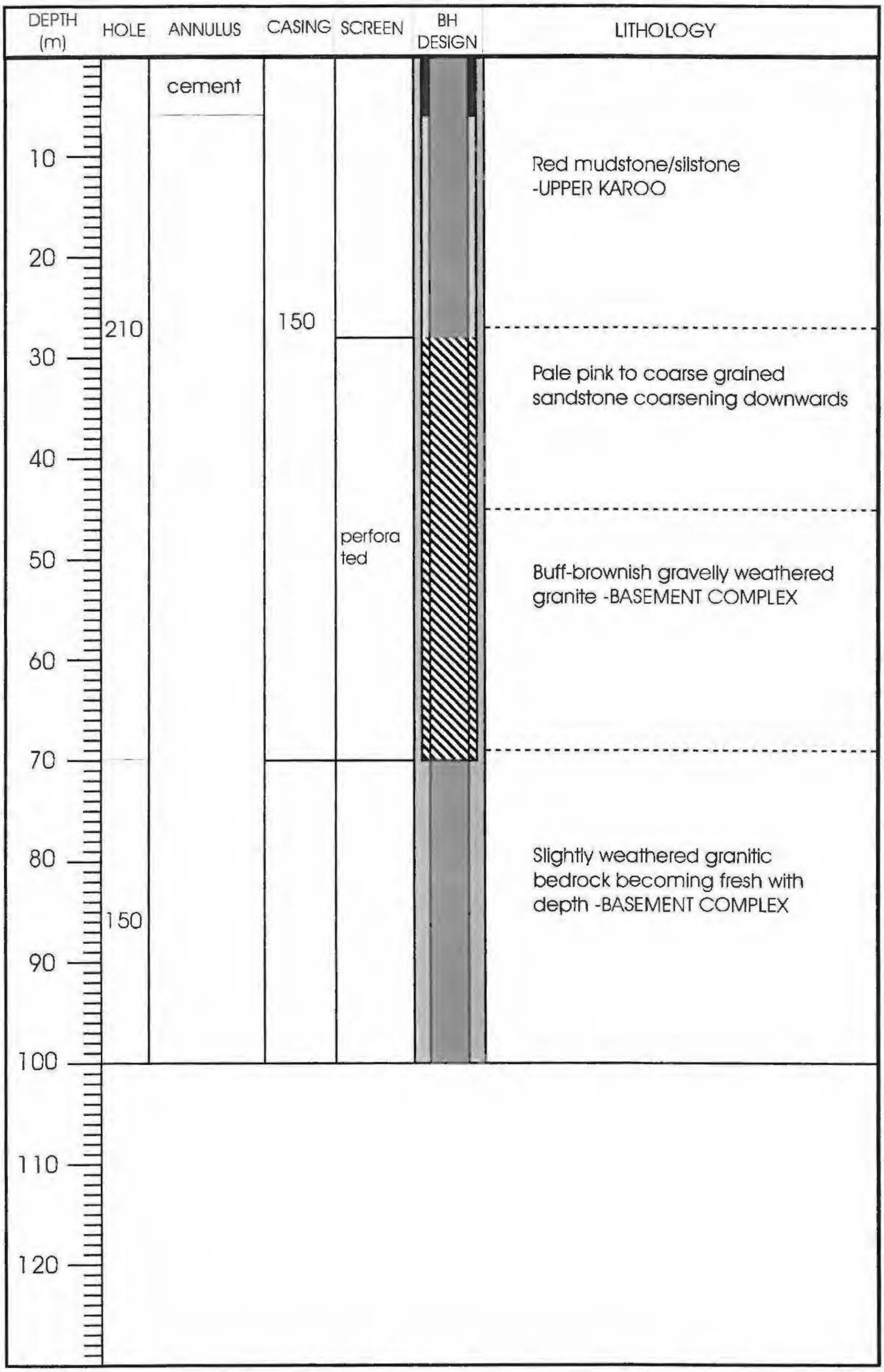
BH ID: 6-KWEK-211

LOCALITY: Zimasko 1

GRID REF: QK 367332

DRILLING METHOD: Percusion

DATE DRILLED: 21.05.96



Red mudstone/silstone -UPPER KAROO

Pale pink to coarse grained sandstone coarsening downwards

Buff-brownish gravelly weathered granite -BASEMENT COMPLEX

Slightly weathered granitic bedrock becoming fresh with depth -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

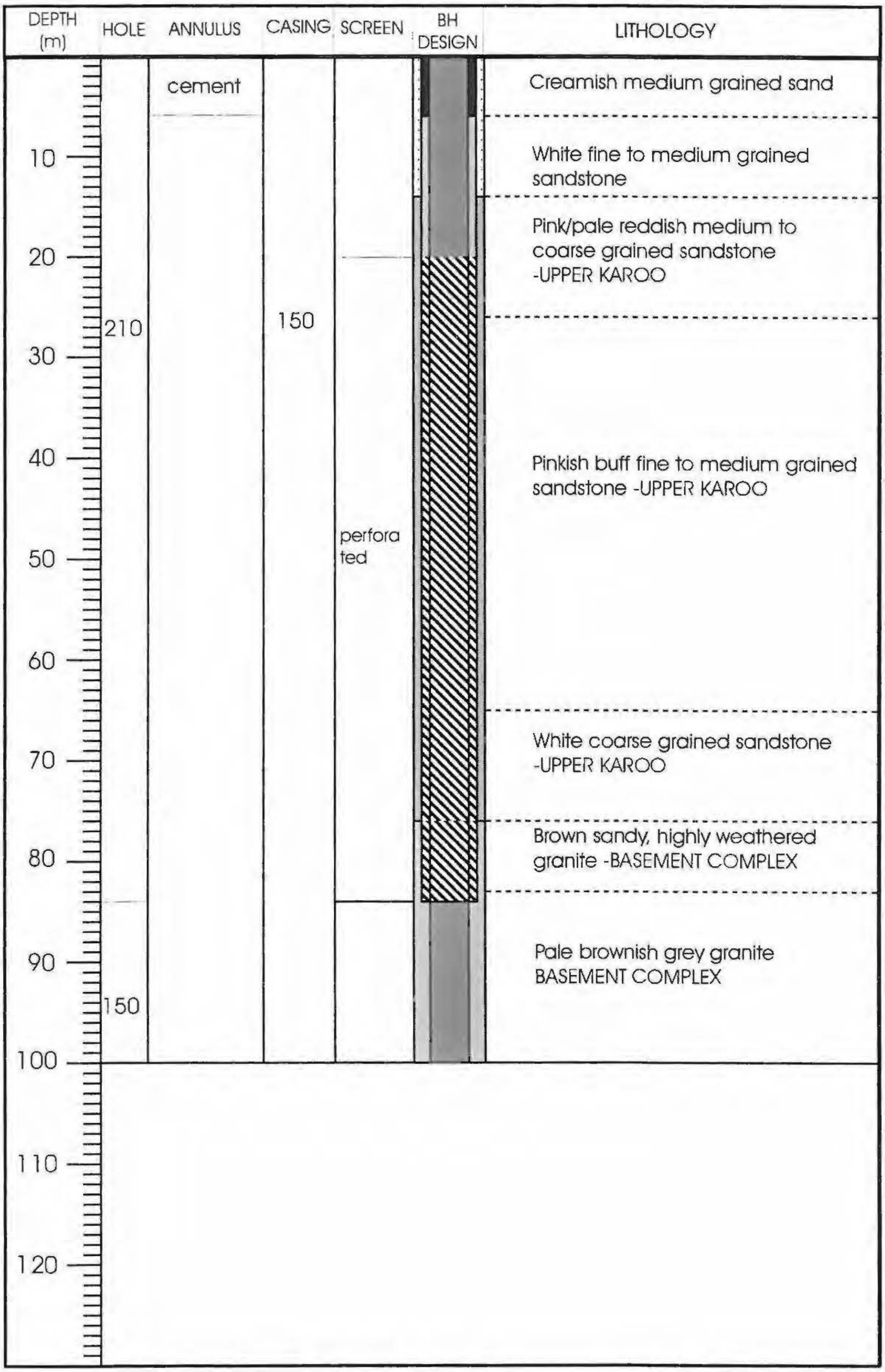
BH ID: 6-KWEK-213

LOCALITY: Zenzeleni

GRID REF: QK 334314

DRILLING METHOD: Percusion

DATE DRILLED: 20.04.96



Creamish medium grained sand

White fine to medium grained sandstone

Pink/pale reddish medium to coarse grained sandstone -UPPER KAROO

Pinkish buff fine to medium grained sandstone -UPPER KAROO

White coarse grained sandstone -UPPER KAROO

Brown sandy, highly weathered granite -BASEMENT COMPLEX

Pale brownish grey granite BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

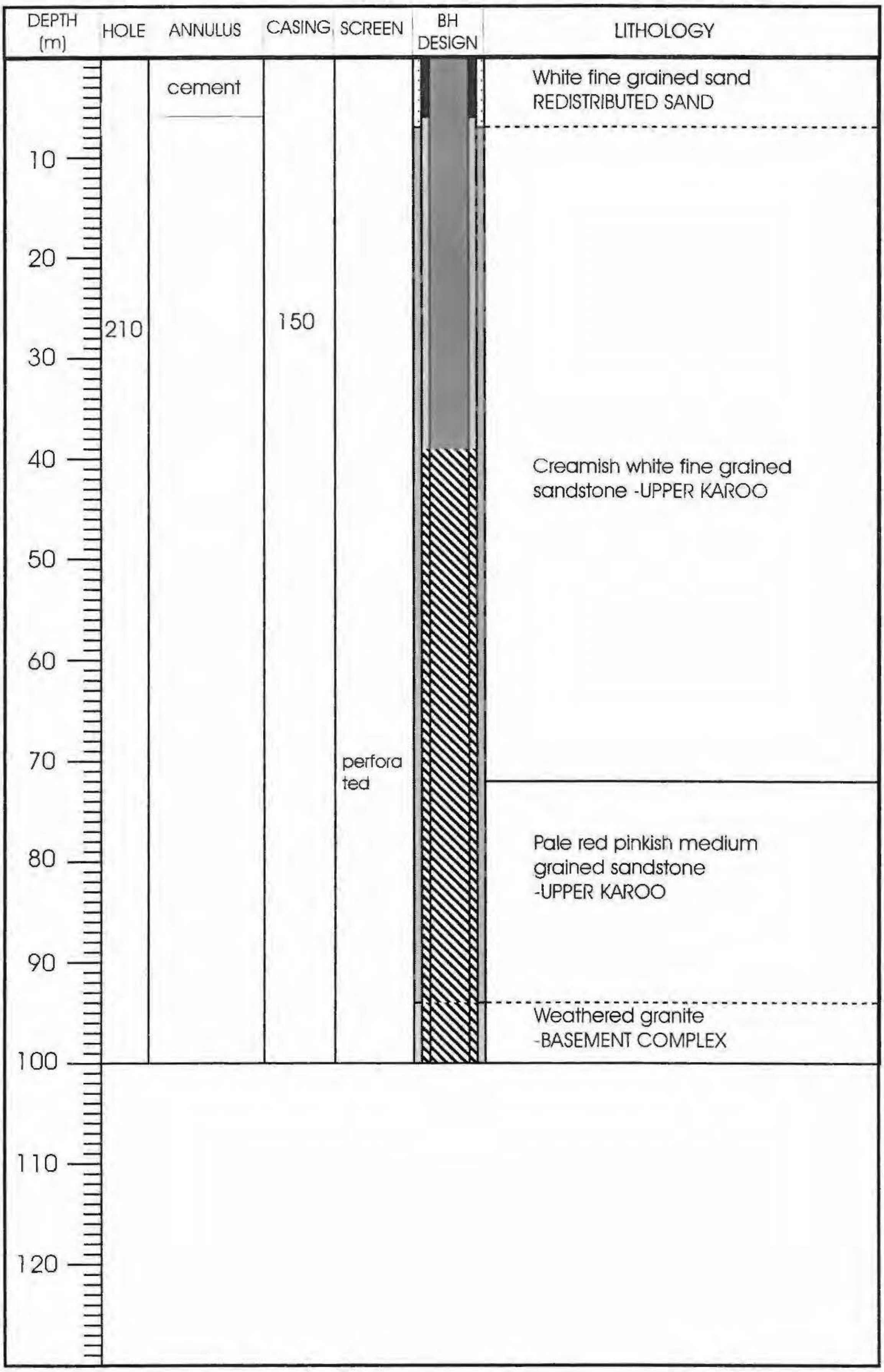
BH ID: 6-KWEK-214

LOCALITY: Bambazonke

GRID REF: QK 322323

DRILLING METHOD: Percussion

DATE DRILLED: 01.05.96



WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

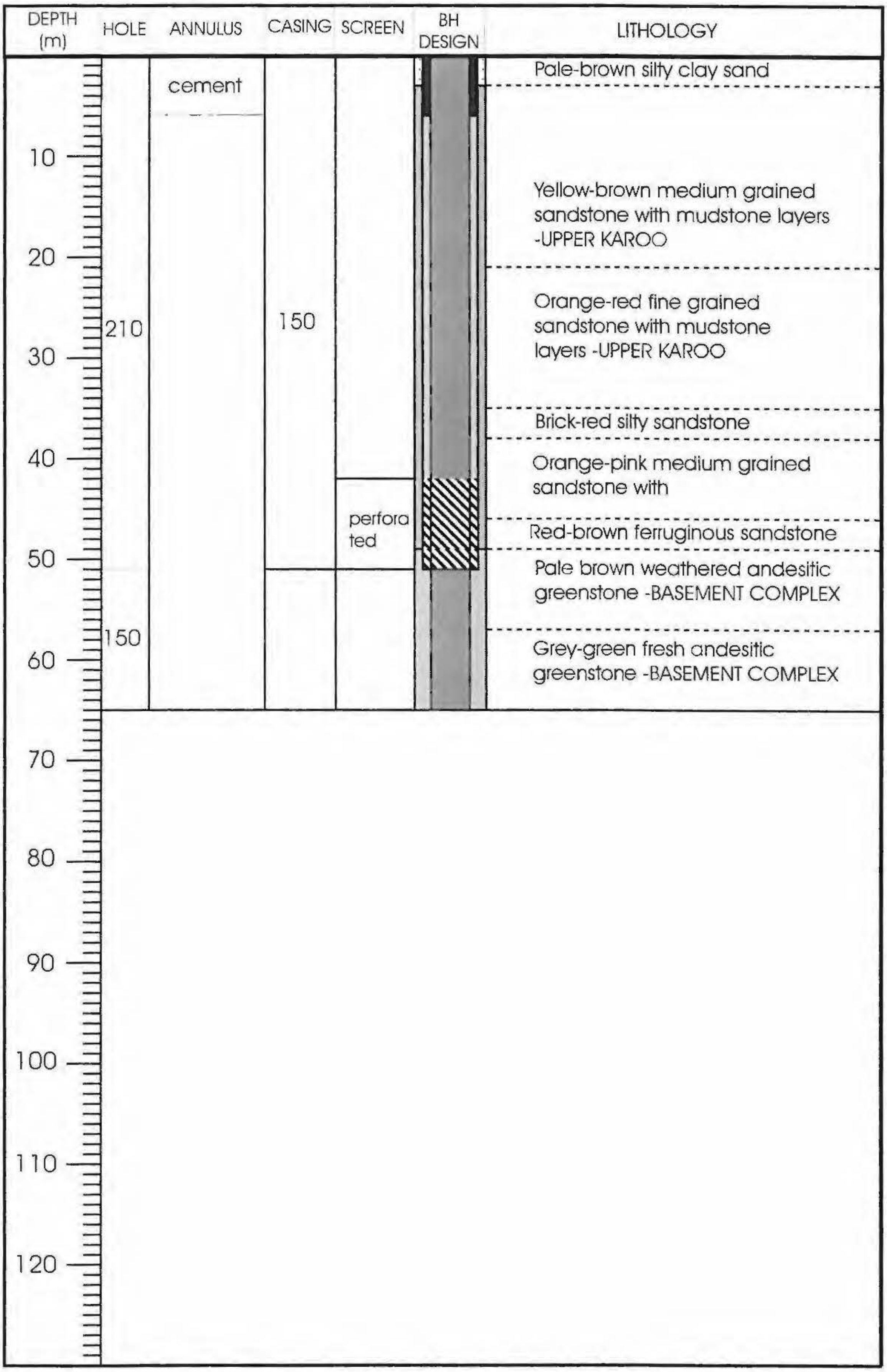
BH ID: 6-KWEK-215

LOCALITY: Gwarazimba

GRID REF: Qk338352

DRILLING METHOD: Percusion

DATE DRILLED: 16.05.97



Pale-brown silty clay sand

Yellow-brown medium grained sandstone with mudstone layers -UPPER KAROO

Orange-red fine grained sandstone with mudstone layers -UPPER KAROO

Brick-red silty sandstone

Orange-pink medium grained sandstone with

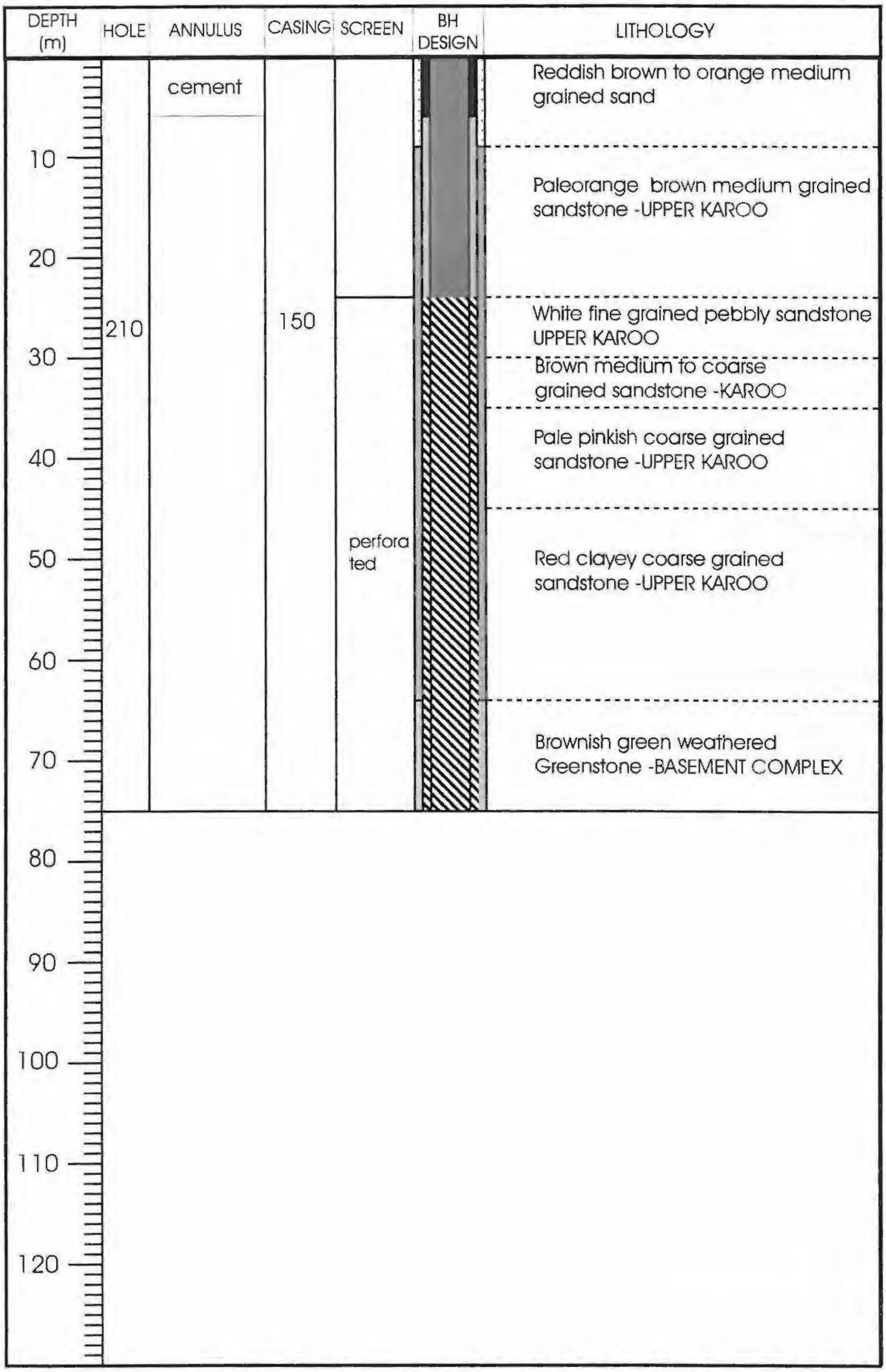
Red-brown ferruginous sandstone

Pale brown weathered andesitic greenstone -BASEMENT COMPLEX

Grey-green fresh andesitic greenstone -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT	KWEKWE
BH ID	6-KWEK-216
LOCALITY	Madabu
GRID REF	QK 341213
DRILLING METHOD	Percussion
DATE DRILLED	24.03.96



Reddish brown to orange medium grained sand

Paleorange brown medium grained sandstone -UPPER KAROO

White fine grained pebbly sandstone UPPER KAROO

Brown medium to coarse grained sandstone -KAROO

Pale pinkish coarse grained sandstone -UPPER KAROO

Red clayey coarse grained sandstone -UPPER KAROO

Brownish green weathered Greenstone -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

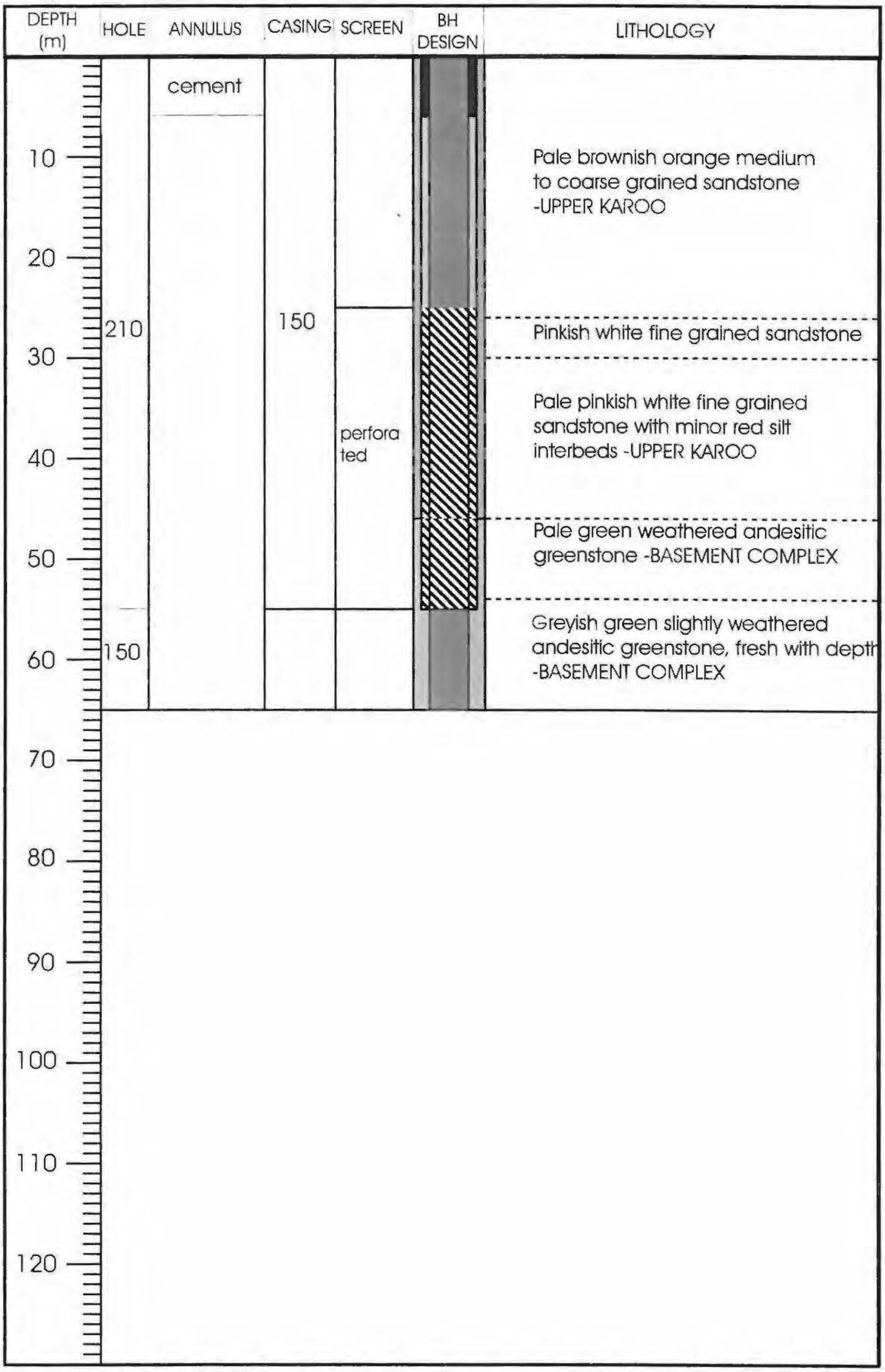
BH ID: 6-KWEK-217

LOCALITY: Siziba

GRID REF: QK 342207

DRILLING METHOD: Percussion

DATE DRILLED: 21.02.96



Pale brownish orange medium to coarse grained sandstone -UPPER KAROO

Pinkish white fine grained sandstone

Pale pinkish white fine grained sandstone with minor red silt interbeds -UPPER KAROO

Pale green weathered andesitic greenstone -BASEMENT COMPLEX

Greyish green slightly weathered andesitic greenstone, fresh with depth -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

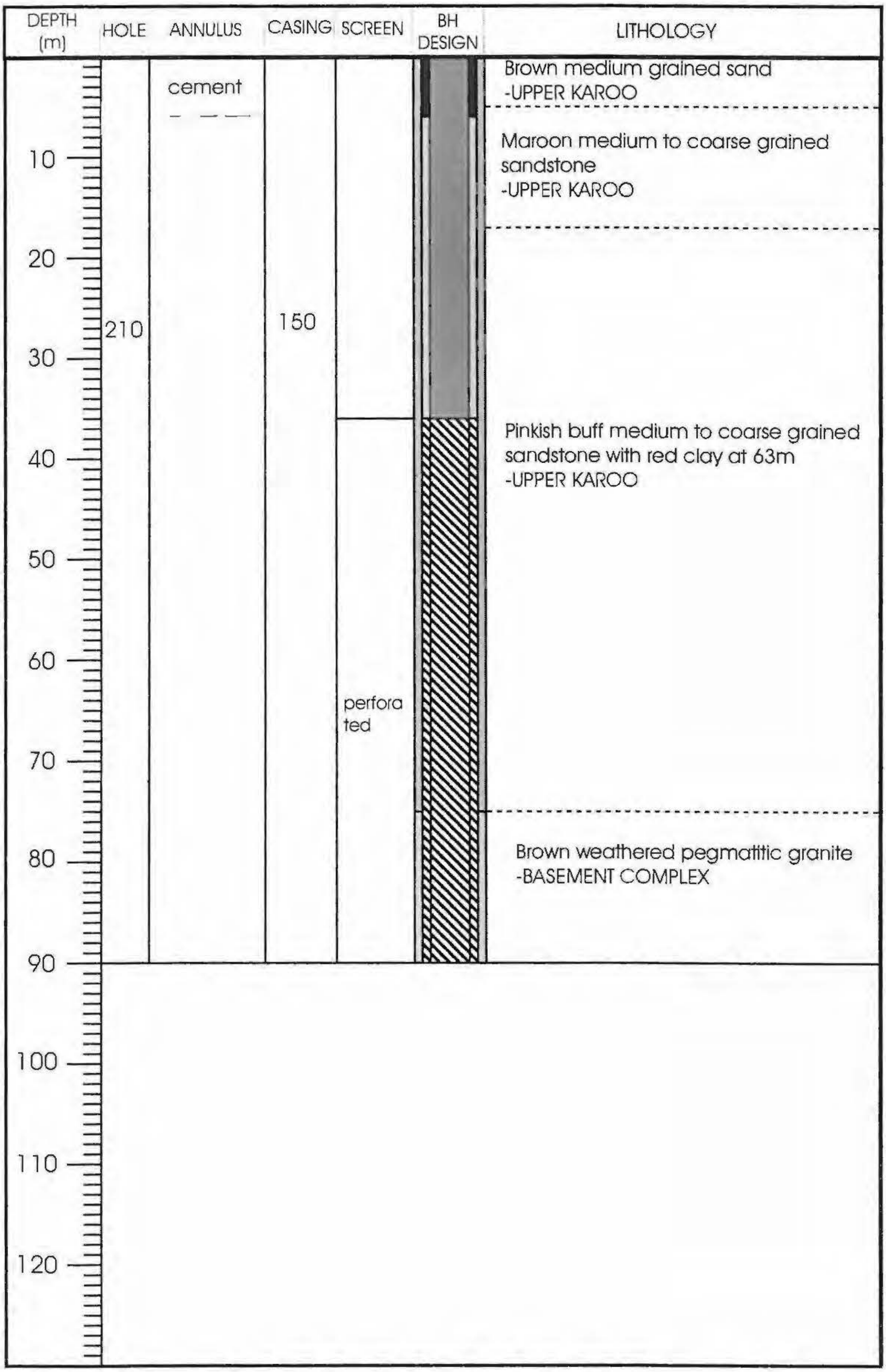
BH ID: 6-KWEK-218

LOCALITY: Mancimeza

GRID REF: QK 351226

DRILLING METHOD: Percusion

DATE DRILLED: 14.02.96



Brown medium grained sand
-UPPER KAROO

Maroon medium to coarse grained sandstone
-UPPER KAROO

Pinkish buff medium to coarse grained sandstone with red clay at 63m
-UPPER KAROO

Brown weathered pegmatitic granite
-BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT
KWEKWE

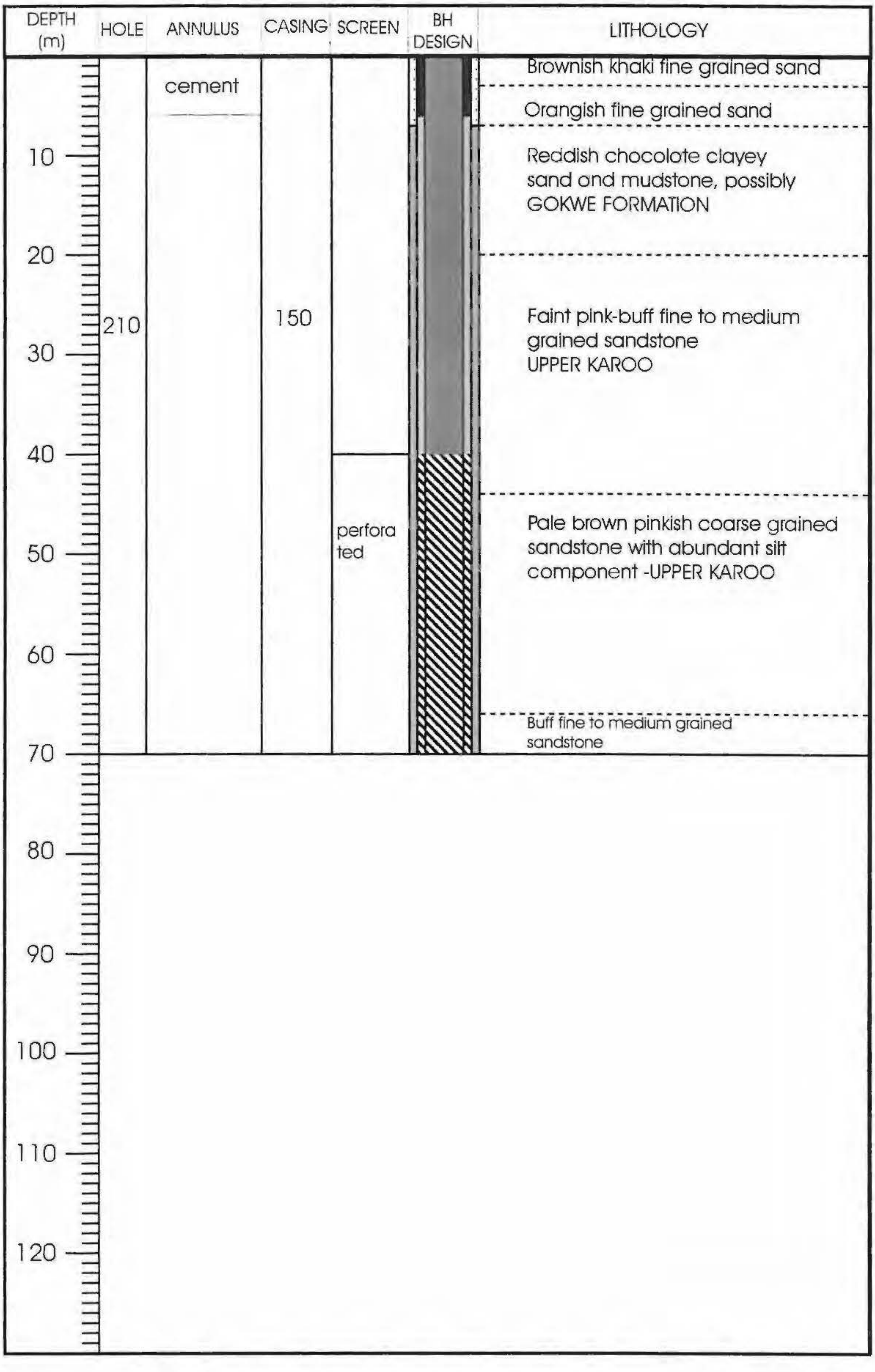
BH ID
6-KWEK-219

LOCALITY
Zanke

GRID REF
QK 352238

DRILLING METHOD
Percussion

DATE DRILLED
18.02.96



Brownish khaki fine grained sand

Orangish fine grained sand

Reddish chocolote clayey sand ond mudstone, possibly GOKWE FORMATION

Faint pink-buff fine to medium grained sandstone UPPER KAROO

Pale brown pinkish coarse grained sandstone with abundant silt component -UPPER KAROO

Buff fine to medium grained sandstone

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

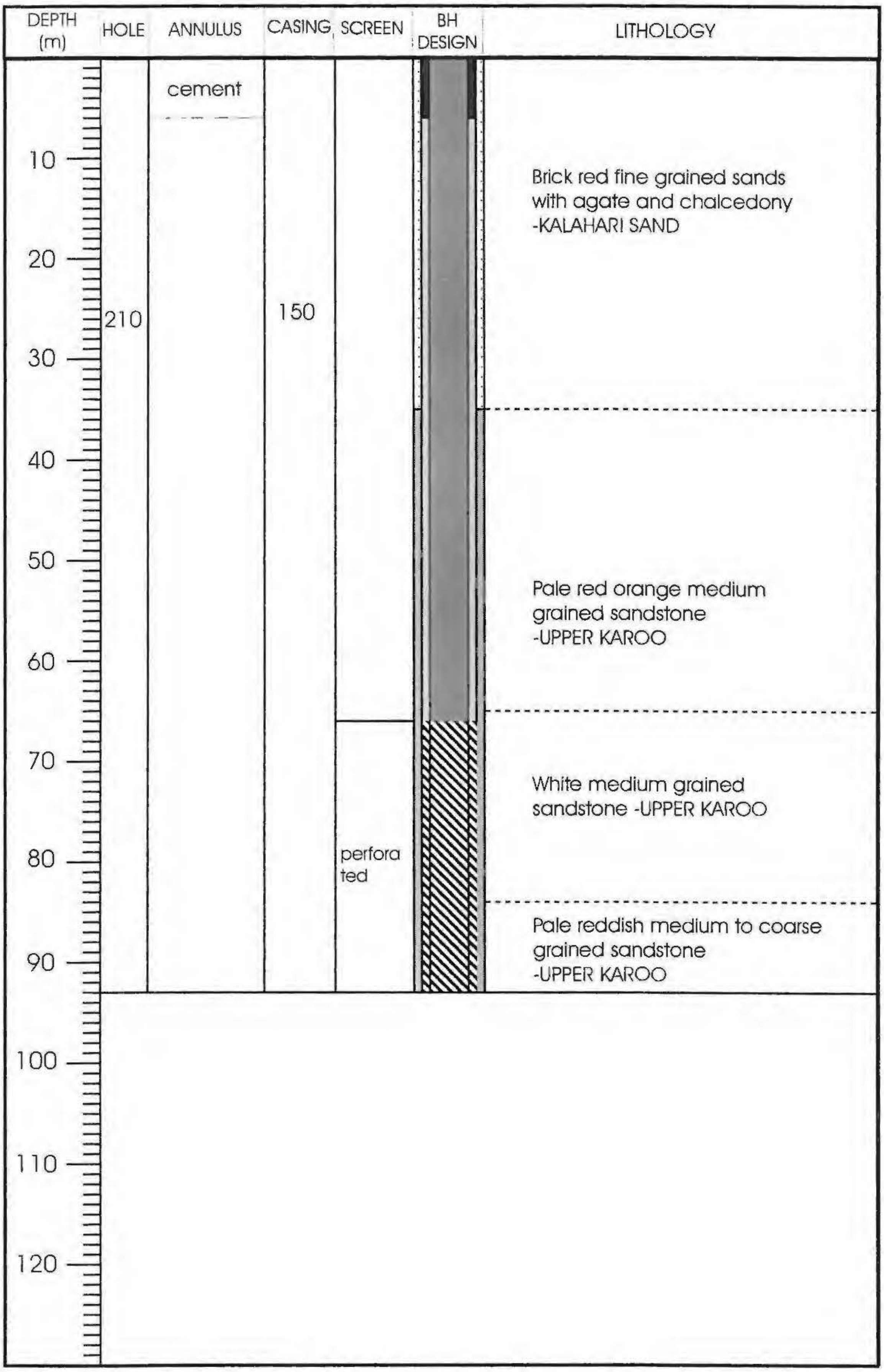
BH ID: 6-KWEK-220

LOCALITY: Ngomambi

GRID REF: QK 324298

DRILLING METHOD: Percusion

DATE DRILLED: 24.02.96



Brick red fine grained sands with agate and chalcedony -KALAHARI SAND

Pale red orange medium grained sandstone -UPPER KAROO

White medium grained sandstone -UPPER KAROO

Pale reddish medium to coarse grained sandstone -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

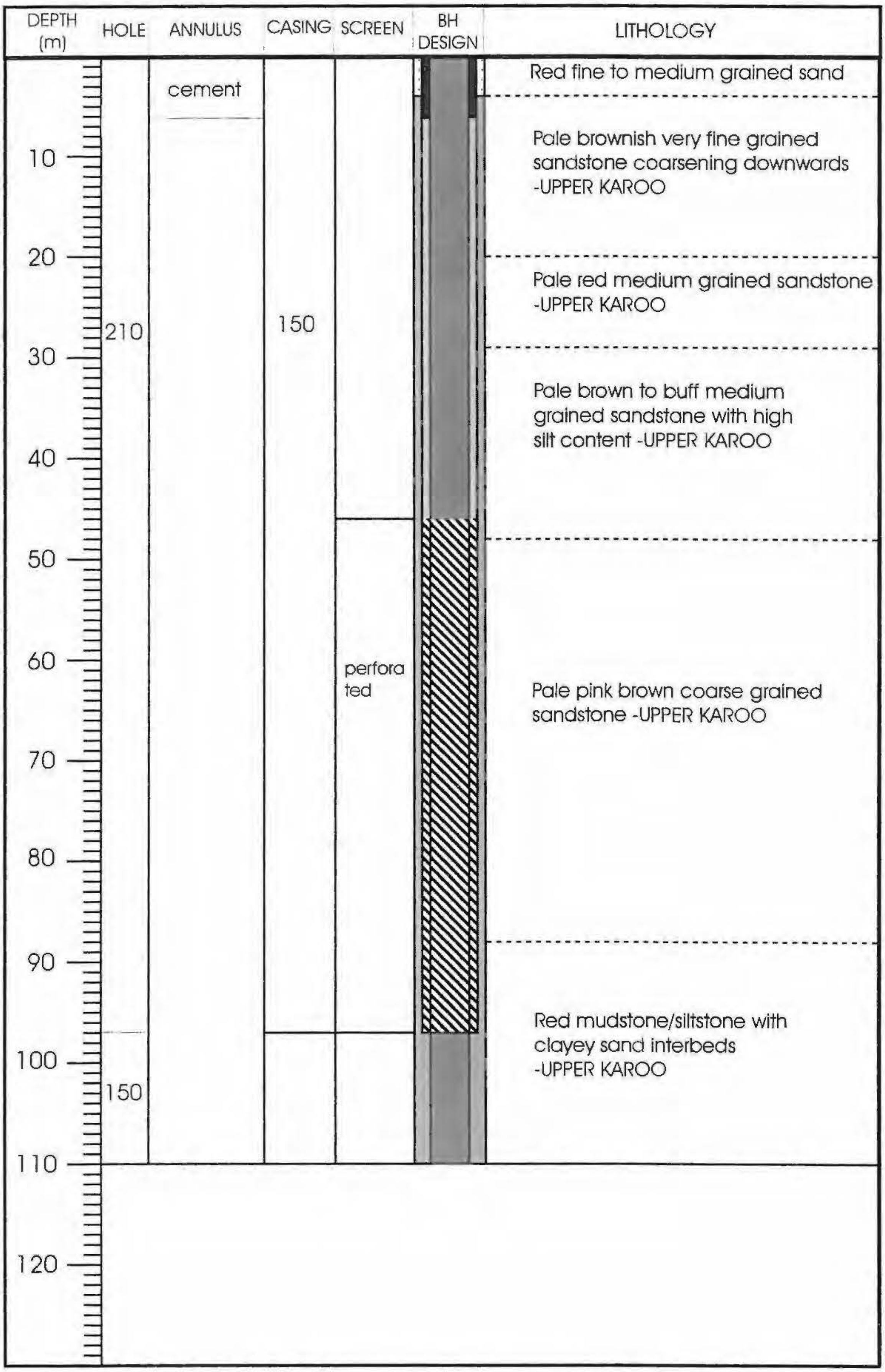
BH ID: 6-KWEK-221

LOCALITY: Sinangeni

GRID REF: QK 322309

DRILLING METHOD: Percussion

DATE DRILLED: 20.02.96



Red fine to medium grained sand

Pale brownish very fine grained sandstone coarsening downwards -UPPER KAROO

Pale red medium grained sandstone -UPPER KAROO

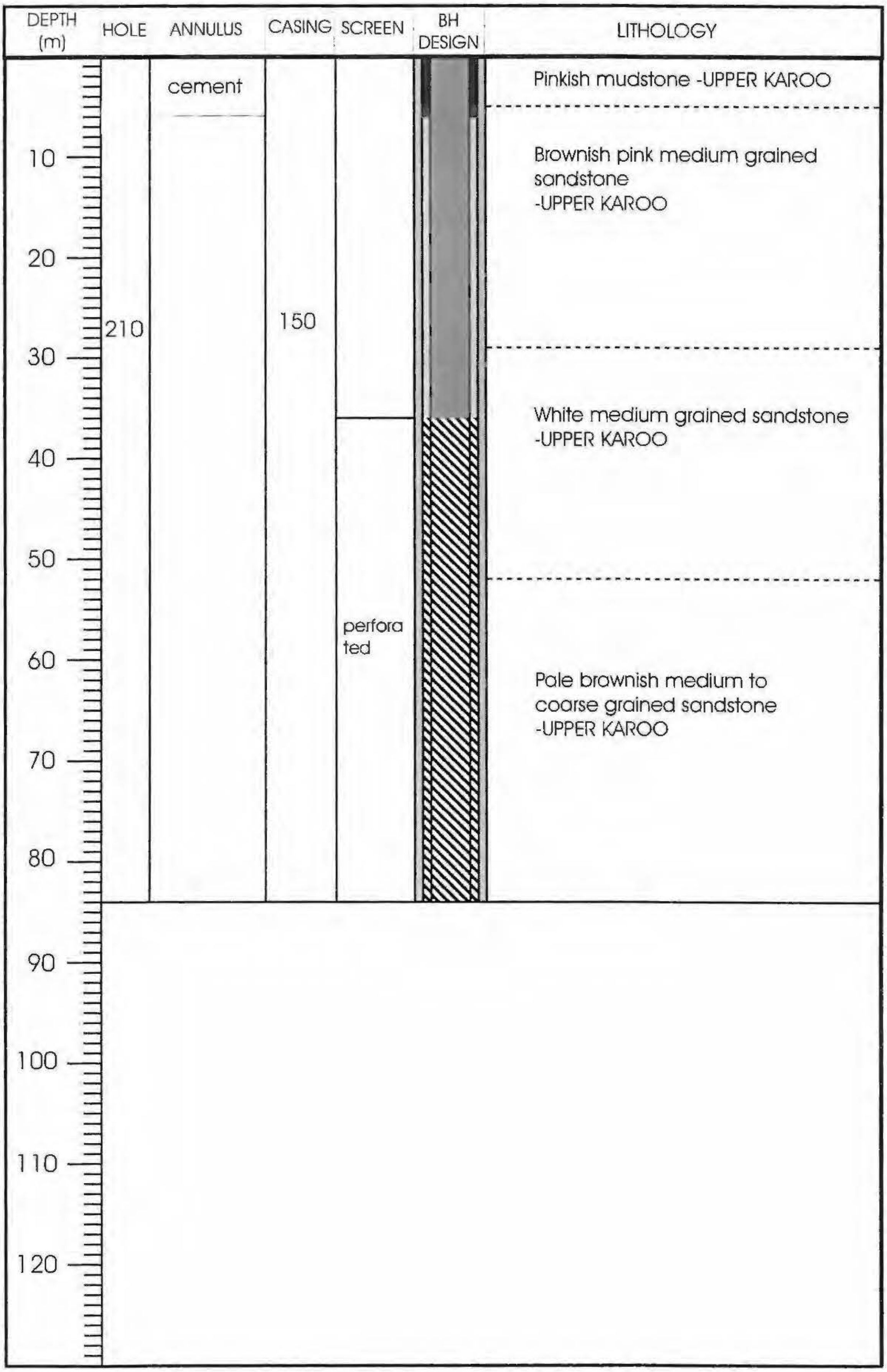
Pale brown to buff medium grained sandstone with high silt content -UPPER KAROO

Pale pink brown coarse grained sandstone -UPPER KAROO

Red mudstone/siltstone with clayey sand interbeds -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT	KWEKWE
BH ID	6-KWEK-223
LOCALITY	Kuwirirana
GRID REF	Qk335287
DRILLING METHOD	Percusion
DATE DRILLED	19.03.96



Pinkish mudstone -UPPER KAROO

Brownish pink medium grained sandstone -UPPER KAROO

White medium grained sandstone -UPPER KAROO

Pale brownish medium to coarse grained sandstone -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

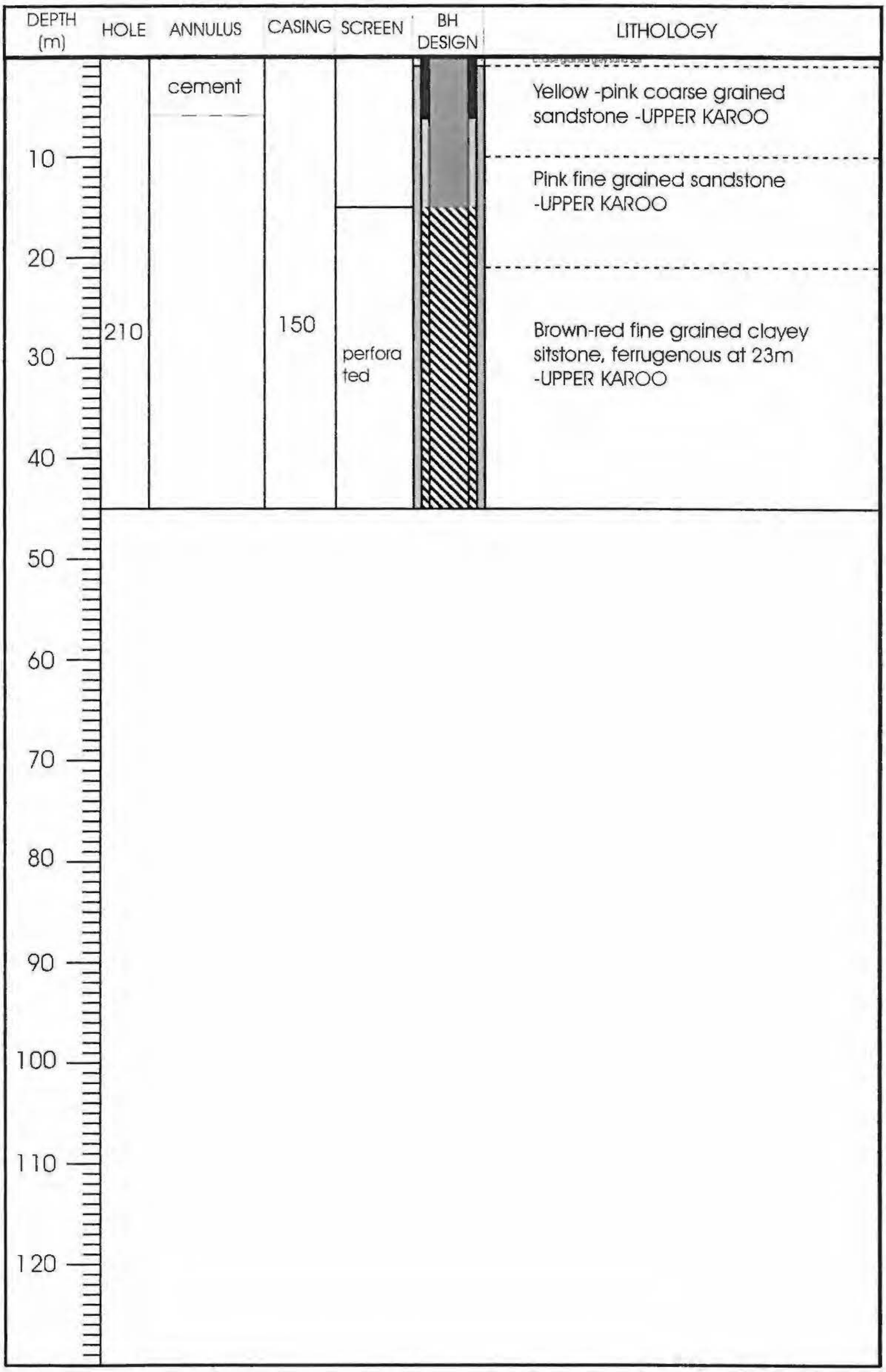
BH ID: 6-KWEK-

LOCALITY: Sakhululwa

GRID REF: Qk318369

DRILLING METHOD: Percusion

DATE DRILLED: 14.04.97



Coarse grained grey sand soil

Yellow -pink coarse grained sandstone -UPPER KAROO

Pink fine grained sandstone -UPPER KAROO

Brown-red fine grained clayey sitstone, ferrugenous at 23m -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

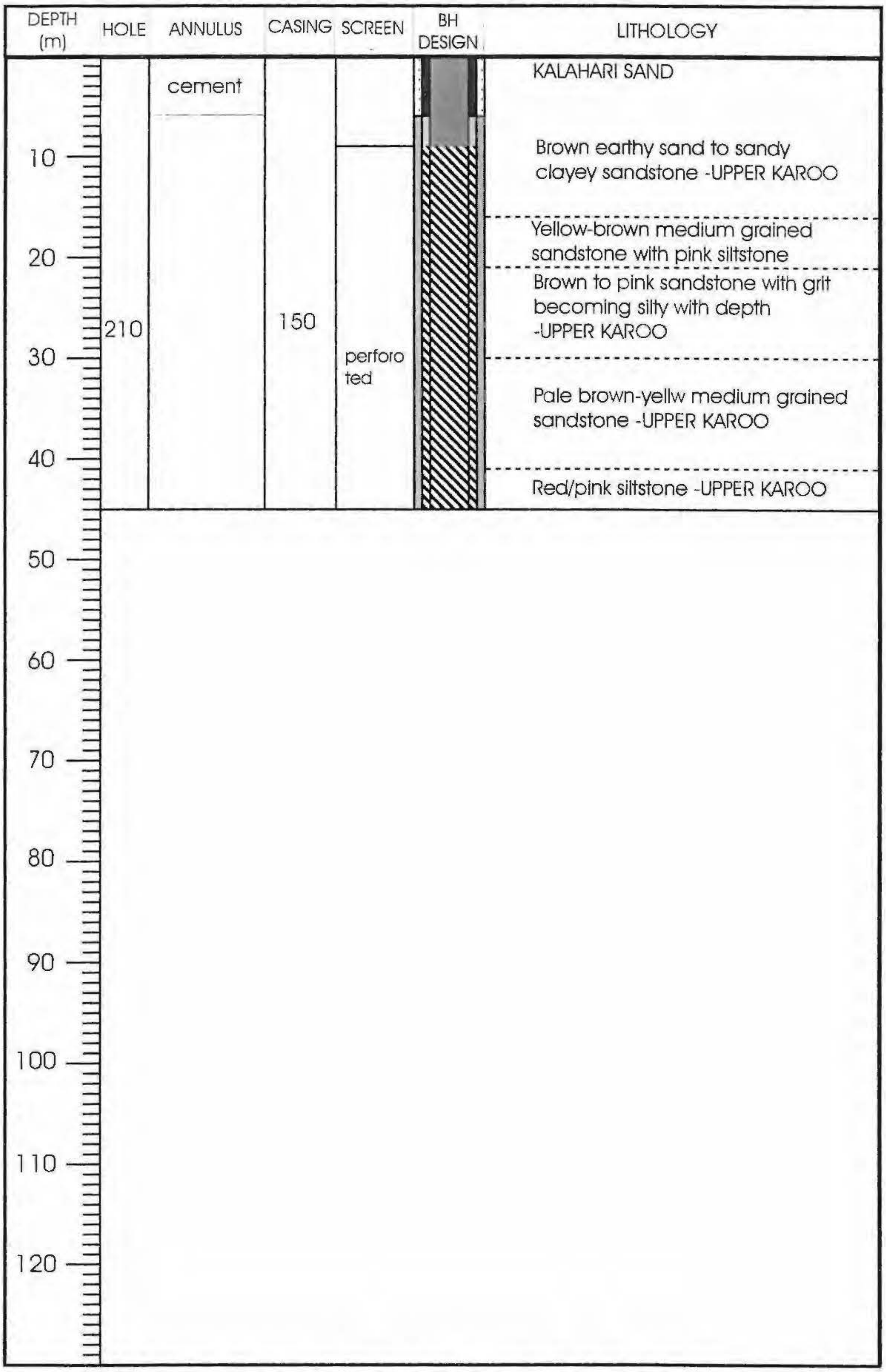
BH ID: 6-KWEK-240

LOCALITY: Simakani

GRID REF: QK 293378

DRILLING METHOD: Percusion

DATE DRILLED: 09.05.97



KALAHARI SAND

Brown earthy sand to sandy clayey sandstone -UPPER KAROO

Yellow-brown medium grained sandstone with pink siltstone

Brown to pink sandstone with grit becoming silty with depth -UPPER KAROO

Pale brown-yellw medium grained sandstone -UPPER KAROO

Red/pink siltstone -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

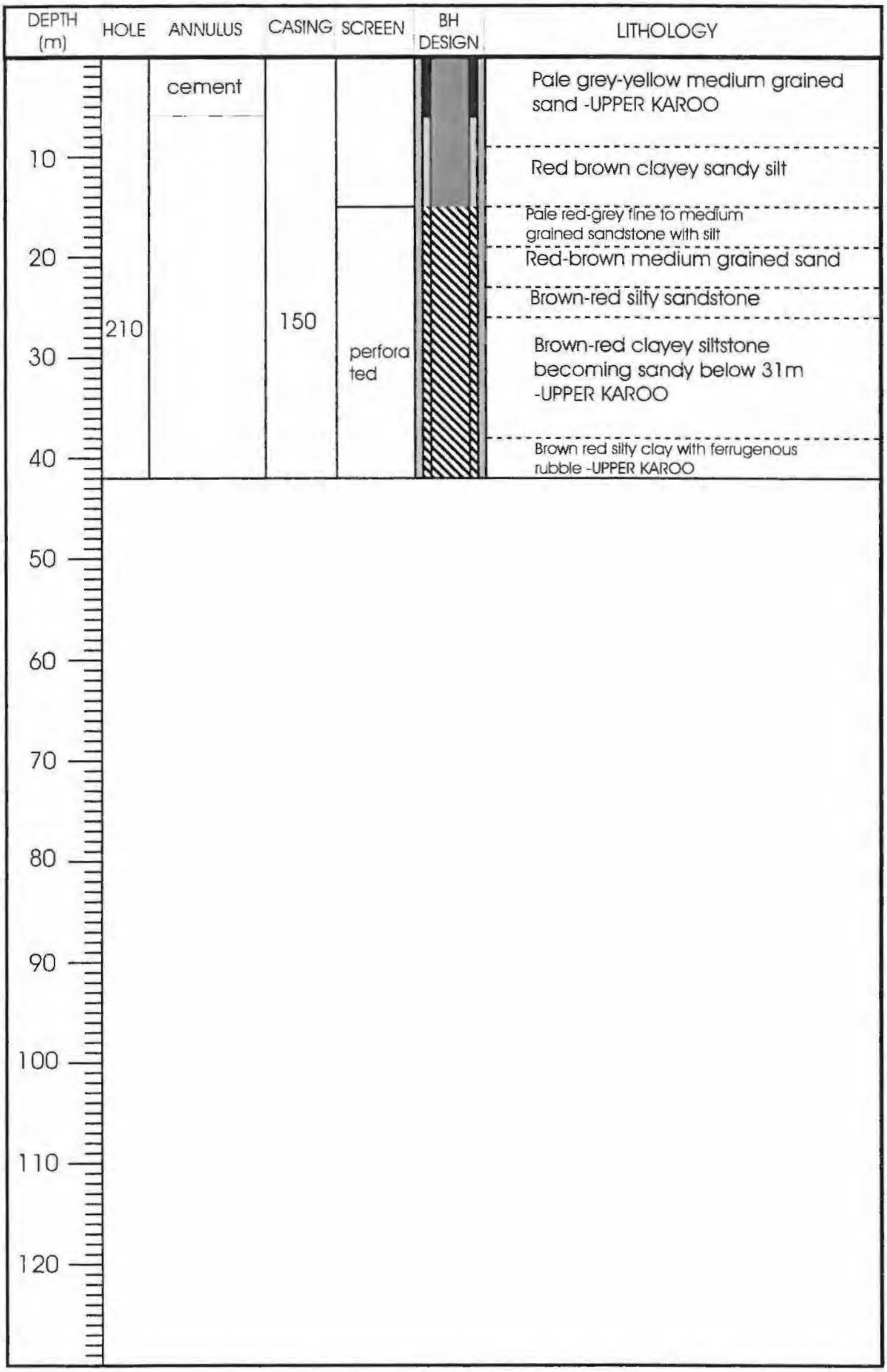
BH ID: 6-KWEK-241

LOCALITY: Chamatendera

GRID REF: QK 145355

DRILLING METHOD: Percusion

DATE DRILLED: 20.04.97



Pale grey-yellow medium grained sand -UPPER KAROO

Red brown clayey sandy silt

Pale red-grey fine to medium grained sandstone with silt

Red-brown medium grained sand

Brown-red silty sandstone

Brown-red clayey siltstone becoming sandy below 31m -UPPER KAROO

Brown red silty clay with ferrugenous rubble -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

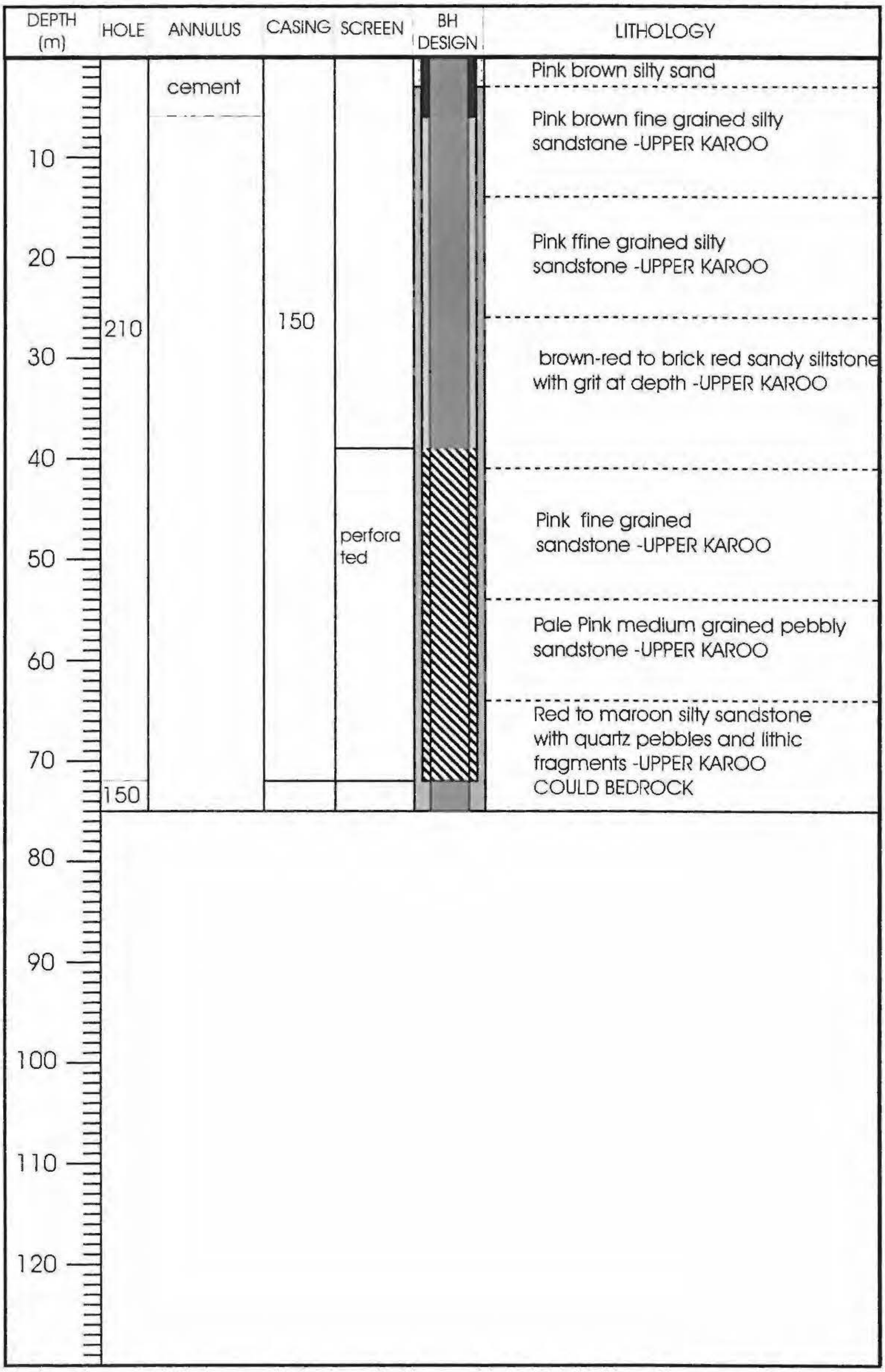
BH ID: 6-KWEK-243

LOCALITY: Meeting

GRID REF: QK 333375

DRILLING METHOD: Percussion

DATE DRILLED: 10.05.97



Pink brown silty sand

Pink brown fine grained silty sandstone -UPPER KAROO

Pink ffine grained silty sandstone -UPPER KAROO

brown-red to brick red sandy siltstone with grit at depth -UPPER KAROO

Pink fine grained sandstone -UPPER KAROO

Pale Pink medium grained pebbly sandstone -UPPER KAROO

Red to maroon silty sandstone with quartz pebbles and lithic fragments -UPPER KAROO COULD BEDROCK

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

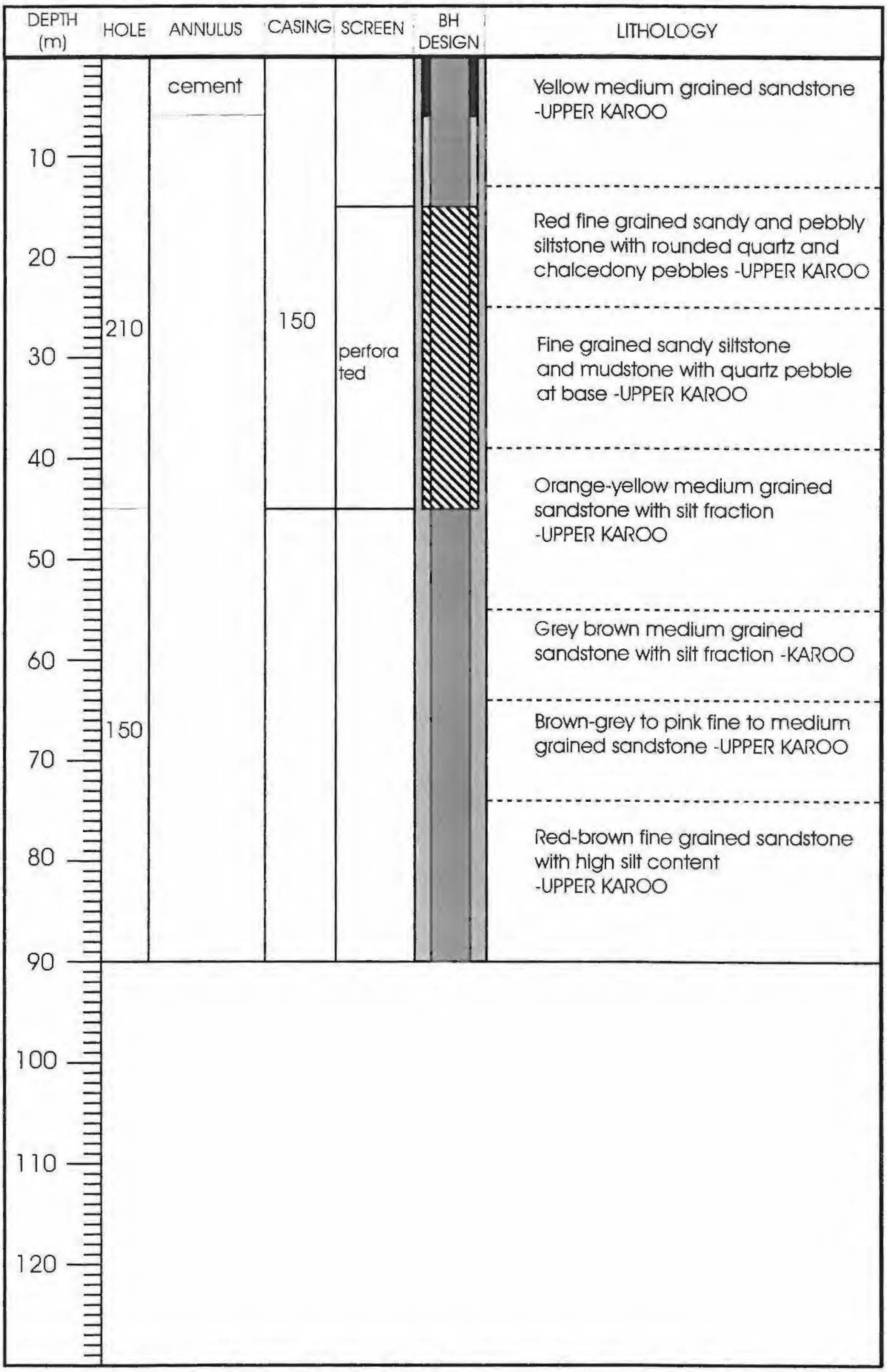
BH ID: 6-KWEK-247

LOCALITY: Ganyani

GRID REF: QK 123322

DRILLING METHOD: Percusion

DATE DRILLED: 09.04.97



Yellow medium grained sandstone -UPPER KAROO

Red fine grained sandy and pebbly siltstone with rounded quartz and chalcedony pebbles -UPPER KAROO

Fine grained sandy siltstone and mudstone with quartz pebble at base -UPPER KAROO

Orange-yellow medium grained sandstone with silt fraction -UPPER KAROO

Grey brown medium grained sandstone with silt fraction -KAROO

Brown-grey to pink fine to medium grained sandstone -UPPER KAROO

Red-brown fine grained sandstone with high silt content -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

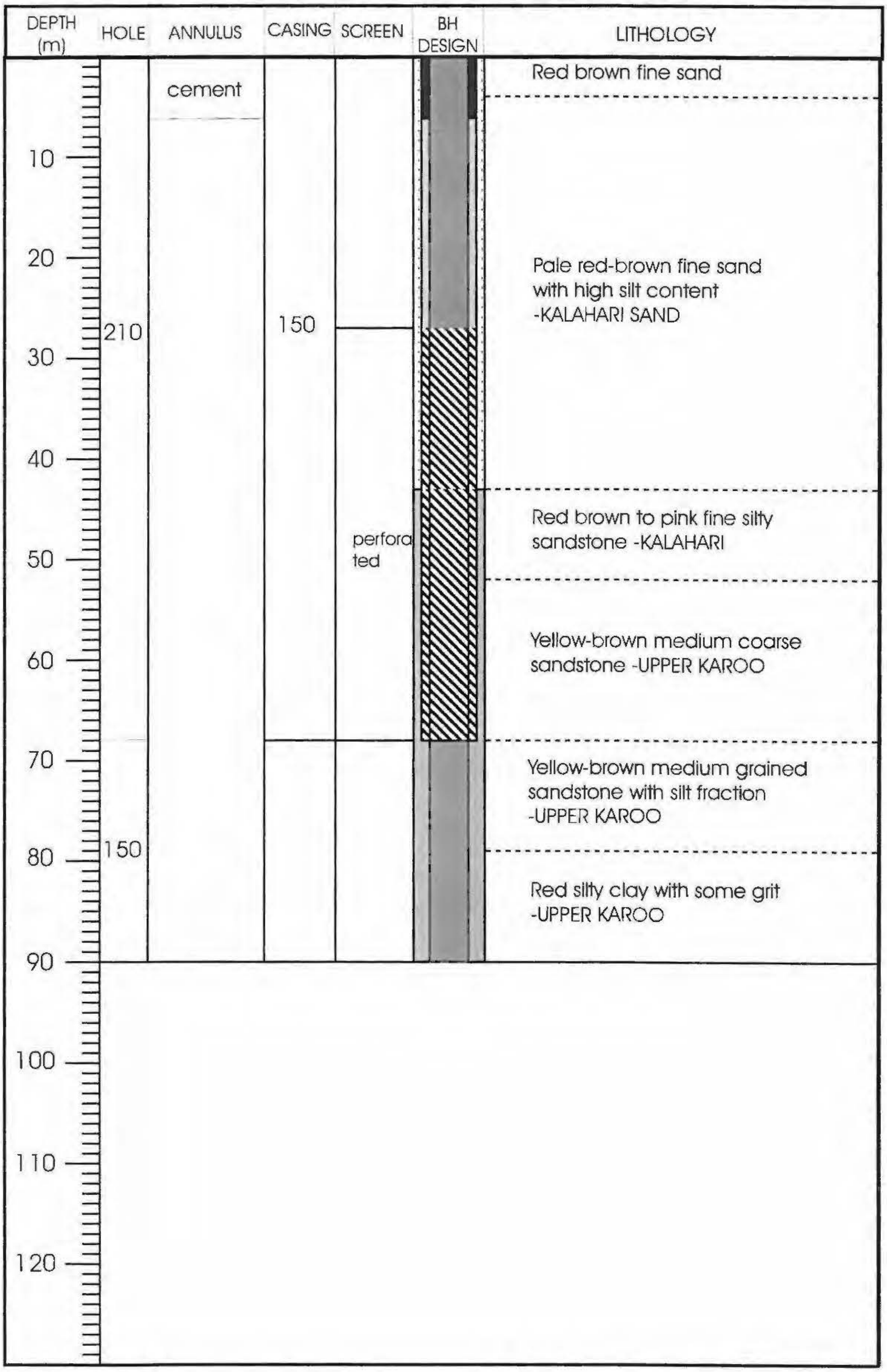
BH ID: 6-KWEK-248

LOCALITY: Makusu

GRID REF: Qk156313

DRILLING METHOD: Percusion

DATE DRILLED: 09.04.98



Red brown fine sand

Pale red-brown fine sand with high silt content -KALAHARI SAND

Red brown to pink fine silty sandstone -KALAHARI

Yellow-brown medium coarse sandstone -UPPER KAROO

Yellow-brown medium grained sandstone with silt fraction -UPPER KAROO

Red silty clay with some grit -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

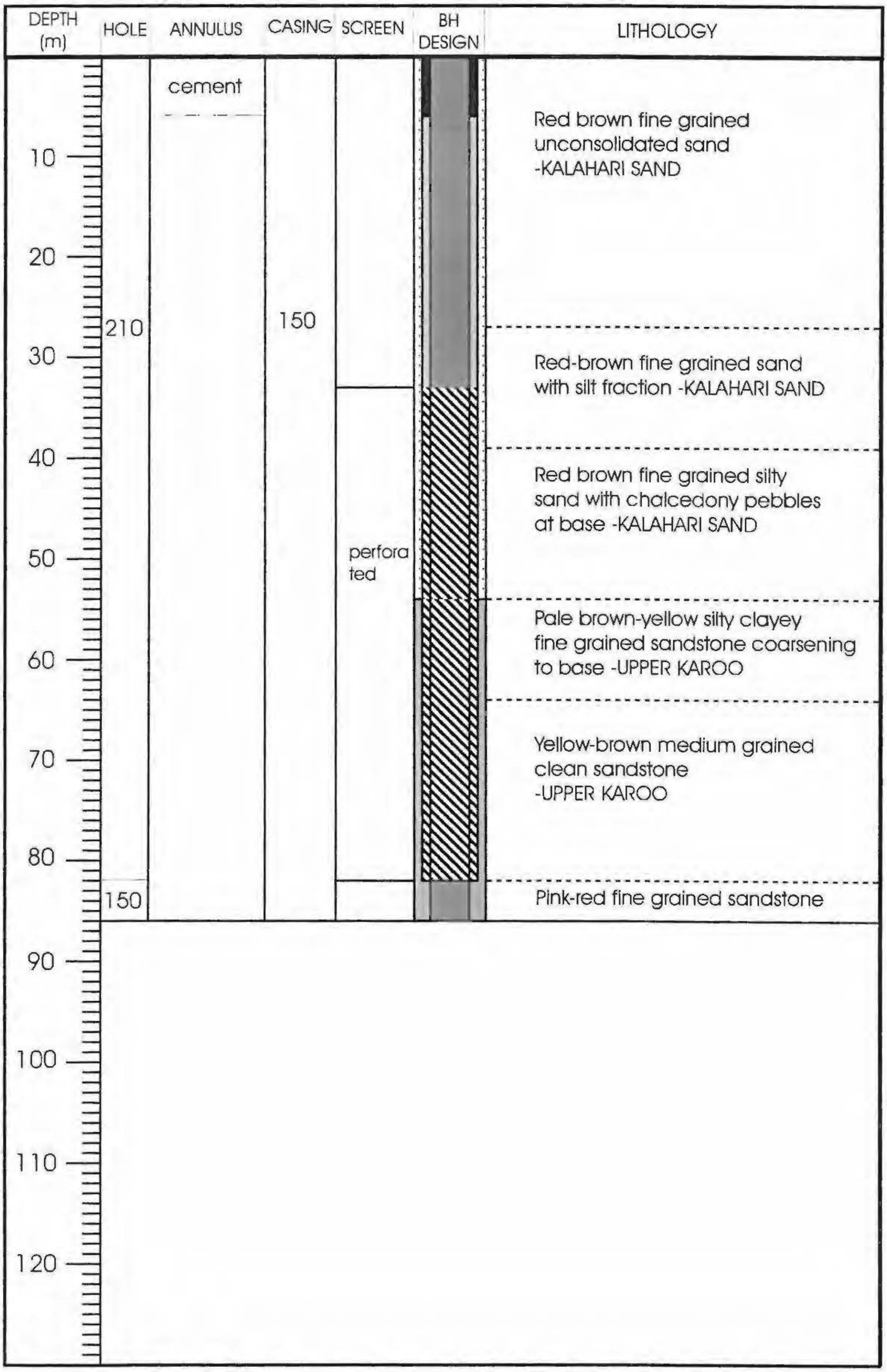
BH ID: 6-KWEK-250

LOCALITY: Thabisa

GRID REF: QK 211335

DRILLING METHOD: Percusion

DATE DRILLED: 29.04.97



Red brown fine grained unconsolidated sand -KALAHARI SAND

Red-brown fine grained sand with silt fraction -KALAHARI SAND

Red brown fine grained silty sand with chalcedony pebbles at base -KALAHARI SAND

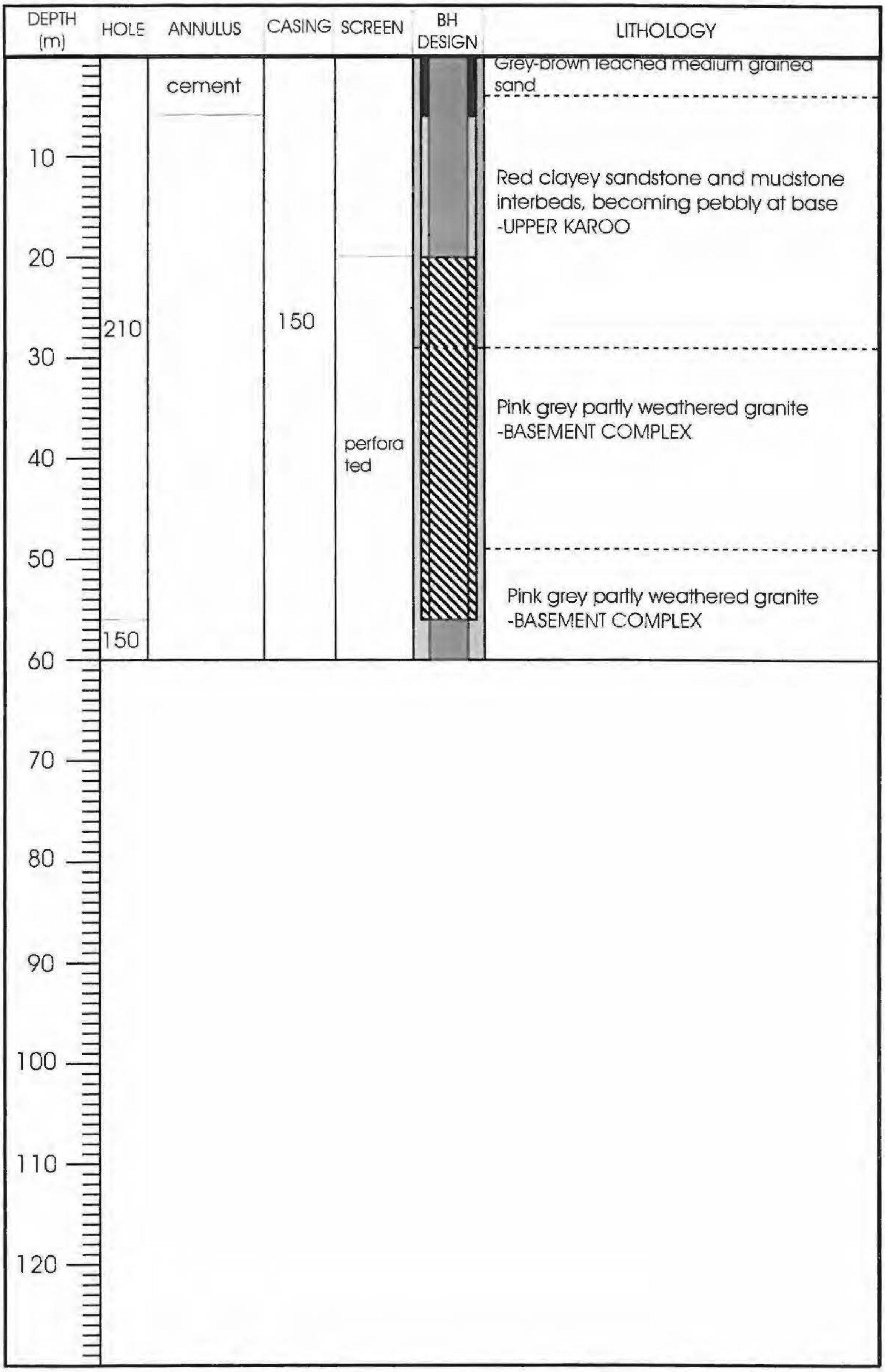
Pale brown-yellow silty clayey fine grained sandstone coarsening to base -UPPER KAROO

Yellow-brown medium grained clean sandstone -UPPER KAROO

Pink-red fine grained sandstone

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT			BH ID
KWEKWE			6-KWEK-256
LOCALITY	GRID REF	DRILLING METHOD	DATE DRILLED
Ndege	QK 120320	AIR/DTH	29.01.95



Grey-brown leached medium grained sand

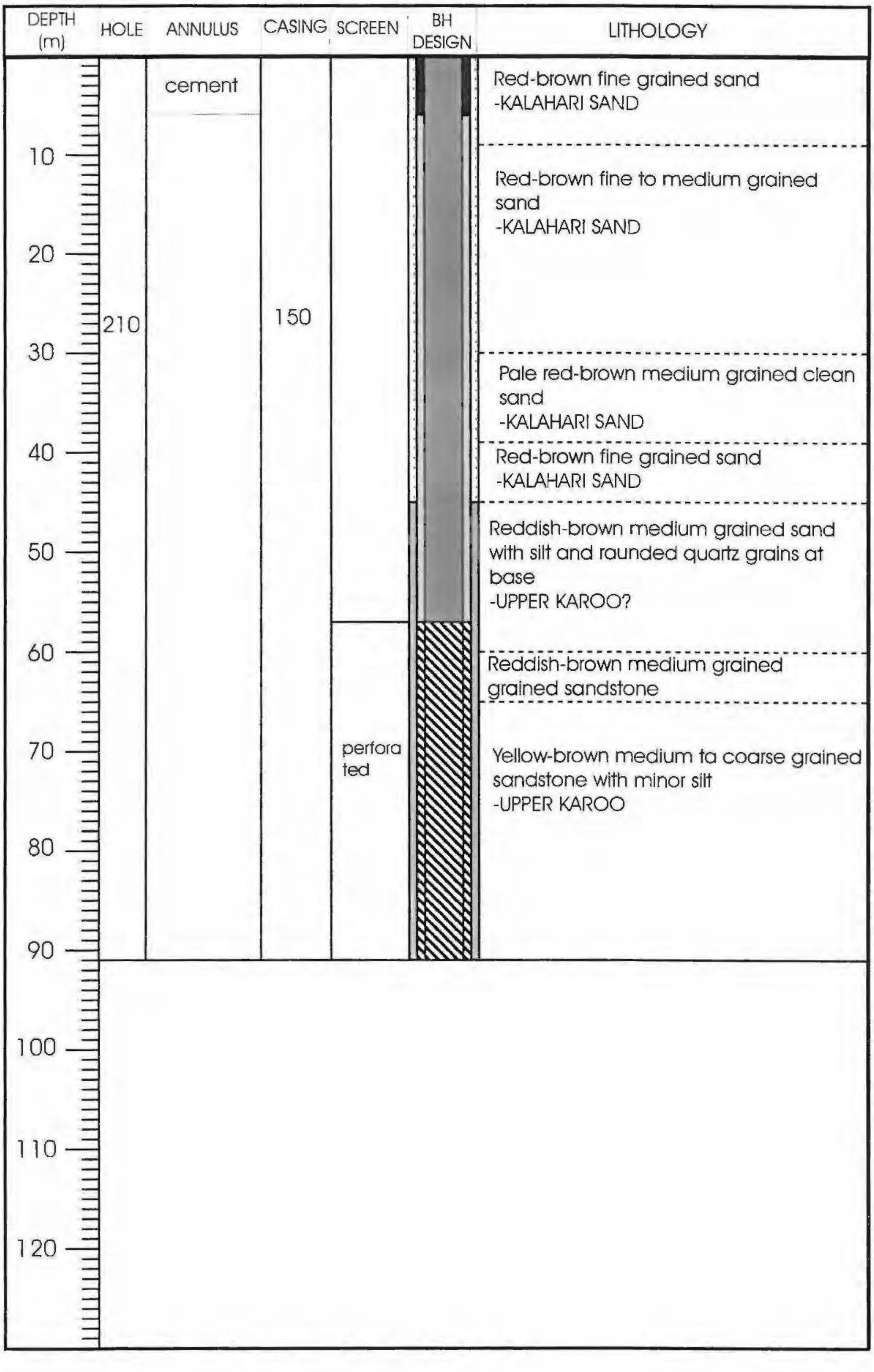
Red clayey sandstone and mudstone interbeds, becoming pebbly at base -UPPER KAROO

Pink grey partly weathered granite -BASEMENT COMPLEX

Pink grey partly weathered granite -BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT	KWEKWE
BH ID	6-KWEK-257
LOCALITY	Dendera Sec. Sch
GRID REF	QK 209309
DRILLING METHOD	Percusion
DATE DRILLED	09.04.97



Red-brown fine grained sand
-KALAHARI SAND

Red-brown fine to medium grained sand
-KALAHARI SAND

Pale red-brown medium grained clean sand
-KALAHARI SAND

Red-brown fine grained sand
-KALAHARI SAND

Reddish-brown medium grained sand with silt and rounded quartz grains at base
-UPPER KAROO?

Reddish-brown medium grained grained sandstone

Yellow-brown medium to coarse grained sandstone with minor silt
-UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

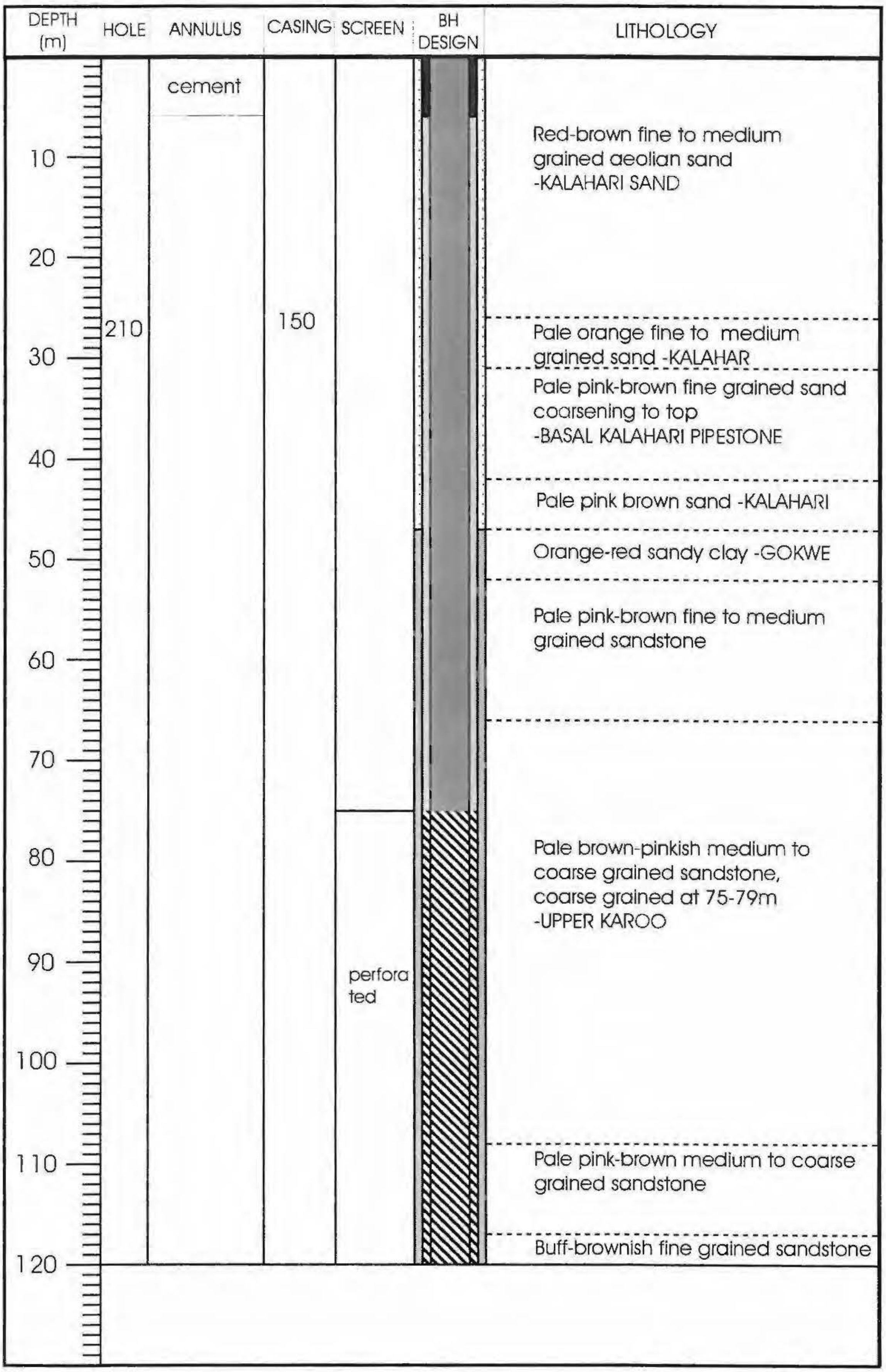
BH ID: 6-KWEK-

LOCALITY: Mloyiswa

GRID REF: QK 253304

DRILLING METHOD: Percusion

DATE DRILLED: 14.05.99



Red-brown fine to medium grained aeolian sand -KALAHARI SAND

Pale orange fine to medium grained sand -KALAHAR

Pale pink-brown fine grained sand coarsening to top -BASAL KALAHARI PIPESTONE

Pale pink brown sand -KALAHARI

Orange-red sandy clay -GOKWE

Pale pink-brown fine to medium grained sandstone

Pale brown-pinkish medium to coarse grained sandstone, coarse grained at 75-79m -UPPER KAROO

Pale pink-brown medium to coarse grained sandstone

Buff-brownish fine grained sandstone

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

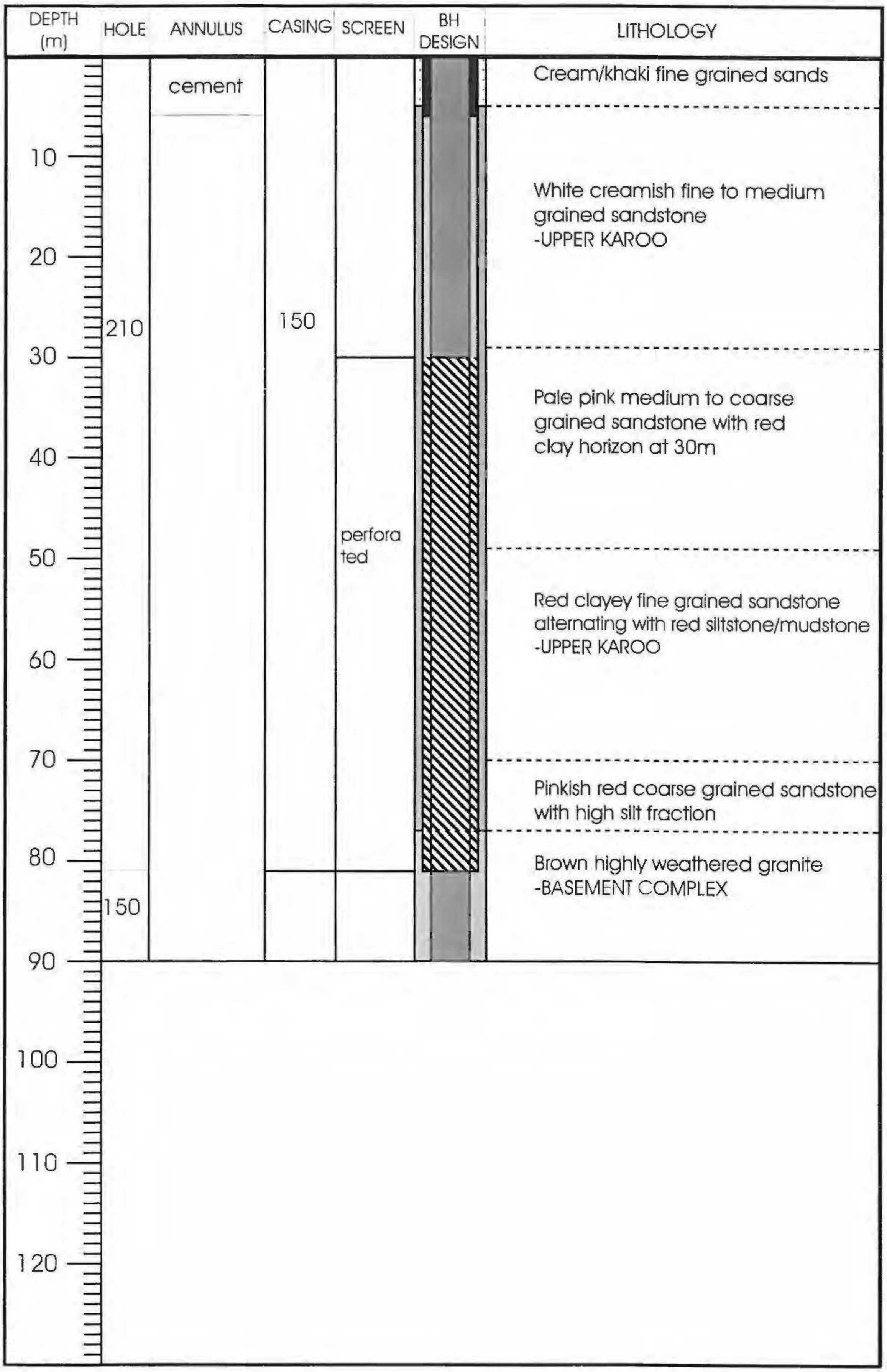
BH ID: 6-KWEK-

LOCALITY: Newline

GRID REF: QK 123322

DRILLING METHOD: Percusion

DATE DRILLED: 09.04.97



Cream/khaki fine grained sands

White creamish fine to medium grained sandstone
-UPPER KAROO

Pale pink medium to coarse grained sandstone with red clay horizon at 30m

Red clayey fine grained sandstone alternating with red siltstone/mudstone
-UPPER KAROO

Pinkish red coarse grained sandstone with high silt fraction

Brown highly weathered granite
-BASEMENT COMPLEX

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

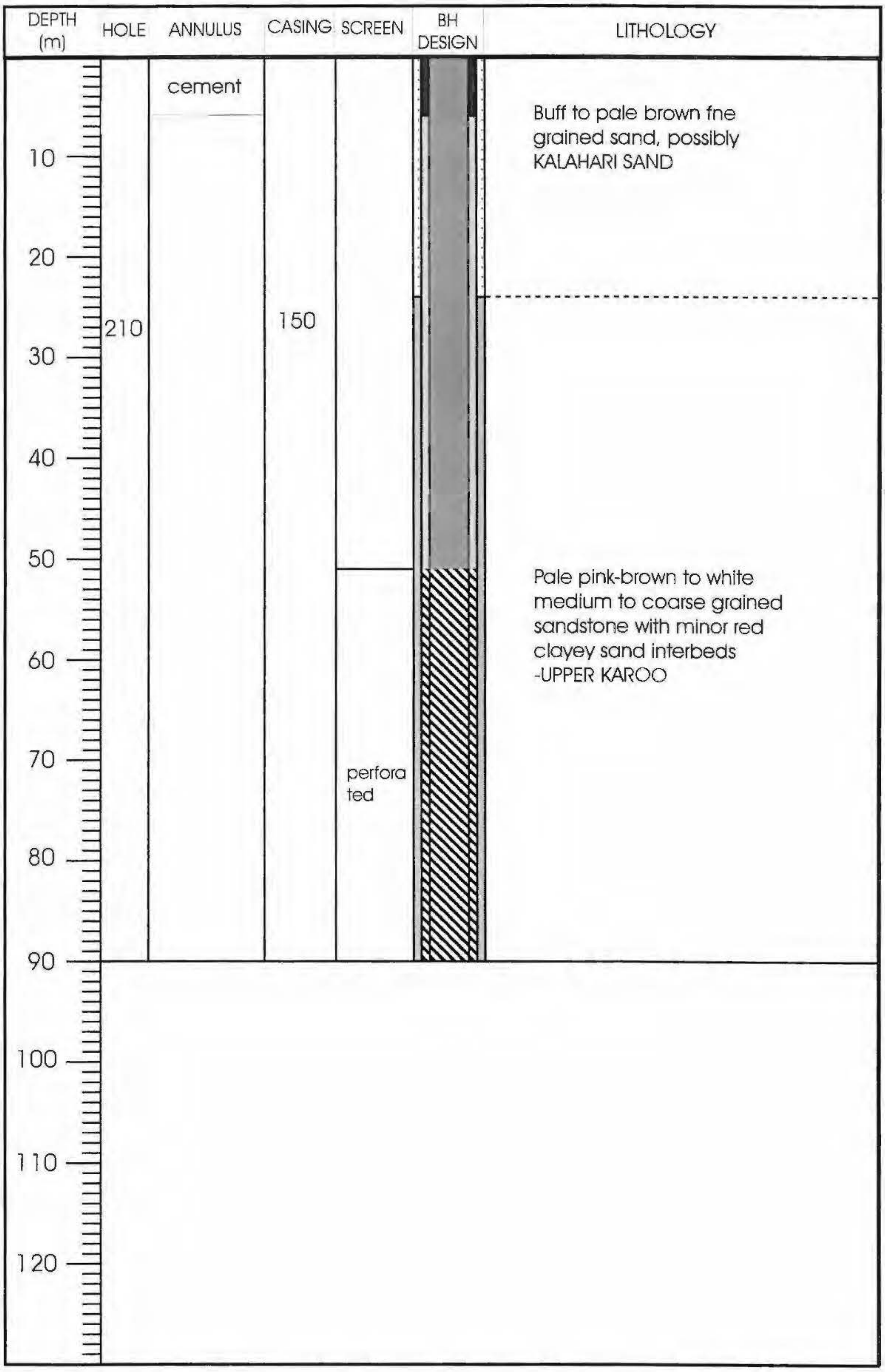
BH ID: 6-KWEK-

LOCALITY: Dalamayezi

GRID REF: Qk307248

DRILLING METHOD: Percusion

DATE DRILLED: 25.01.95



Buff to pale brown fne grained sand, possibly KALAHARI SAND

Pale pink-brown to white medium to coarse grained sandstone with minor red clayey sand interbeds -UPPER KAROO

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

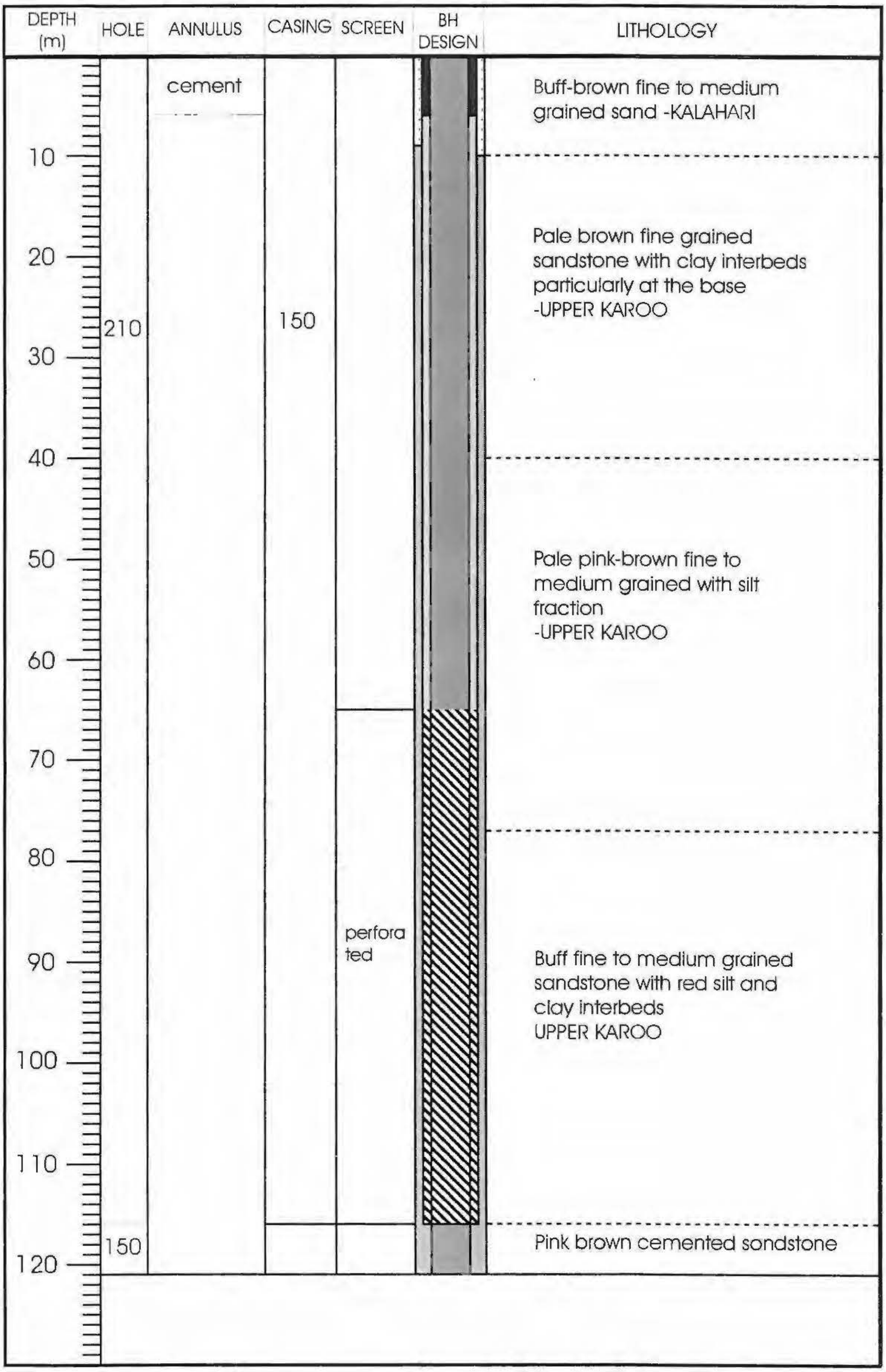
BH ID: 6-KWEK-

LOCALITY: Bhobho

GRID REF: Qk293275

DRILLING METHOD: Percusion

DATE DRILLED: 02.11.94



Buff-brown fine to medium grained sand -KALAHARI

Pale brown fine grained sandstone with clay interbeds particularly at the base -UPPER KAROO

Pale pink-brown fine to medium grained with silt fraction -UPPER KAROO

Buff fine to medium grained sandstone with red silt and clay interbeds UPPER KAROO

Pink brown cemented sondstone

WELL LOG : LITHOLOGY & CONSTRUCTION

DISTRICT: KWEKWE

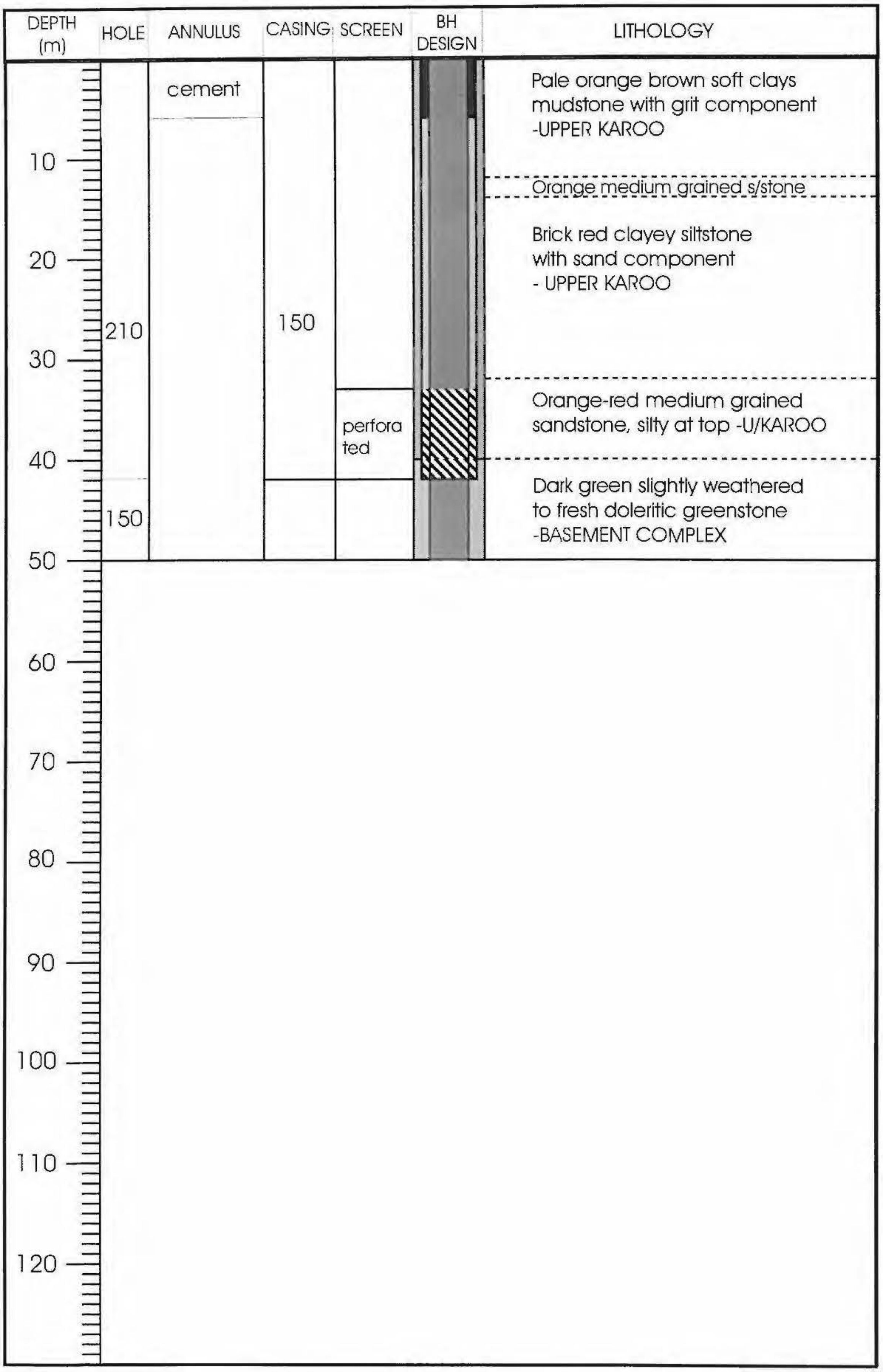
BH ID: 6-KWEK-

LOCALITY: Gwaba

GRID REF: QK 335386

DRILLING METHOD: Percussion

DATE DRILLED: 29.04.97



Pale orange brown soft clays mudstone with grit component -UPPER KAROO

Orange medium grained s/stone

Brick red clayey siltstone with sand component - UPPER KAROO

Orange-red medium grained sandstone, silty at top -U/KAROO

Dark green slightly weathered to fresh doleritic greenstone -BASEMENT COMPLEX

APPENDIX 2

PUMPING TEST DATA AND INTERPRETATIONS

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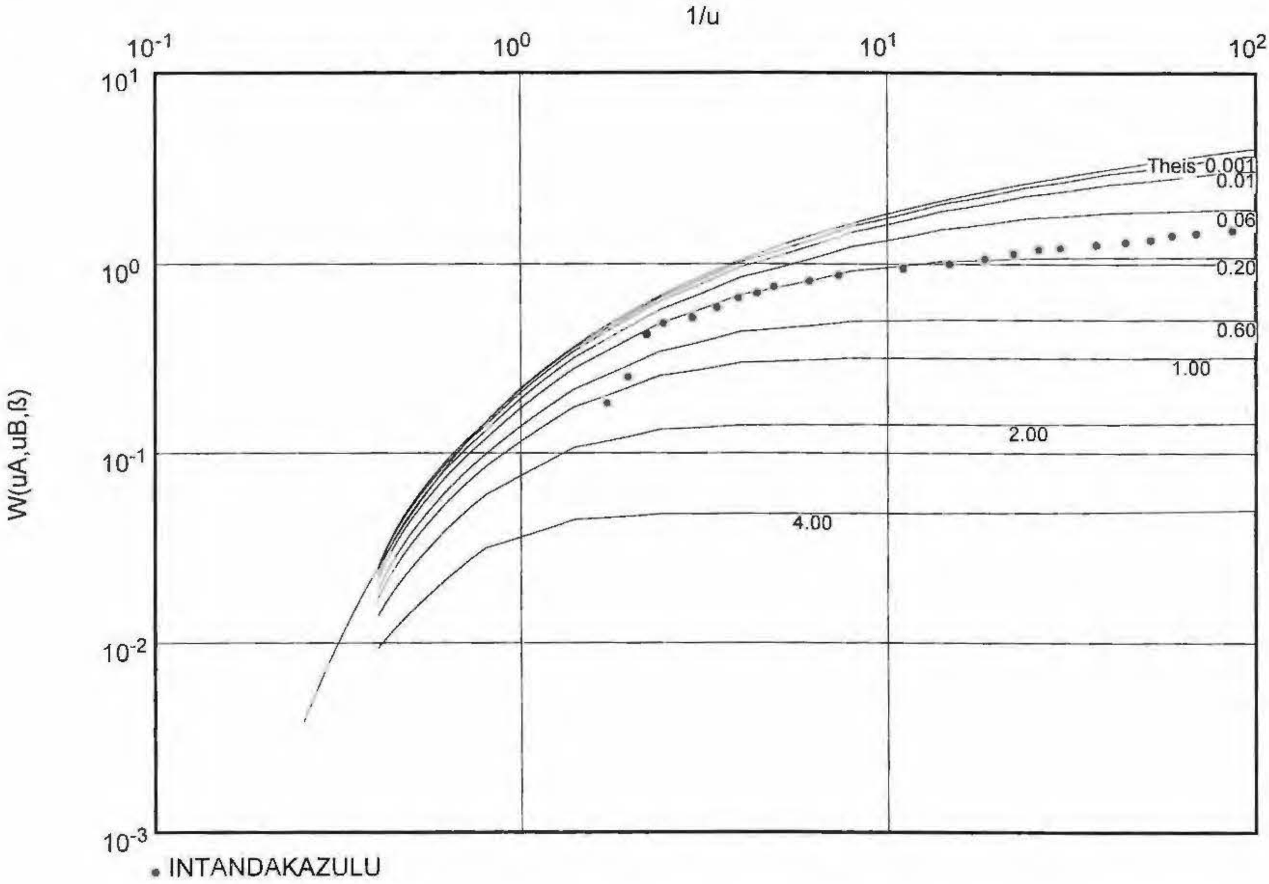
Pumping Test No. 6 KWEK-204	Test conducted on: 21.10.1999
Discharge 1.00 l/s	



Transmissivity [m²/d]: 4.33×10^{0}

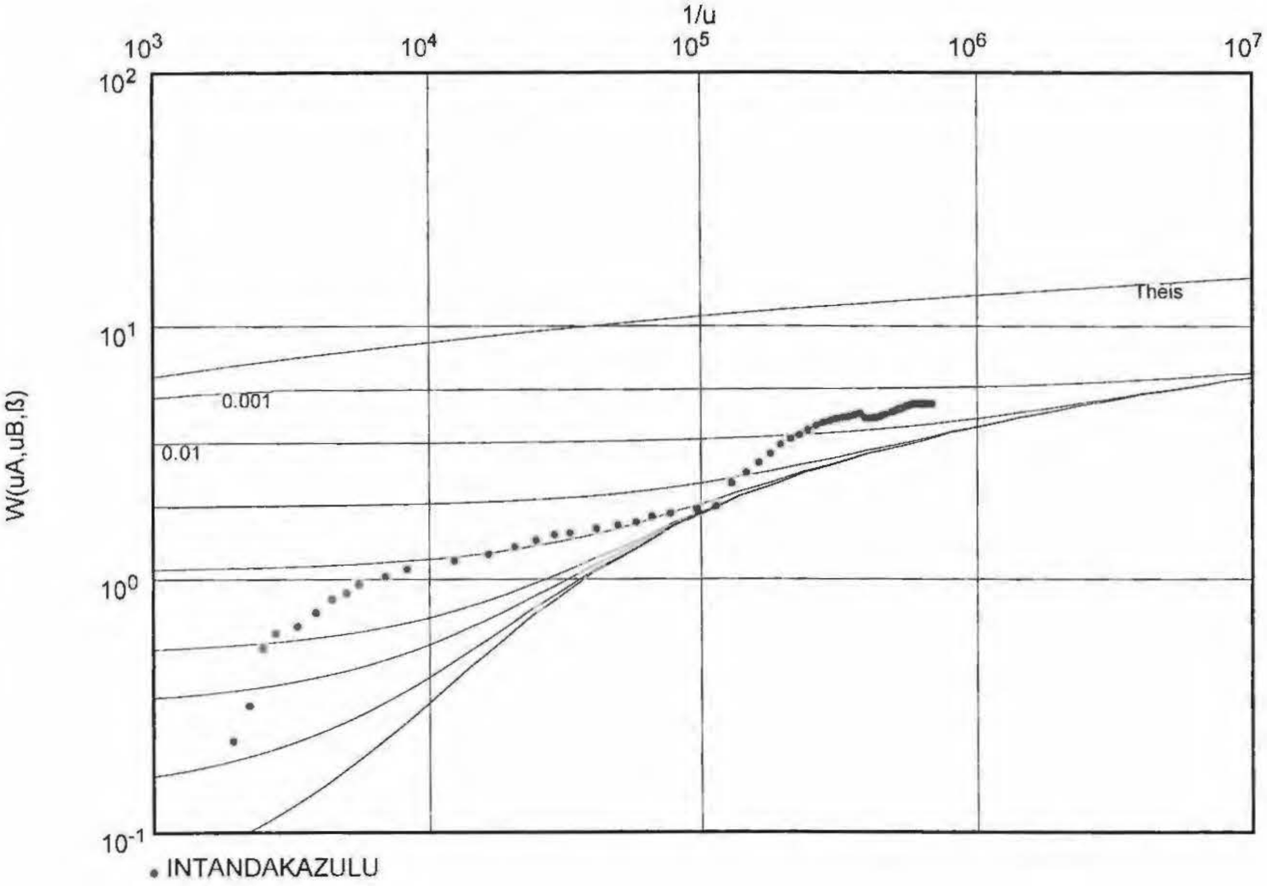
Hydraulic conductivity [m/d]: 3.33×10^{-1}

Aquifer thickness [m]: 13.000

Storativity: 4.89×10^{4}

Waterloo Hydrogeologi 180 Columbia St. W. Waterloo,Ontario,Canada ph.(519)746-1798	Pumping test analysis NEUMAN's method Unconfined aquifer with delayed watertable response	Page 1 Project: MSc Thesis Evaluated by: JTN / Date: 25.10.1999

Pumping Test No. 6 KWEK-204	Test conducted on: 21.10.1999
Discharge 1.00 l/s	



Transmissivity [m²/d]: 5.46 x 10^0

Hydraulic conductivity [m/d]: 4.20 x 10^{-1}

Aquifer thickness [m]: 13.000

Storativity: 5.48 x 10^1

Pumping Test No. 6 KWEK-204

Test conducted on: 21.10.1999

INTANDAKAZULU

Discharge 1.00 l/s

Distance from the pumping well 0.001 m

Static water level: 53.100 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00486	53.390	0.290	
2	0.00556	53.500	0.400	
3	0.00625	53.770	0.670	
4	0.00694	53.870	0.770	
5	0.00833	53.920	0.820	
6	0.00972	54.030	0.930	
7	0.01111	54.150	1.050	
8	0.01250	54.210	1.110	
9	0.01389	54.300	1.200	
10	0.01736	54.390	1.290	
11	0.02083	54.480	1.380	
12	0.03125	54.590	1.490	
13	0.04167	54.680	1.580	
14	0.05208	54.790	1.690	
15	0.06250	54.900	1.800	
16	0.07292	54.990	1.890	
17	0.08333	55.020	1.920	
18	0.10417	55.100	2.000	
19	0.12500	55.160	2.060	
20	0.14583	55.220	2.120	
21	0.16667	55.330	2.230	
22	0.19444	55.390	2.290	
23	0.24306	55.470	2.370	
24	0.28472	55.540	2.440	
25	0.32639	56.110	3.010	
26	0.36806	56.420	3.320	
27	0.40972	56.740	3.640	
28	0.45139	57.050	3.950	
29	0.49306	57.390	4.290	
30	0.53472	57.630	4.530	
31	0.57639	57.800	4.700	
32	0.61806	58.020	4.920	
33	0.65972	58.210	5.110	
34	0.70139	58.370	5.270	
35	0.74306	58.440	5.340	
36	0.78472	58.560	5.460	
37	0.82639	58.610	5.510	
38	0.86806	58.640	5.540	
39	0.90972	58.750	5.650	
40	0.95139	58.820	5.720	
41	0.99306	58.580	5.480	
42	1.03472	58.580	5.480	
43	1.07639	58.590	5.490	
44	1.11806	58.650	5.550	
45	1.15972	58.750	5.650	
46	1.22917	58.870	5.770	
47	1.27083	58.940	5.840	
48	1.31250	59.070	5.970	
49	1.35417	59.090	5.990	
50	1.39583	59.230	6.130	

Pumping Test No. 6 KWEK-204

Test conducted on: 21.10.1999

INTANDAKAZULU

Discharge 1.00 l/s

Distance from the pumping well 0.001 m

Static water level: 53.100 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
51	1.43750	59.270	6.170	
52	1.47917	59.330	6.230	
53	1.52083	59.330	6.230	
54	1.56250	59.330	6.230	
55	1.60417	59.330	6.230	
56	1.64583	59.330	6.230	
57	1.68750	59.330	6.230	
58	1.72917	59.330	6.230	

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Pumping test analysis
Recovery method after
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Project: MSc Thesis

Evaluated by: JTN

Date: 24.03.1999

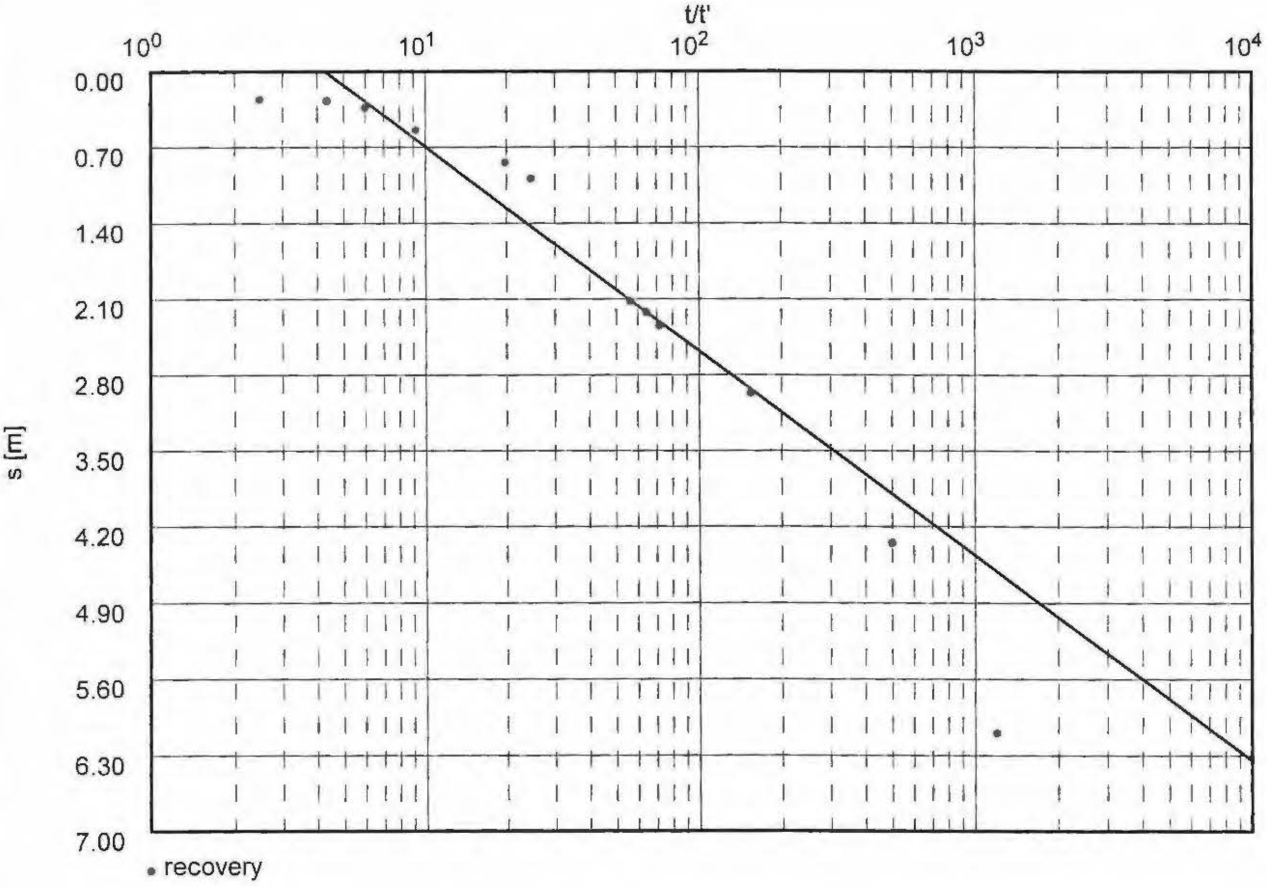
Pumping Test No. 6 KWEK-204

Test conducted on: 21.10.1999

Inthandokazulu

Discharge 1.00 l/s

Pumping test duration: 1.66667 d



Transmissivity [m²/d]: 8.39 x 10^0

Hydraulic conductivity [m/d]: 6.45 x 10^{-1}

Aquifer thickness [m]: 13.000

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Pumping test analysis
Recovery method after
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Unconfined aquifer

Project: MSc Thesis

Evaluated by: JTN | Date: 24.03.1999

Pumping Test No. 6 KWEK-204 | Test conducted on: 21.10.1999

Inthandokazulu | recovery

Discharge 1.00 l/s

Static water level: 0.000 m below datum | Pumping test duration: 1.66667 d

	Time from end of pumping [d]	Water level [m]	Residual drawdown [m]	Corrected drawdown [m]
2	0.00139	9.750	9.750	6.094
3	0.00333	5.520	5.520	4.348
4	0.01086	3.420	3.420	2.970
5	0.02357	2.610	2.610	2.348
6	0.02627	2.450	2.450	2.219
7	0.03006	2.330	2.330	2.121
8	0.07037	1.030	1.030	0.989
9	0.08848	0.870	0.870	0.841
10	0.20323	0.550	0.550	0.538
11	0.33326	0.340	0.340	0.336
12	0.49550	0.270	0.270	0.267
13	1.12574	0.260	0.260	0.257

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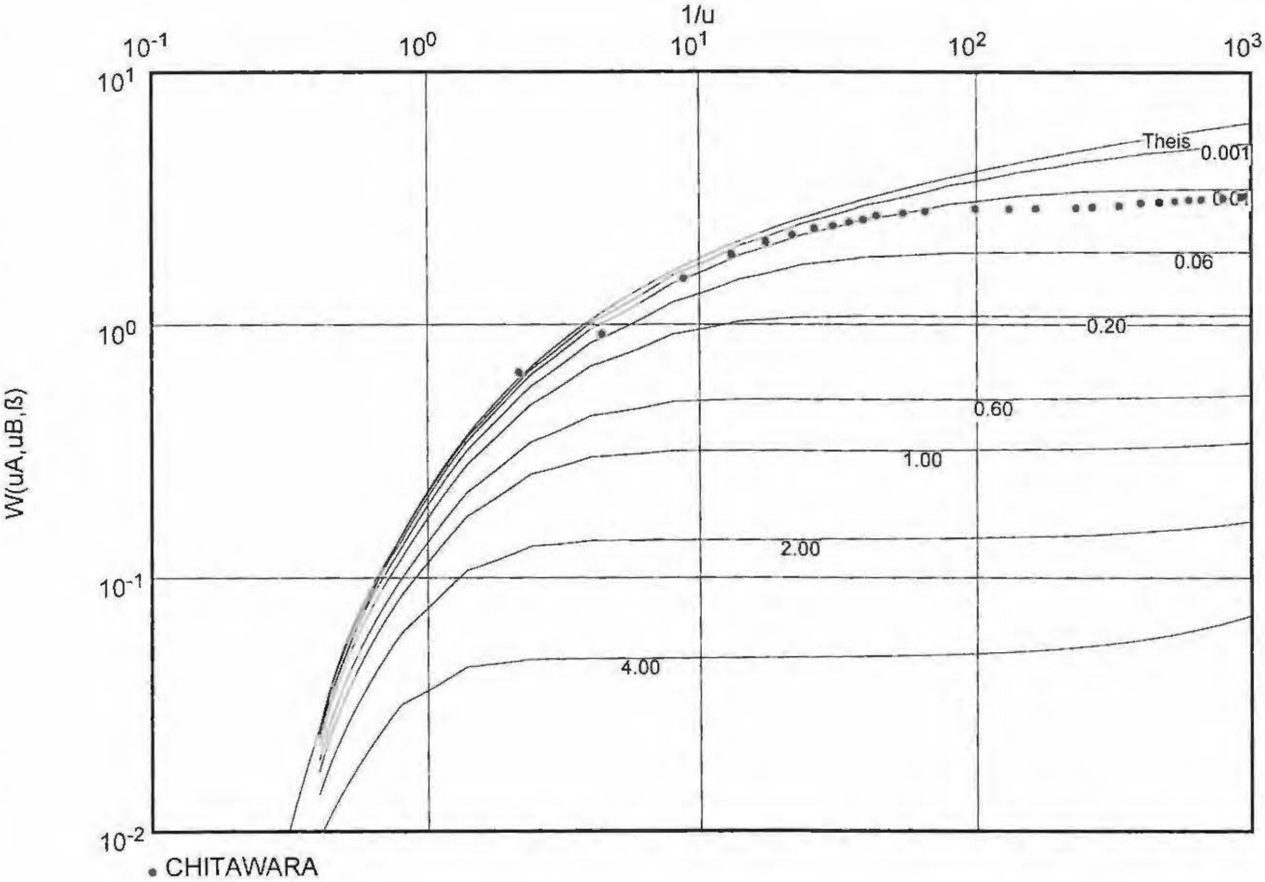
Evaluated by: JTN

Date: 25.02.2000

Pumping Test No. 6 KWEK-235

Test conducted on: 22.10.1999

Discharge 1.50 l/s



Transmissivity [m²/d]: 1.15×10^{1}

Hydraulic conductivity [m/d]: 5.51×10^{-1}

Aquifer thickness [m]: 21.000

Storativity: 2.60×10^{0}

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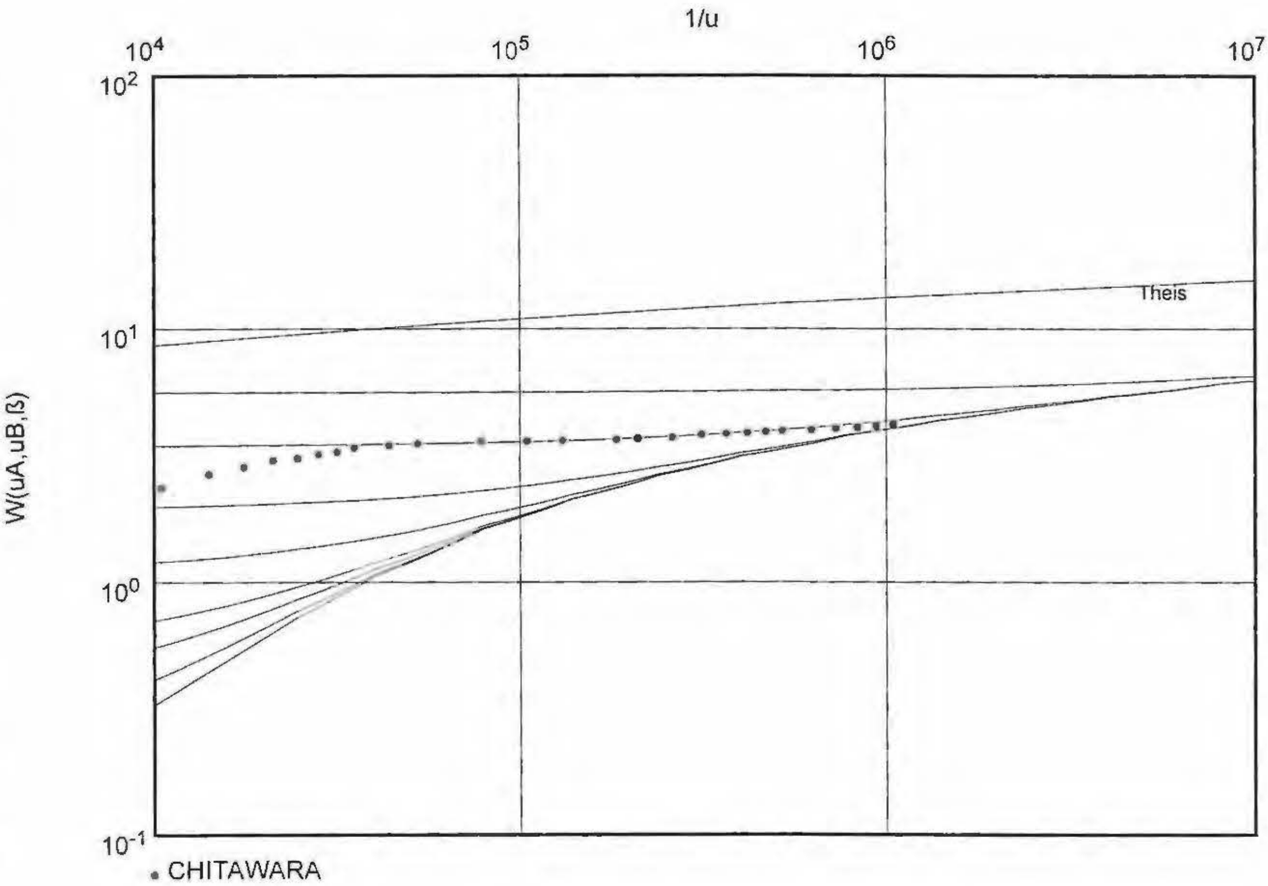
Pumping Test No. 6 KWEK-235	Test conducted on: 22.10.1999
Chitwara	
Discharge 1.50 l/s	



Transmissivity [m²/d]: 1.45×10^1

Hydraulic conductivity [m/d]: 6.93×10^{-1}

Aquifer thickness [m]: 21.000

Storativity: 4.12×10^{-3}

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Pumping test analysis
NEUMAN's method
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Pumping Test No. 6 KWEK-235

Test conducted on: 22.10.1999

CHITAWARA

Discharge 1.50 l/s

Distance from the pumping well 0.075 m

Static water level: 60.400 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00069	60.980	0.580	
2	0.00139	61.220	0.820	
3	0.00278	61.760	1.360	
4	0.00417	62.080	1.680	
5	0.00556	62.290	1.890	
6	0.00694	62.420	2.020	
7	0.00833	62.550	2.150	
8	0.00972	62.590	2.190	
9	0.01111	62.670	2.270	
10	0.01250	62.720	2.320	
11	0.01389	62.810	2.410	
12	0.01736	62.860	2.460	
13	0.02083	62.900	2.500	
14	0.03125	62.960	2.560	
15	0.04167	62.960	2.560	
16	0.05208	62.970	2.570	
17	0.07292	62.990	2.590	
18	0.08333	63.010	2.610	
19	0.10417	63.040	2.640	
20	0.12500	63.110	2.710	
21	0.14583	63.130	2.730	
22	0.16667	63.150	2.750	
23	0.18750	63.180	2.780	
24	0.20833	63.200	2.800	
25	0.25000	63.230	2.830	
26	0.29167	63.270	2.870	
27	0.33333	63.290	2.890	
28	0.37500	63.340	2.940	
29	0.41700	63.390	2.990	

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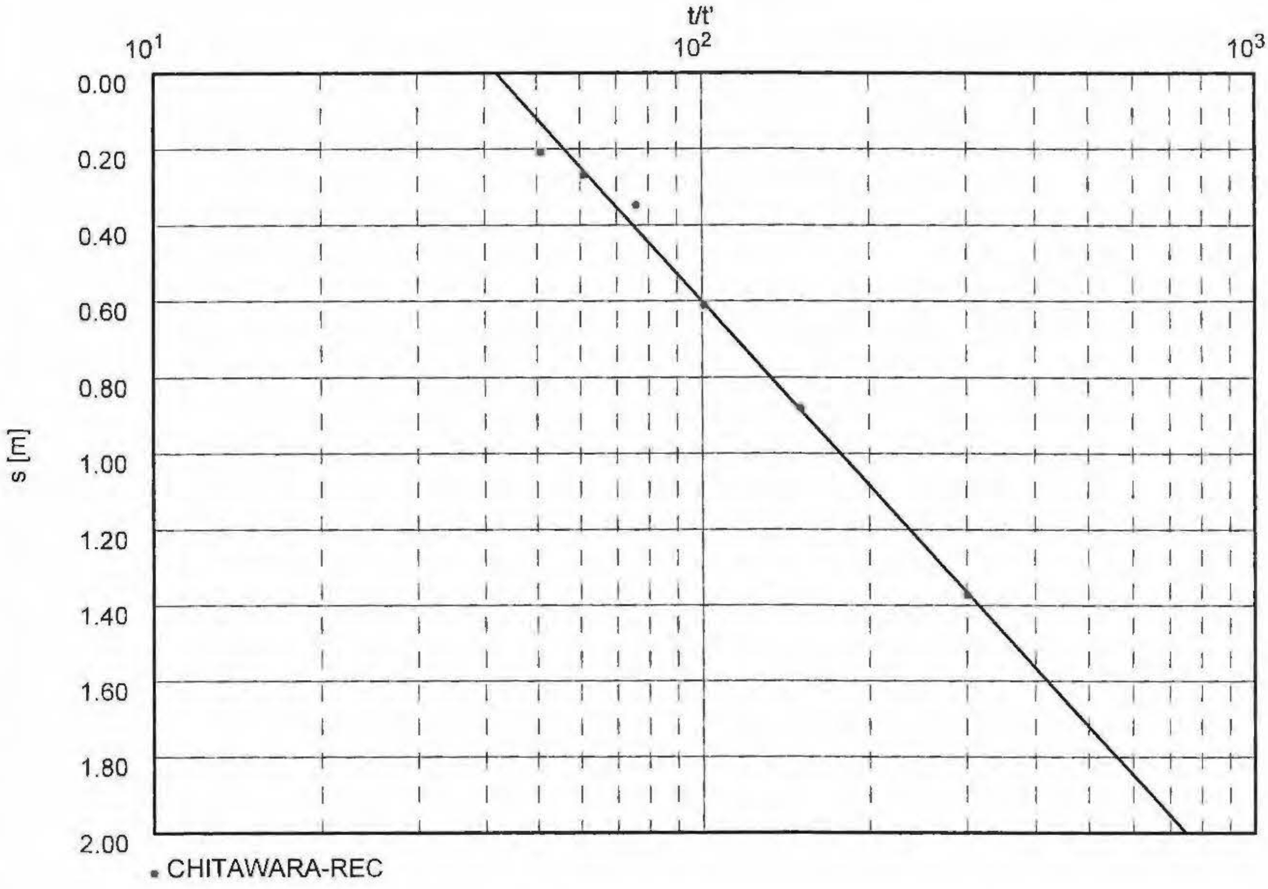
Pumping Test No. 6 KWEK-235

Test conducted on: 22.10.1999

Chitwara

Discharge 1.50 l/s

Pumping test duration: 0.41670 d



Transmissivity [m²/d]: 1.48×10^1

Hydraulic conductivity [m/d]: 7.05×10^{-1}

Aquifer thickness [m]: 21.000

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Pumping Test No. 6 KWEK-235

Test conducted on: 22.10.1999

Chitwara

CHITAWARA-REC

Discharge 1.50 l/s

Distance from the pumping well 0.075 m

Static water level: 60.400 m below datum

Pumping test duration: 0.41670 d

	Time from end of pumping [d]	Water level [m]	Residual drawdown [m]	Corrected drawdown [m]
2	0.00139	61.820	1.420	1.372
3	0.00278	61.300	0.900	0.881
4	0.00417	61.020	0.620	0.611
5	0.00556	60.750	0.350	0.347
6	0.00694	60.670	0.270	0.268
7	0.00833	60.610	0.210	0.209
8	0.00972	60.220	-0.180	-0.181
9	0.01111	60.250	-0.150	-0.151
10	0.01250	60.270	-0.130	-0.130
11	0.01389	60.280	-0.120	-0.120
12	0.01736	60.300	-0.100	-0.100

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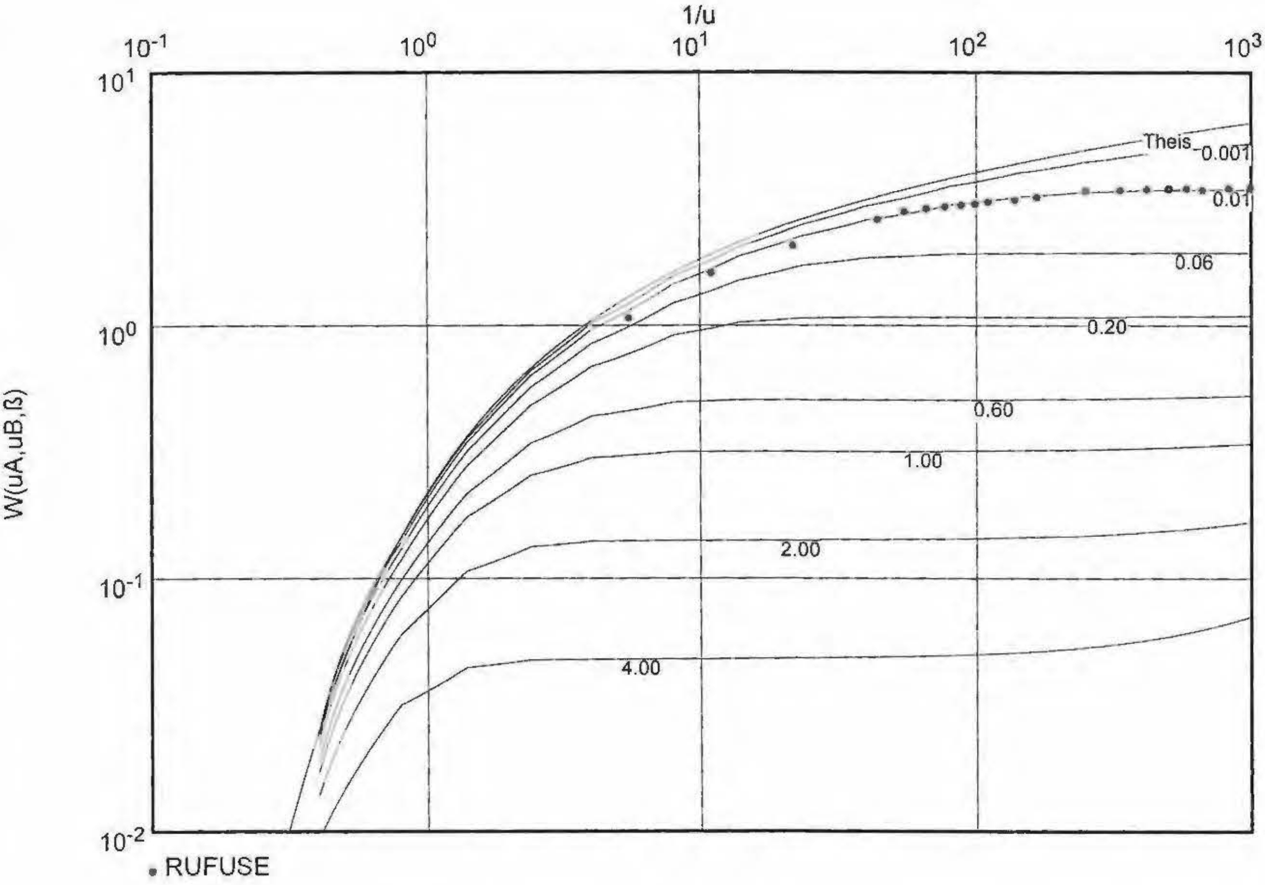
Pumping Test No. 6KWEK-234

Test conducted on: 25.10.1999

Discharge 1.81 l/s



Transmissivity [m²/d]: 4.40×10^0

Hydraulic conductivity [m/d]: 1.76×10^{-1}

Aquifer thickness [m]: 25.000

Specific yield: 3.94×10^3

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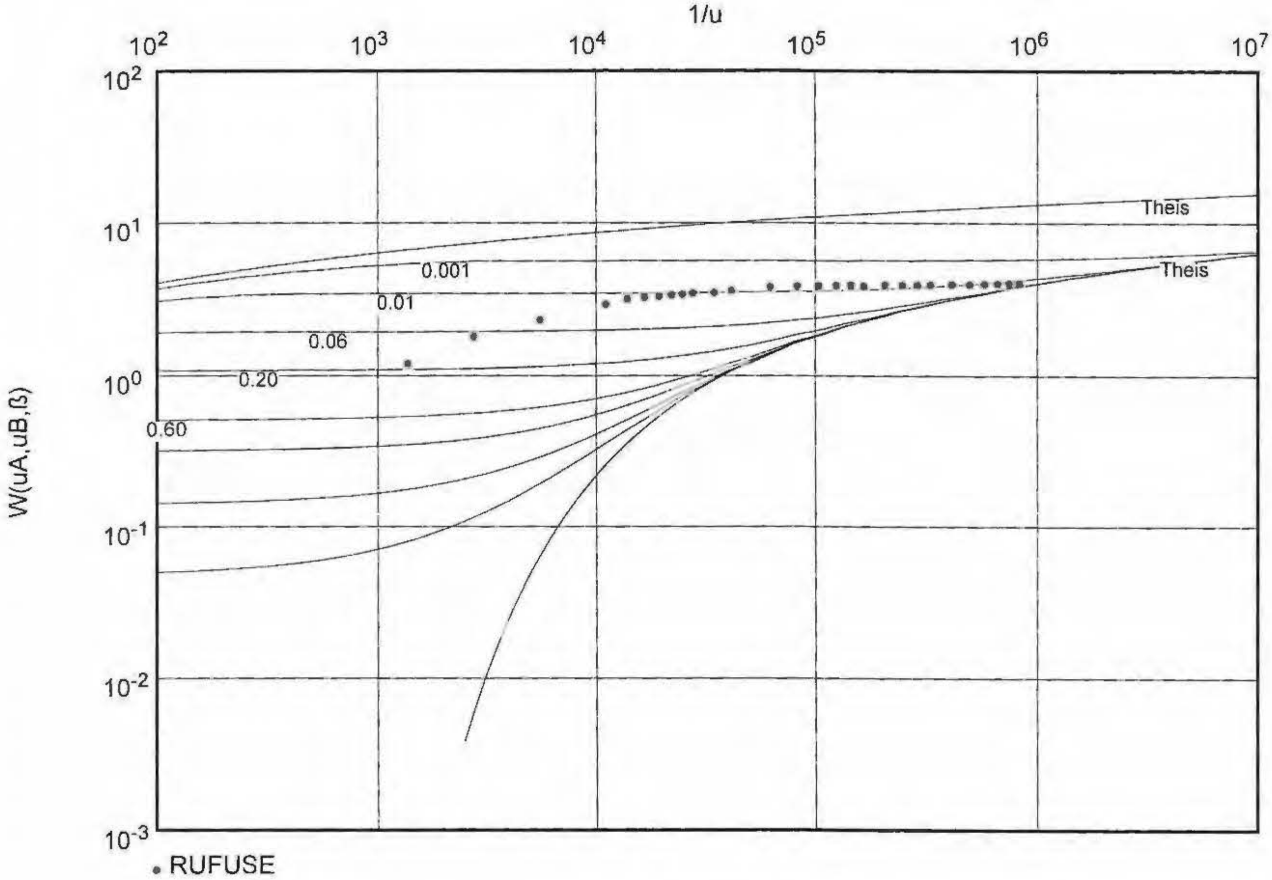
Pumping Test No. 6KWEK-234	Test conducted on: 25.10.1999
Discharge 1.81 l/s	



Transmissivity [m²/d]: 4.94 x 10^0

Hydraulic conductivity [m/d]: 1.97 x 10^{-1}

Aquifer thickness [m]: 25.000

Specific yield: 1.76 x 10^1

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Date: 27.02.2000

Pumping Test No. 6KWEK-234

Test conducted on: 25.10.1999

RUFUSE

Discharge 1.81 l/s

Distance from the pumping well 0.075 m

Static water level: 11.640 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00069	14.660	3.020	
2	0.00139	16.180	4.540	
3	0.00278	17.470	5.830	
4	0.00417	8.610	-3.030	
5	0.00556	19.050	7.410	
6	0.00694	19.620	7.980	
7	0.00833	19.830	8.190	
8	0.00972	19.960	8.320	
9	0.01111	20.100	8.460	
10	0.01250	20.200	8.560	
11	0.01389	20.350	8.710	
12	0.01736	20.460	8.820	
13	0.02083	20.720	9.080	
14	0.03125	21.260	9.620	
15	0.04167	21.320	9.680	
16	0.05208	21.400	9.760	
17	0.06250	21.450	9.810	
18	0.07292	21.480	9.840	
19	0.08333	21.320	9.680	
20	0.10417	21.510	9.870	
21	0.12500	21.520	9.880	
22	0.14583	21.550	9.910	
23	0.16667	21.580	9.940	
24	0.20833	21.610	9.970	
25	0.25000	21.620	9.980	
26	0.29167	21.680	10.040	
27	0.33333	21.730	10.090	
28	0.37500	21.770	10.130	
29	0.41667	21.780	10.140	

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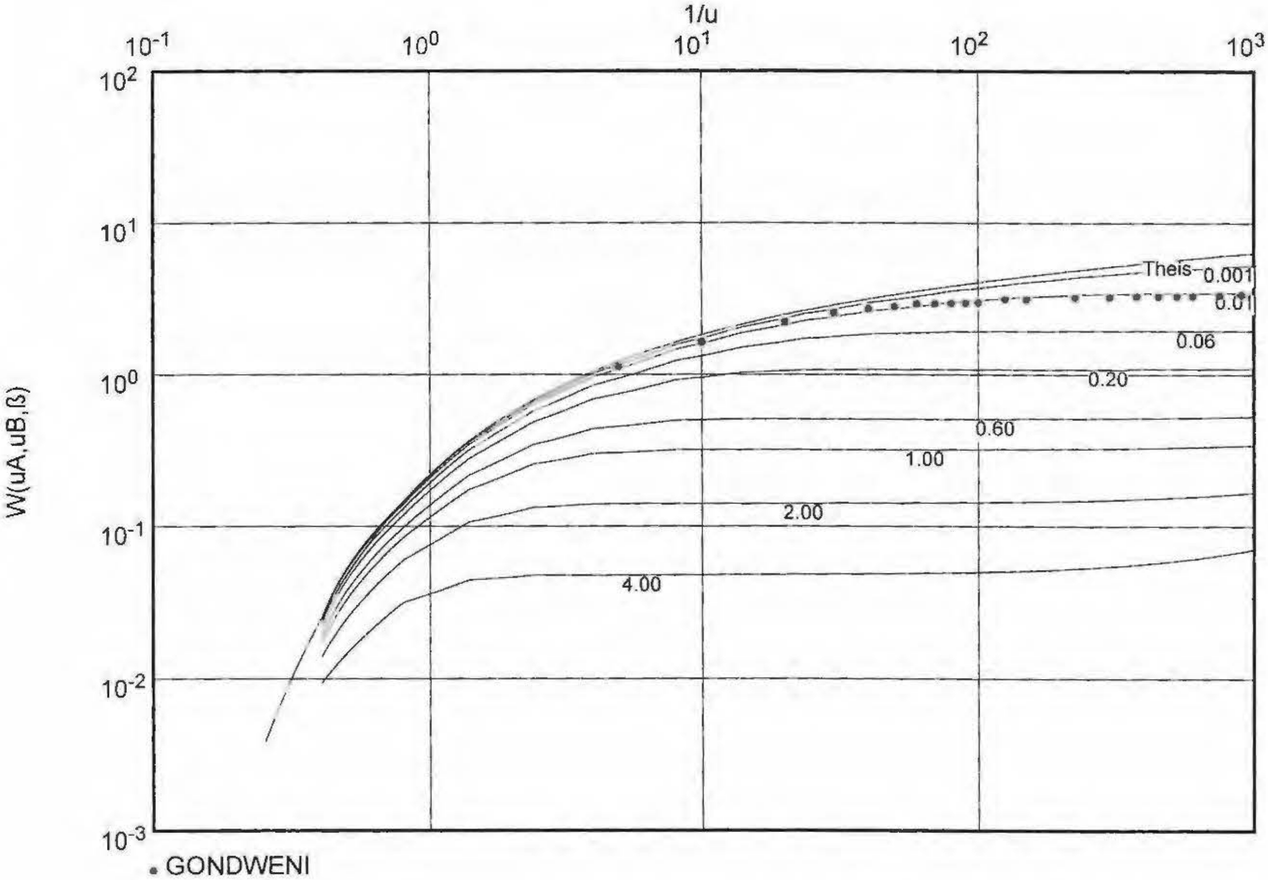
Pumping Test No. 6 KWEK-237	Test conducted on: 23.10.1999
Gondweni	
Discharge 2.20 l/s	



Transmissivity [m²/d]: 1.20 x 10^1

Hydraulic conductivity [m/d]: 3.43 x 10^{-1}

Aquifer thickness [m]: 35.000

Specific yield: 1.18 x 10^4

Hydraulic conductivity vertical [m/d]: 7.47 x 10^2

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Pumping test analysis
NEUMAN's method
Unconfined aquifer with
delayed watertable response

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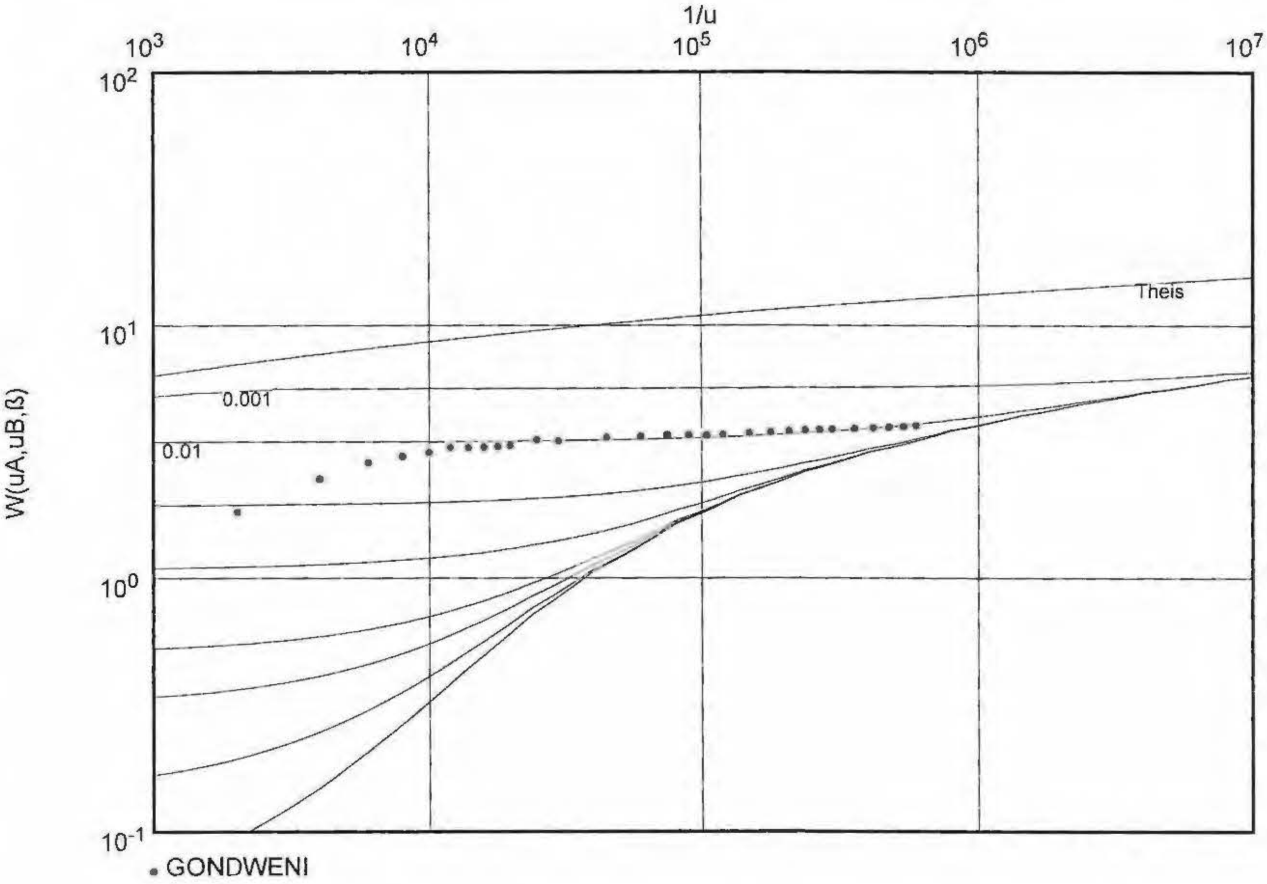
Pumping Test No. 6 KWEK-237	Test conducted on: 23.10.1999
Gondweni	
Discharge 2.20 l/s	



Transmissivity [m²/d]: 1.34 x 10^1

Hydraulic conductivity [m/d]: 3.85 x 10^{-1}

Aquifer thickness [m]: 35.000

Specific yield: 6.65 x 10^1

Hydraulic conductivity vertical [m/d]: 8.38 x 10^2

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Project: MSc Thesis

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Pumping Test No. 6 KWEK-237

Test conducted on: 23.10.1999

Gondweni

GONDWENI

Discharge 2.20 l/s

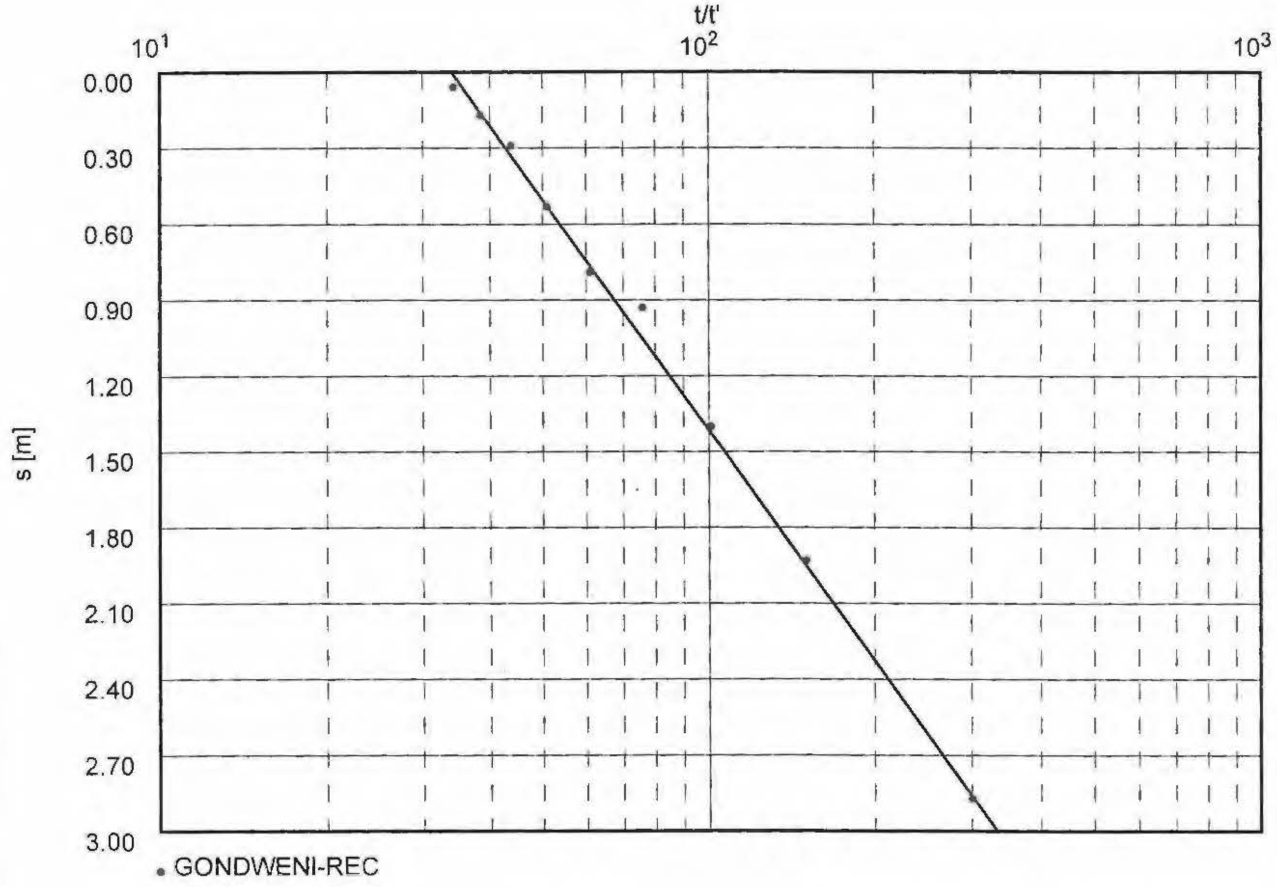
Distance from the pumping well 0.075 m

Static water level: 73.700 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00069	75.110	1.410	
2	0.00139	75.750	2.050	
3	0.00278	76.470	2.770	
4	0.00417	76.910	3.210	
5	0.00556	77.110	3.410	
6	0.00694	77.230	3.530	
7	0.00833	77.380	3.680	
8	0.00972	77.390	3.690	
9	0.01111	77.400	3.700	
10	0.01250	77.420	3.720	
11	0.01389	77.450	3.750	
12	0.01736	77.655	3.955	
13	0.02083	77.620	3.920	
14	0.03125	77.740	4.040	
15	0.04167	77.770	4.070	
16	0.05208	77.820	4.120	
17	0.06250	77.830	4.130	
18	0.07292	77.820	4.120	
19	0.08333	77.840	4.140	
20	0.10417	77.900	4.200	
21	0.12500	77.940	4.240	
22	0.14583	77.970	4.270	
23	0.16667	78.010	4.310	
24	0.18750	78.040	4.340	
25	0.20833	78.050	4.350	
26	0.25000	78.070	4.370	
27	0.29167	78.100	4.400	
28	0.33333	78.120	4.420	
29	0.37500	78.150	4.450	
30	0.41667	78.190	4.490	

Waterloo Hydrogeologi 180 Columbia St. W. Waterloo,Ontario,Canada ph.(519)746-1798	Pumping test analysis Recovery method after THEIS & JACOB Confined aquifer	Page 1 Project: MSc Thesis Evaluated by: JTN Date: 26.02.2000

Pumping Test No. 6 KWEK-237	Test conducted on: 23.10.1999
Gondweni	
Discharge 2.20 l/s	
	Pumping test duration: 0.41667 d



Transmissivity [m²/d]: 1.15×10^1

Hydraulic conductivity [m/d]: 3.28×10^{-1}

Aquifer thickness [m]: 35.000

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Pumping test analysis
Recovery method after
THEIS & JACOB
Confined aquifer

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Pumping Test No. 6 KWEK-237	Test conducted on: 23.10.1999
Gondweni	GONDWENI-REC
Discharge 2.20 l/s	Distance from the pumping well 0.075 m
Static water level: 73.700 m below datum	Pumping test duration: 0.41667 d

	Time from end of pumping [d]	Water level [m]	Residual drawdown [m]	
2	0.00139	76.570	2.870	
3	0.00278	75.630	1.930	
4	0.00417	75.100	1.400	
5	0.00556	74.630	0.930	
6	0.00694	74.490	0.790	
7	0.00833	74.230	0.530	
8	0.00972	73.990	0.290	
9	0.01111	73.870	0.170	
10	0.01250	73.760	0.060	

APPENDIX 3

SLUG TEST DATA AND INTERPRETATIONS

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slug/bail test analysis
BOUWER-RICE's method

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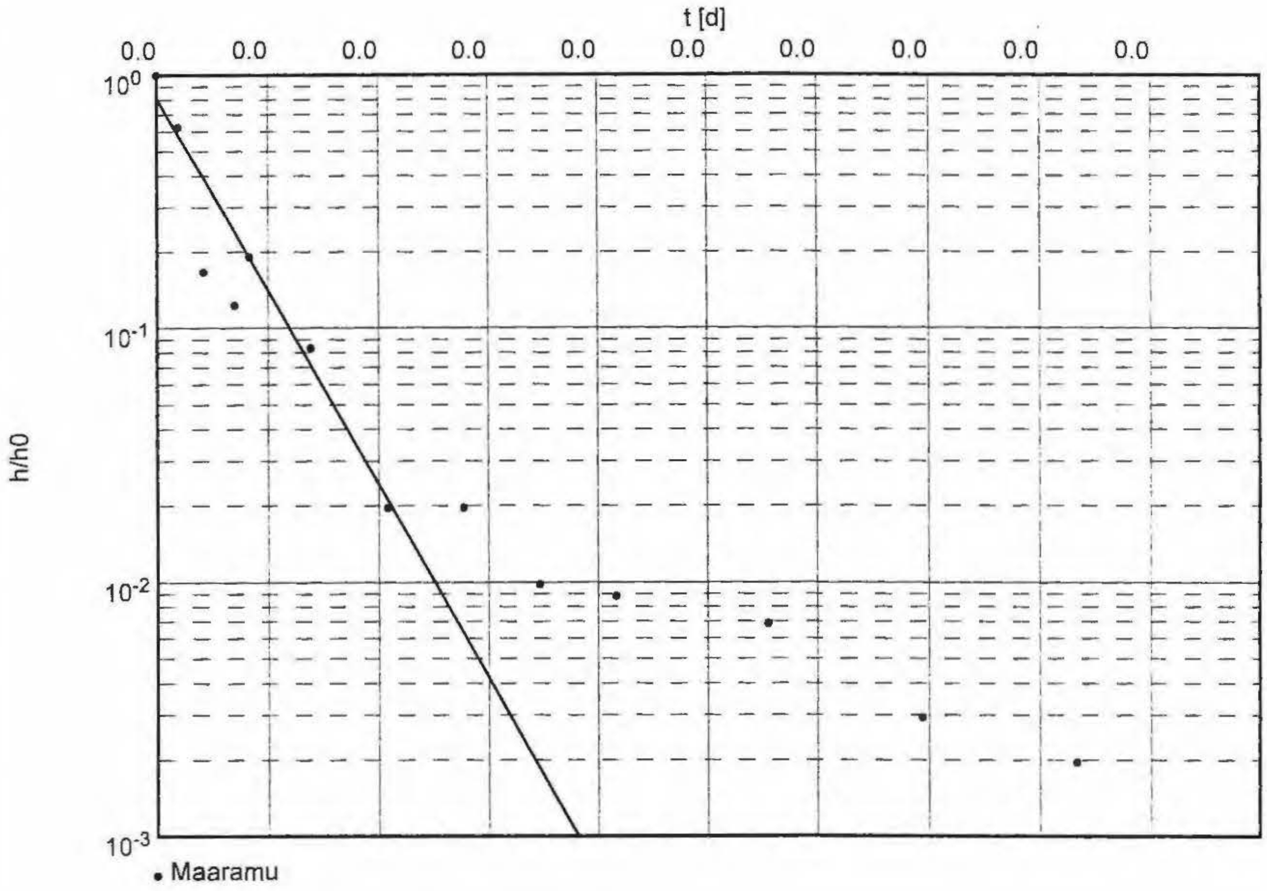
Slug Test No. 6kwek-260

Test conducted on: Dec 1998

Maaramu



Hydraulic conductivity [m/d]: 1.23×10^{-1}

Slug Test No. 6kwek-260

Test conducted on: Dec 1998

Maaramu

Maaramu

Static water level: 37.200 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00000	36.180	-1.020	
2	0.00097	37.835	0.635	
3	0.00208	37.370	0.170	
4	0.00347	37.075	-0.125	
5	0.00417	37.005	-0.195	
6	0.00694	37.115	-0.085	
7	0.01042	37.180	-0.020	
8	0.01389	37.180	-0.020	
9	0.01736	37.190	-0.010	
10	0.02083	37.191	-0.009	
11	0.02778	37.193	-0.007	
12	0.03472	37.197	-0.003	
13	0.04167	37.198	-0.002	

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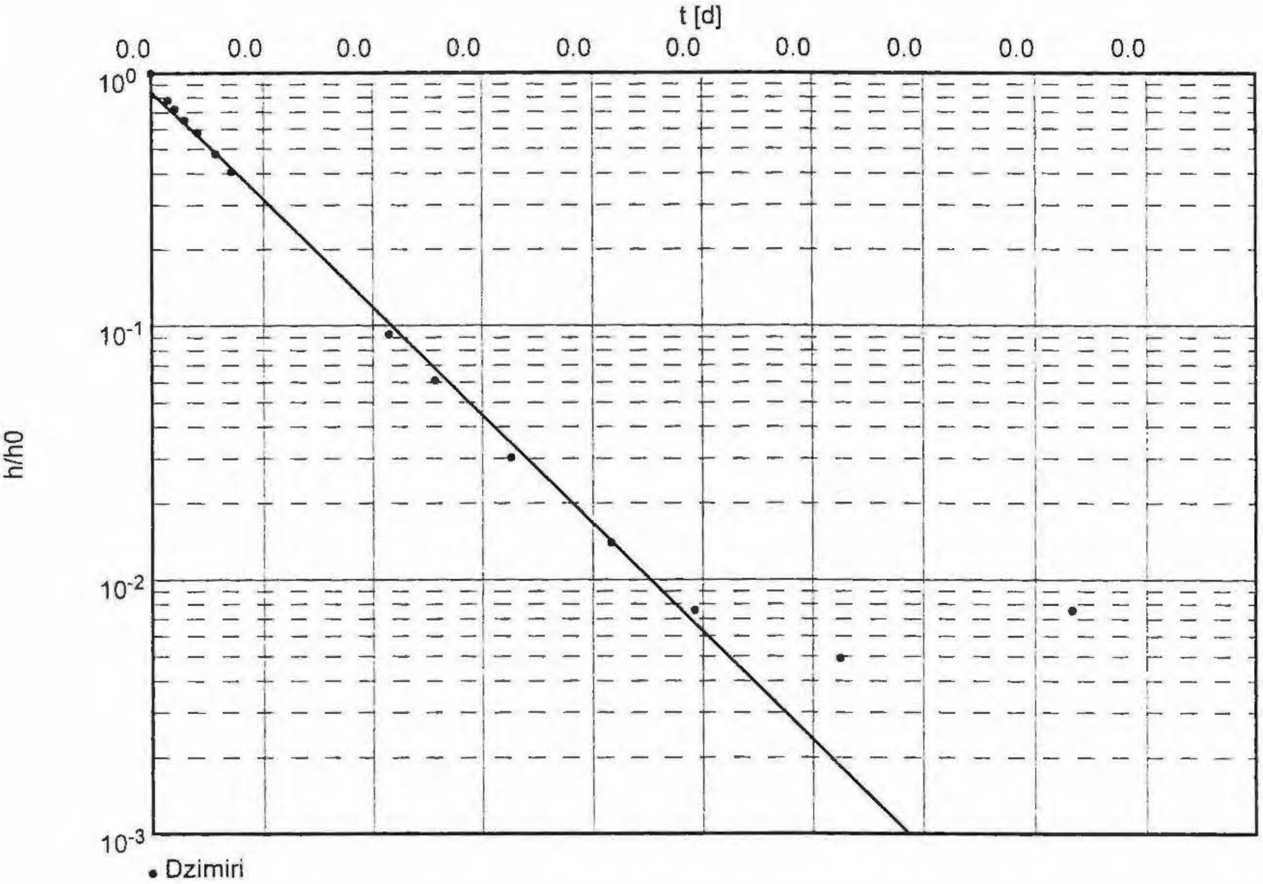
Slug Test No. 6kwek-268

Test conducted on: Dec 1998

Dzimiri



Hydraulic conductivity [m/d]: 7.79×10^{-2}

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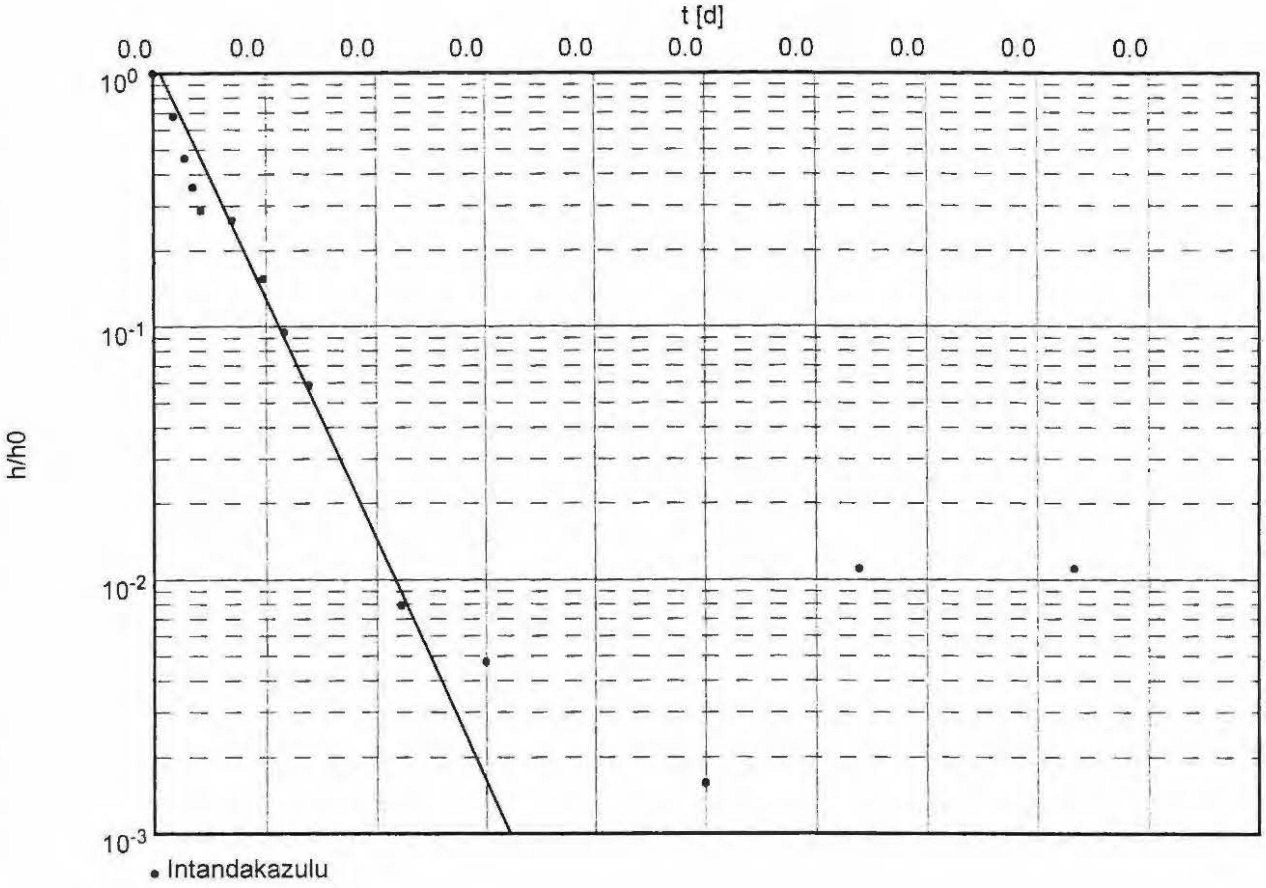
Slug Test No. 6kwek-268	Test conducted on: Dec 1998
Dzimiri	Dzimiri

Static water level: 13.540 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00000	10.900	-2.640	
2	0.00076	11.478	-2.062	
3	0.00105	11.642	-1.898	
4	0.00146	11.823	-1.717	
5	0.00205	12.007	-1.533	
6	0.00285	12.279	-1.261	
7	0.00355	12.467	-1.073	
8	0.01076	13.296	-0.244	
9	0.01285	13.379	-0.161	
10	0.01632	13.460	-0.080	
11	0.02083	13.503	-0.037	
12	0.02465	13.520	-0.020	
13	0.03125	13.527	-0.013	
14	0.04167	13.520	-0.020	

Waterloo Hydrogeologi 180 Columbia St. W. Waterloo,Ontario,Canada ph.(519)746-1798	slug/bail test analysis BOUWER-RICE's method	Page 1 Project: MSc Thesis Evaluated by: JTN Date: 02.11.1999

Slug Test No. 6kwek-204	Test conducted on: Dec 1998
Inthandokazulu	



Hydraulic conductivity [m/d]: 1.37×10^{-1}

Waterloo Hydrogeologic 180 Columbia St. W. Waterloo,Ontario,Canada ph.(519)746-1798	slug/bail test analysis BOUWER-RICE's method	Page 2 Project: MSc Thesis Evaluated by: JTN Date: 02.11.1999

Slug Test No. 6kwek-204

Test conducted on: Dec 1998

Inthandokazulu

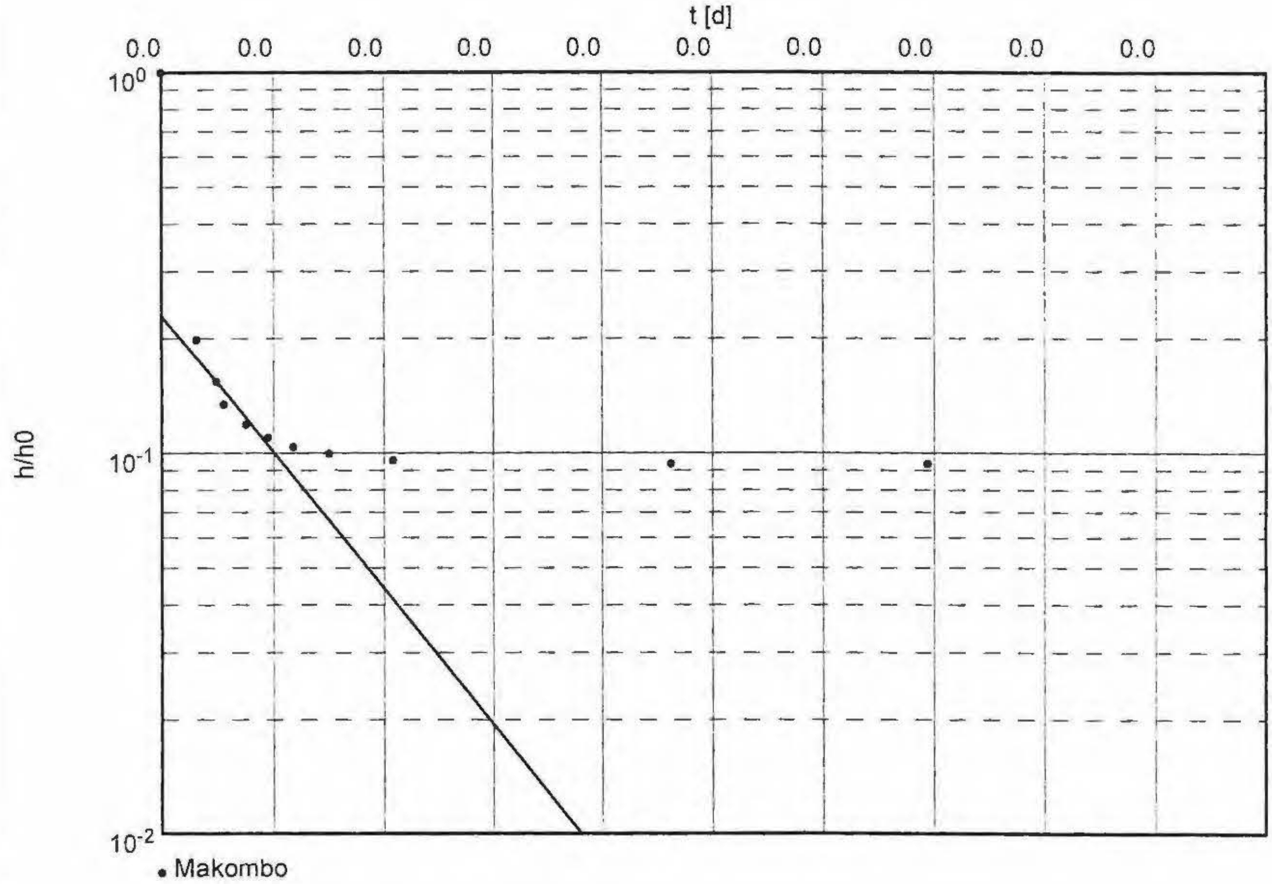
Intandakazulu

Static water level: 51.432 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00000	50.800	-0.632	
2	0.00090	51.860	0.428	
3	0.00139	51.140	-0.292	
4	0.00174	51.207	-0.225	
5	0.00208	51.250	-0.182	
6	0.00347	51.266	-0.166	
7	0.00486	51.334	-0.098	
8	0.00583	51.372	-0.060	
9	0.00694	51.395	-0.037	
10	0.01112	51.427	-0.005	
11	0.01500	51.429	-0.003	
12	0.02500	51.433	0.001	
13	0.03194	51.439	0.007	
14	0.04167	51.439	0.007	

Waterloo Hydrogeologic 180 Columbia St. W. Waterloo,Ontario,Canada ph.(519)746-1798	slug/bail test analysis BOUWER-RICE's method	Page 1 Project: MSc Thesis Evaluated by: JTN | Date: 21.10.1999

Slug Test No. 6kwek-251	Test conducted on: Dec 1998
Makombo	



Hydraulic conductivity [m/d]: 8.06 x 10^{-2}

Slug Test No. 6kwek-251 | Test conducted on: Dec 1998

Makombo | Makombo

Static water level: 57.103 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00000	56.110	-0.993	
2	0.00092	56.906	-0.197	
3	0.00144	56.950	-0.153	
4	0.00165	56.970	-0.133	
5	0.00226	56.985	-0.118	
6	0.00285	56.994	-0.109	
7	0.00354	57.000	-0.103	
8	0.00451	57.004	-0.099	
9	0.00625	57.008	-0.095	
10	0.01389	57.010	-0.093	
11	0.02083	57.010	-0.093	

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BOUWER-RICE's method

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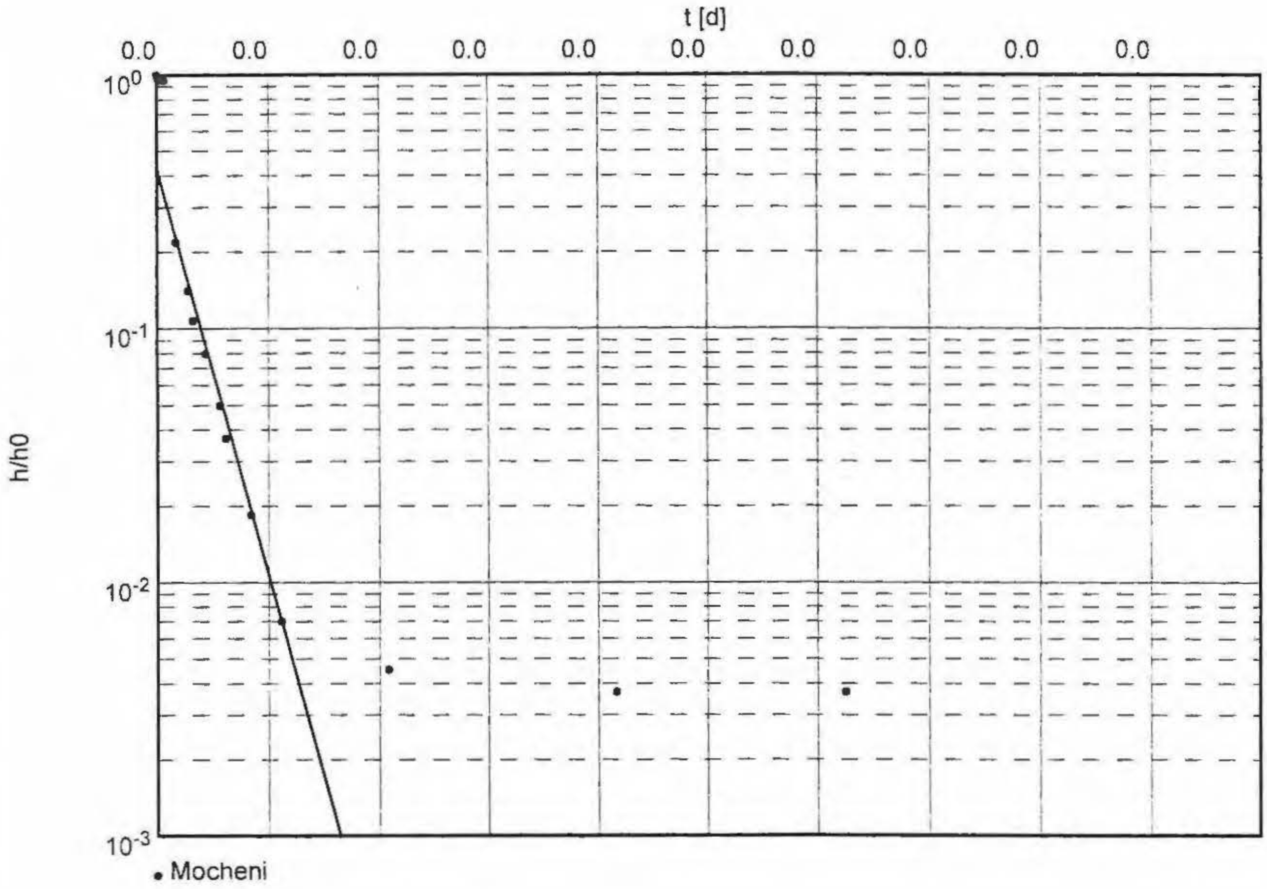
Slug Test No. 6kwek-261	Test conducted on: Dec 1998
Mocheni	



Hydraulic conductivity [m/d]: 5.59×10^{-1}

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Slug Test No. 6kwek-261 | Test conducted on: Dec 1998

Mocheni | Mocheni

Static water level: 55.030 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00000	52.600	-2.430	
2	0.00007	52.713	-2.317	
3	0.00035	52.723	-2.307	
4	0.00085	54.500	-0.530	
5	0.00139	54.688	-0.342	
6	0.00160	54.769	-0.261	
7	0.00216	54.836	-0.194	
8	0.00281	54.909	-0.121	
9	0.00308	54.940	-0.090	
10	0.00422	54.985	-0.045	
11	0.00559	55.013	-0.017	
12	0.01042	55.019	-0.011	
13	0.02083	55.021	-0.009	
14	0.03125	55.021	-0.009	

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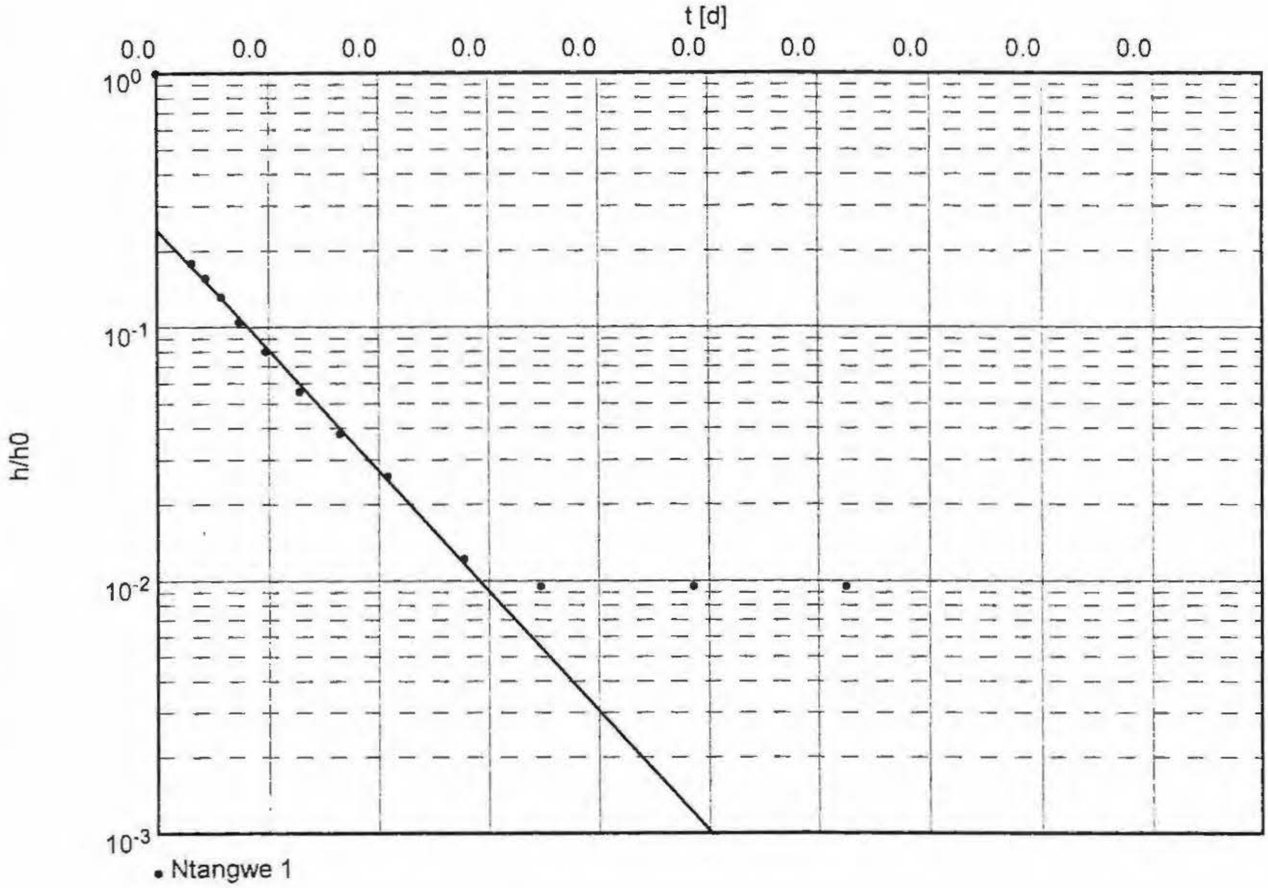
Slug Test No. 6kwek-168

Test conducted on: Dec 1998

Ntangwe 1



Hydraulic conductivity [m/d]: 5.87×10^{-2}

Slug Test No. 6kwek-168 | Test conducted on: Dec 1998

Ntangwe 1 | Ntangwe 1

Static water level: 65.537 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]
1	0.00000	64.800	-0.737
2	0.00042	63.007	-2.530
3	0.00111	63.007	-2.530
4	0.00154	65.405	-0.132
5	0.00215	65.422	-0.115
6	0.00285	65.440	-0.097
7	0.00366	65.460	-0.077
8	0.00486	65.478	-0.059
9	0.00642	65.496	-0.041
10	0.00826	65.509	-0.028
11	0.01042	65.518	-0.019
12	0.01389	65.528	-0.009
13	0.01736	65.530	-0.007
14	0.02431	65.530	-0.007
15	0.03125	65.530	-0.007

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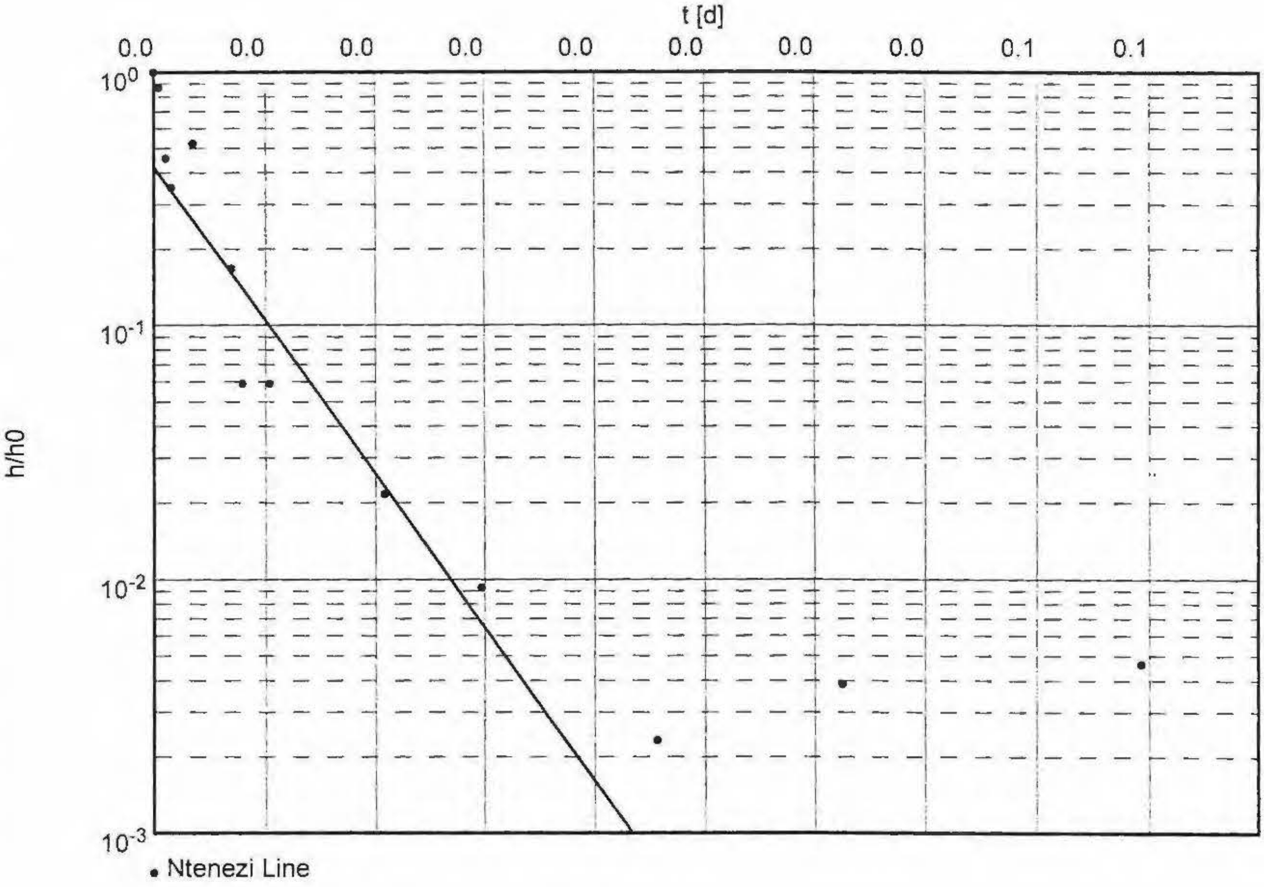
Slug Test No. 6kwek-203	Test conducted on: Dec 1998
Mtenenzi Lune	



Hydraulic conductivity [m/d]: 6.68 x 10^{-2}

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Slug Test No. 6kwek-203

Test conducted on: Dec 1998

Mtenenzi Lune

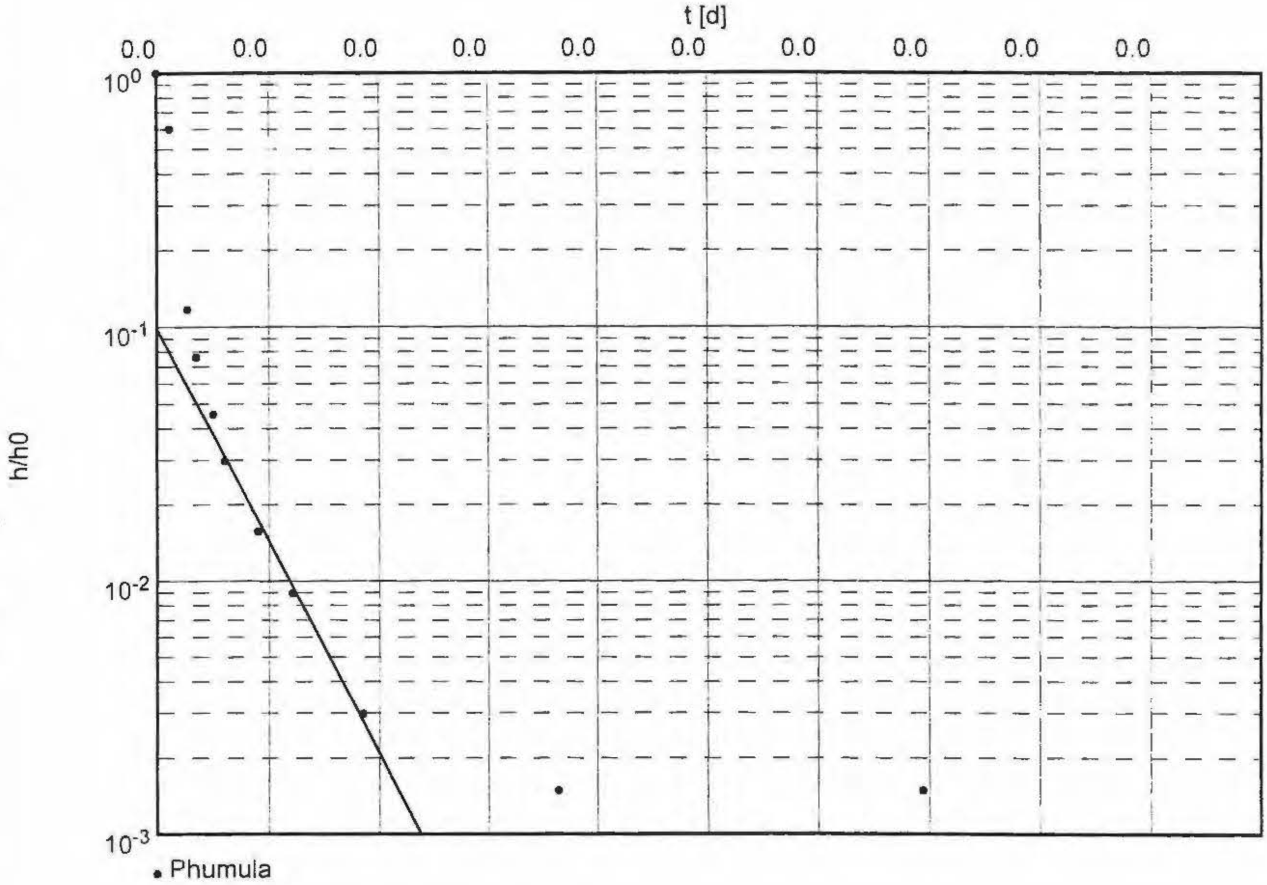
Ntenezi Line

Static water level: 52.609 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]
1	0.00000	51.318	-1.291
2	0.00035	51.487	-1.122
3	0.00076	52.018	-0.591
4	0.00111	52.158	-0.451
5	0.00243	53.283	0.674
6	0.00486	52.393	-0.216
7	0.00556	52.533	-0.076
8	0.00729	52.533	-0.076
9	0.01458	52.581	-0.028
10	0.02083	52.597	-0.012
11	0.03194	52.606	-0.003
12	0.04375	52.604	-0.005
13	0.06250	52.603	-0.006

Waterloo Hydrogeologi 180 Columbia St. W. Waterloo,Ontario,Canada ph.(519)746-1798	slug/bail test analysis BOUWER-RICE's method	Page 1 Project: MSc Thesis Evaluated by: JTN Date: 21.10.1999

Slug Test No. 6kwek-262	Test conducted on: Dec 1998
Phumula	



Hydraulic conductivity [m/d]: 2.24×10^{-1}

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Slug Test No. 6kwek-262	Test conducted on: Dec 1998
Phumula	Phumula

Static water level: 62.040 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00000	60.700	-1.340	
2	0.00035	61.235	-0.805	
3	0.00083	61.883	-0.157	
4	0.00105	61.938	-0.102	
5	0.00150	61.979	-0.061	
6	0.00181	62.000	-0.040	
7	0.00271	62.019	-0.021	
8	0.00365	62.028	-0.012	
9	0.00556	62.036	-0.004	
10	0.01094	62.038	-0.002	
11	0.02083	62.038	-0.002	

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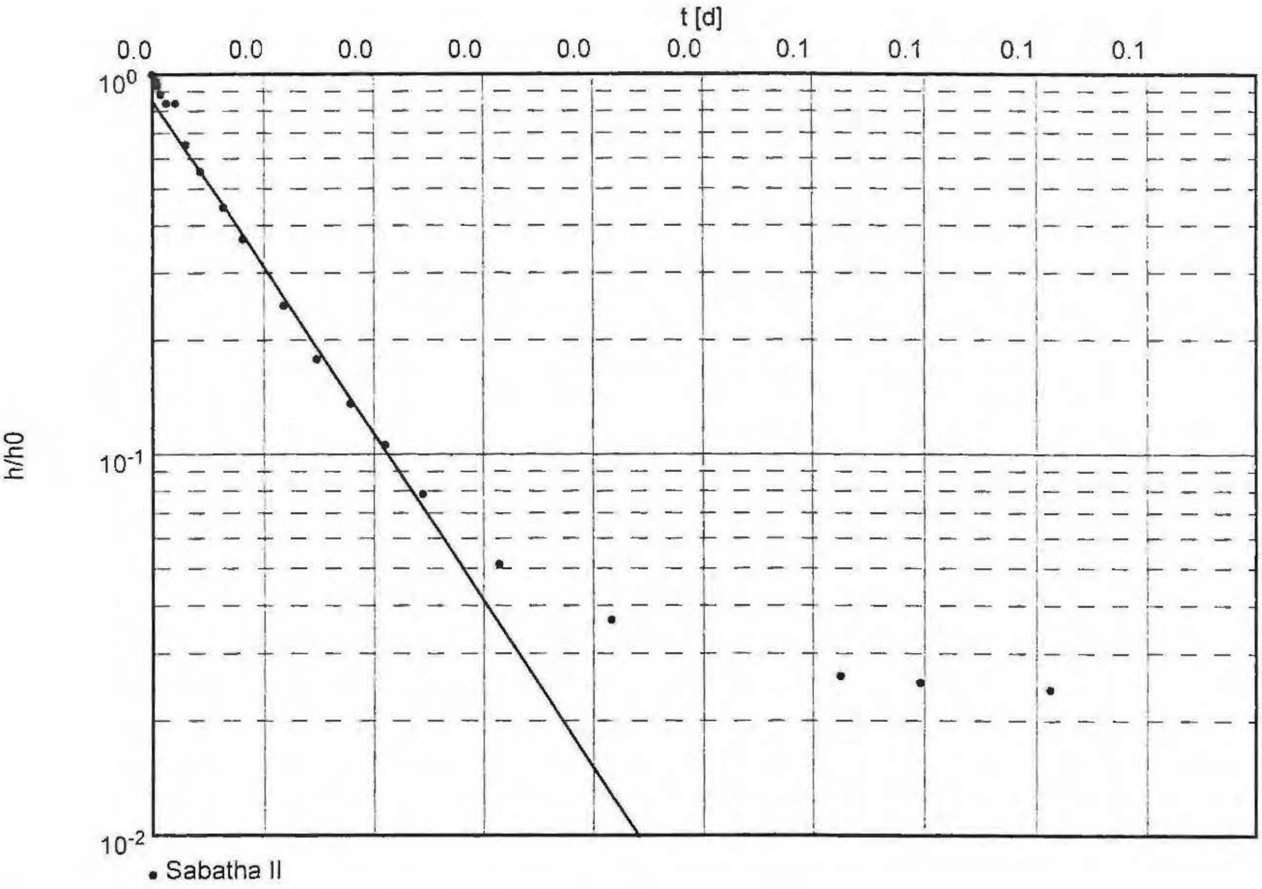
Slug Test No. 6kwek-191

Test conducted on: Dec 1998

Sabatha II



Hydraulic conductivity [m/d]: 5.38 x 10^{-2}

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Slug Test No. 6kwek-191

Test conducted on: Dec 1998

Sabatha II

Sabatha II

Static water level: 23.225 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]
1	0.00000	22.270	-0.955
2	0.00047	22.310	-0.915
3	0.00049	22.334	-0.891
4	0.00077	22.380	-0.845
5	0.00125	22.425	-0.800
6	0.00208	22.425	-0.800
7	0.00299	22.602	-0.623
8	0.00424	22.694	-0.531
9	0.00625	22.799	-0.426
10	0.00806	22.873	-0.352
11	0.01181	22.990	-0.235
12	0.01486	23.055	-0.170
13	0.01792	23.095	-0.130
14	0.02104	23.124	-0.101
15	0.02444	23.150	-0.075
16	0.03146	23.176	-0.049
17	0.04167	23.190	-0.035
18	0.06250	23.200	-0.025
19	0.06965	23.201	-0.024
20	0.08125	23.202	-0.023

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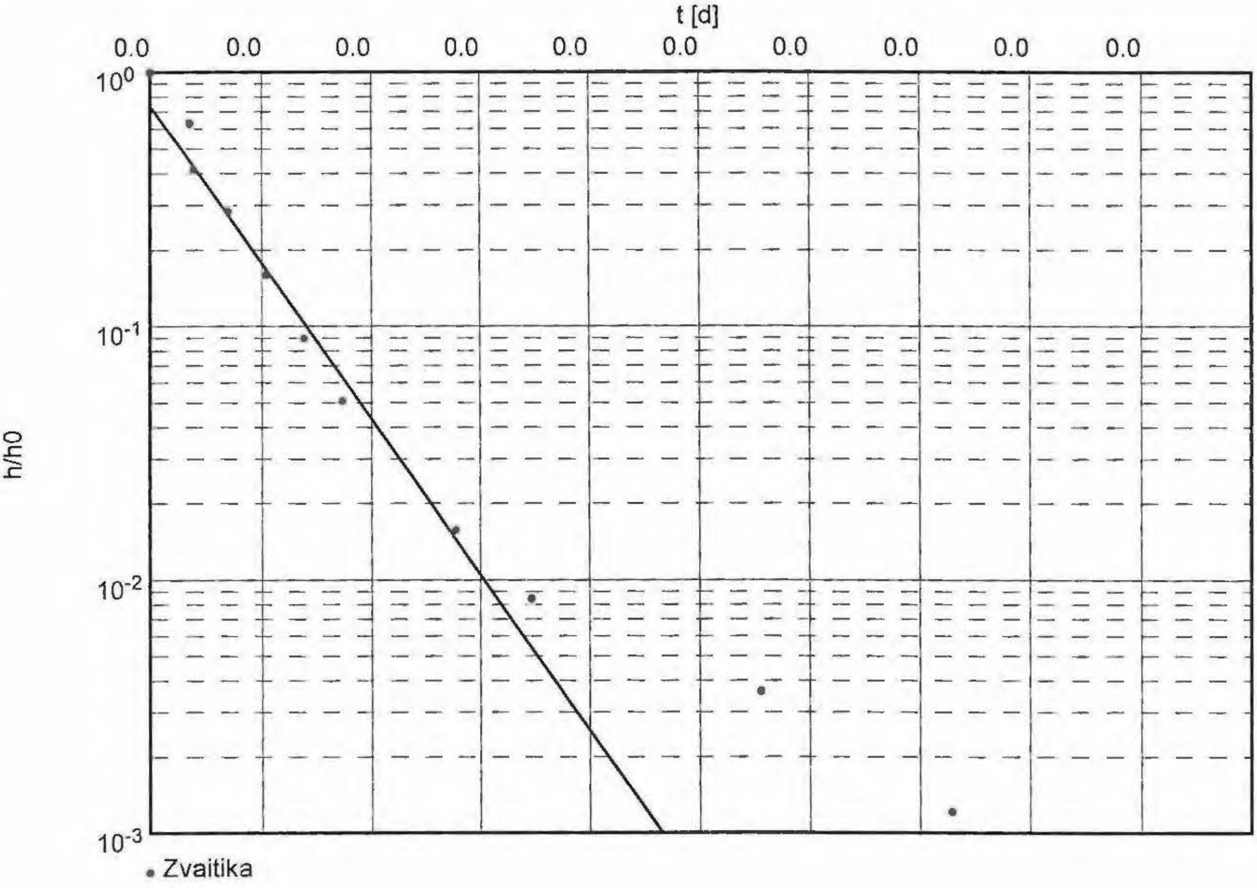
Slug Test No. 6kwek-215	Test conducted on: Dec 1998
Zvaitika	



Hydraulic conductivity [m/d]: 2.77×10^{-1}

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Slug Test No. 6kwek-215	Test conducted on: Dec 1998
Zvaitika	Zvaitika

Static water level: 13.030 m below datum

	Pumping test duration [d]	Water level [m]	Drawdown [m]	
1	0.00000	12.204	-0.826	
2	0.00069	12.508	-0.522	
3	0.00076	12.688	-0.342	
4	0.00139	12.796	-0.234	
5	0.00208	12.898	-0.132	
6	0.00278	12.956	-0.074	
7	0.00347	12.988	-0.042	
8	0.00556	13.017	-0.013	
9	0.00694	13.023	-0.007	
10	0.01111	13.027	-0.003	
11	0.01458	13.029	-0.001	
12	0.01944	13.030	0.000	

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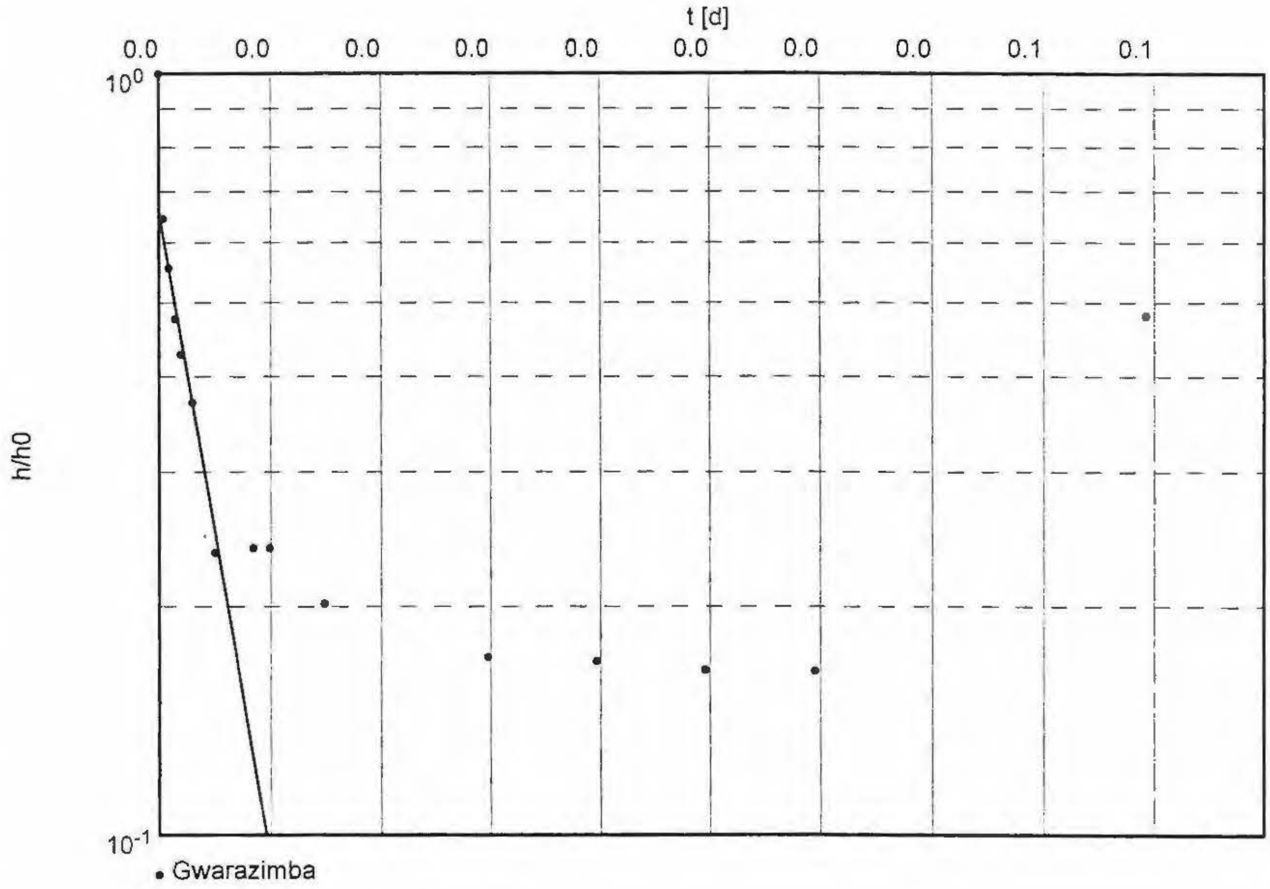
Slug Test No. 6kwek-215	Test conducted on: Dec 1998
Gwarazimba	



Hydraulic conductivity [m/d]: 1.18×10^{-1}

Waterloo Hydrogeologi 180 Columbia St. W. Waterloo,Ontario,Canada ph.(519)746-1798	slug/bail test analysis BOUWER-RICE's method	Page 2 Project: MSc Thesis Evaluated by: JTN Date: 21.10.1999

Slug Test No. 6kwek-215	Test conducted on: Dec 1998
Gwarazimba	Gwarazimba

Static water level: 45.180 m below datum

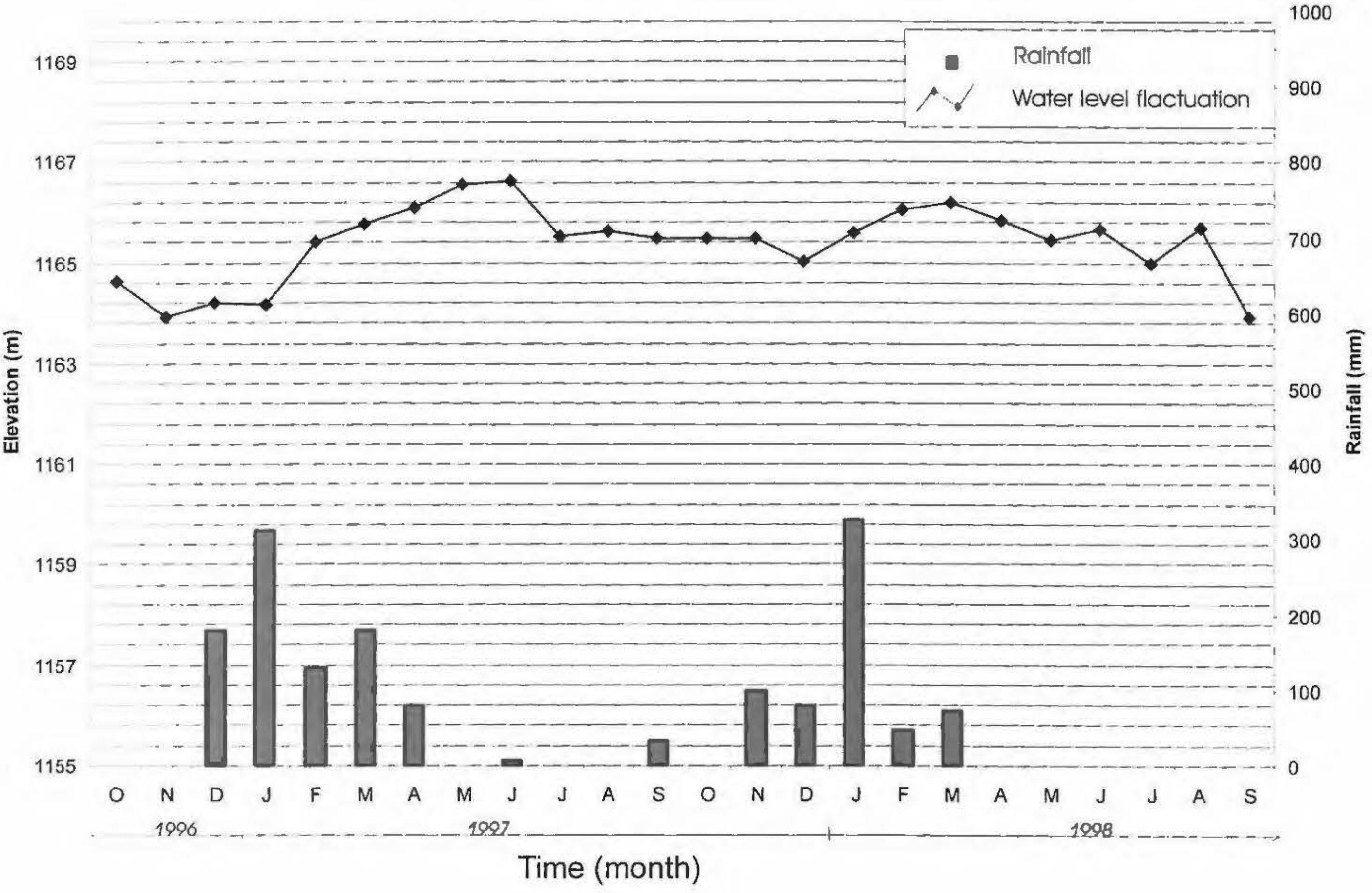
	Pumping test duration [d]	Water level [m]	Drawdown [m]
1	0.00000	42.900	-2.280
2	0.00028	43.709	-1.471
3	0.00062	43.914	-1.266
4	0.00104	44.095	-1.085
5	0.00139	44.205	-0.975
6	0.00208	44.336	-0.844
7	0.00347	44.643	-0.537
8	0.00590	44.636	-0.544
9	0.00694	44.636	-0.544
10	0.01042	44.720	-0.460
11	0.01528	42.660	-2.520
12	0.02083	44.789	-0.391
13	0.02778	44.794	-0.386
14	0.03472	44.804	-0.376
15	0.04167	44.805	-0.375
16	0.06250	44.085	-1.095

APPENDIX 4

HYDROGRAPHS

WELL HYDROGRAPH & WATER LEVEL DATA

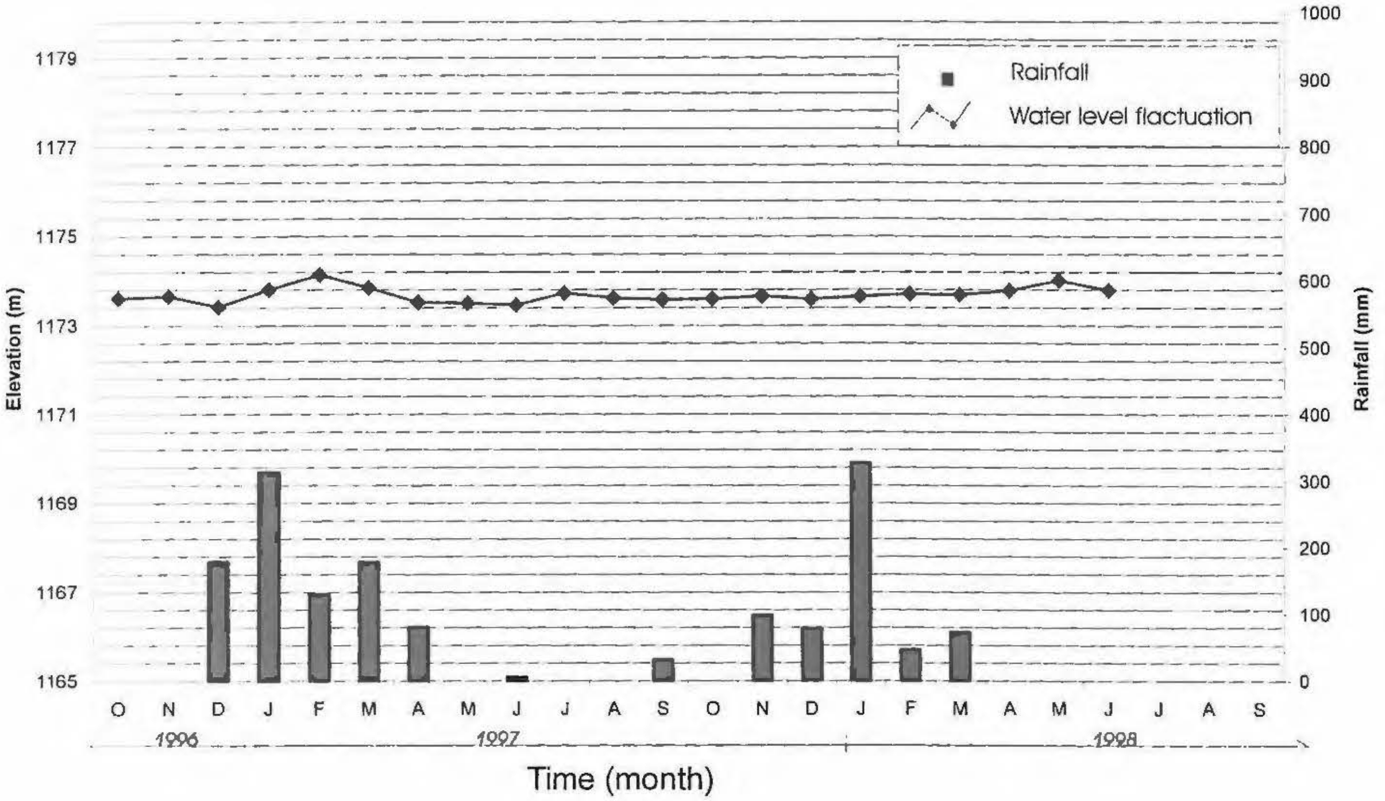
BH-ID	BH-NAME	GRID REF
6-KWEK-285	MUGANDANI	QK 382298



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	18.37	1164.63
Nov-96	19.07	1163.93
Dec-96	18.8	1164.2
Jan-97	18.82	1164.18
Feb-97	17.58	1165.42
Mar-97	17.23	1165.77
Apr-97	16.9	1166.1
May-97	16.44	1166.56
Jun-97	16.38	1166.62
Jul-97	17.49	1165.51
Aug-97	17.38	1165.62
Sep-97	17.5	1165.5
Oct-97	17.5	1165.5
Nov-97	17.51	1165.49
Dec-97	17.98	1165.02
Jan-98	17.42	1165.58
Feb-98	16.96	1166.04
Mar-98	16.79	1166.21
Apr-98	17.17	1165.83
May-98	17.56	1165.44
Jun-98	17.32	1165.68
Jul-98	18	1165
Aug-98	19	1164
Sep-98	19.07	1163.93

WELL HYDROGRAPH & WATER LEVEL DATA

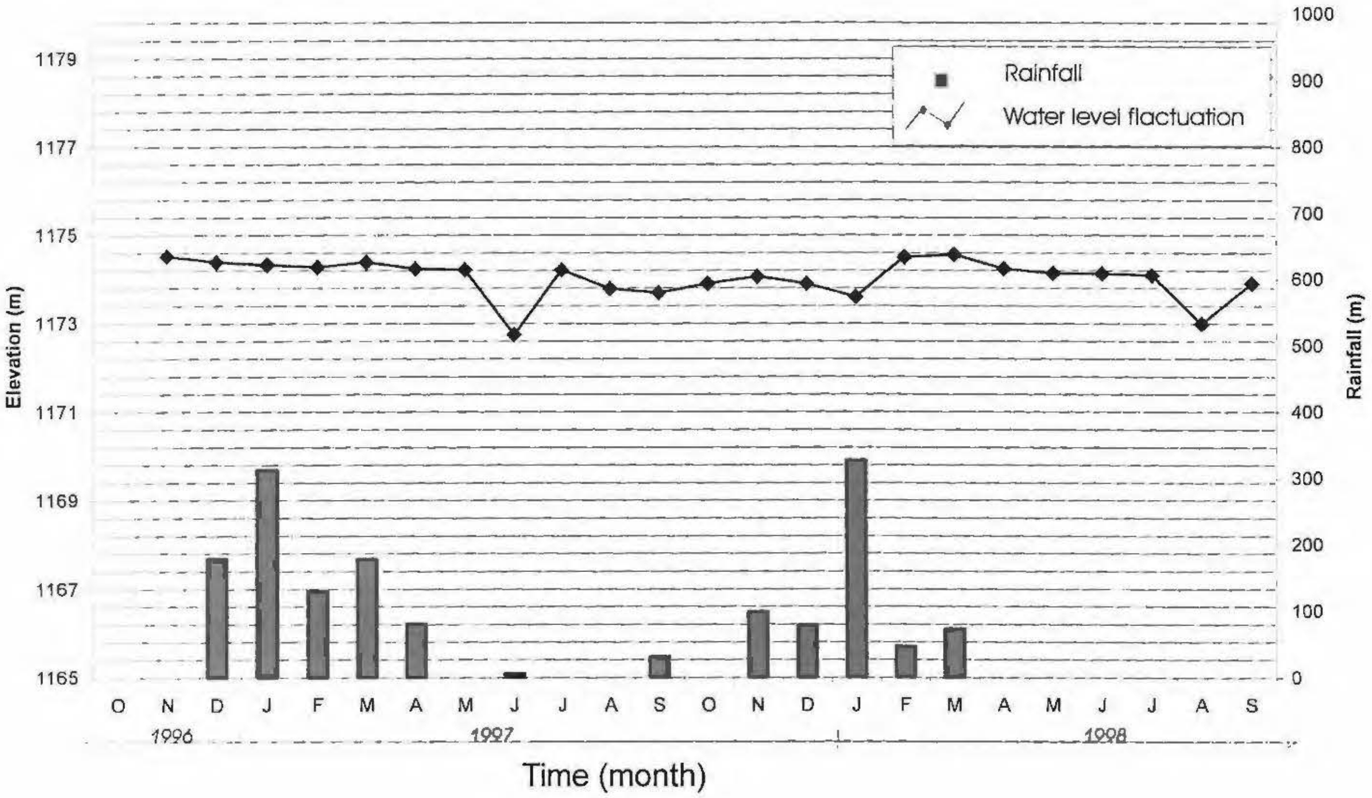
BH-ID	*BH-NAME*	*GRID REF*
6-KWEK-284	MOCHENI	QK 237264



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	54.39	1173.61
Nov-96	54.34	1173.66
Dec-96	54.59	1173.41
Jan-97	54.2	1173.8
Feb-97	53.86	1174.14
Mar-97	54.15	1173.85
Apr-97	54.48	1173.52
May-97	54.51	1173.49
Jun-97	54.54	1173.46
Jul-97	54.28	1173.72
Aug-97	54.38	1173.62
Sep-97	54.42	1173.58
Oct-97	54.39	1173.61
Nov-97	54.34	1173.66
Dec-97	54.41	1173.59
Jan-98	54.35	1173.65
Feb-98	54.3	1173.7
Mar-98	54.31	1173.69
Apr-98	54.22	1173.78
May-98	53.99	1174.01
Jun-98	54.21	1173.79
Jul-98		
Aug-98		
Sep-98		

WELL HYDROGRAPH & WATER LEVEL DATA

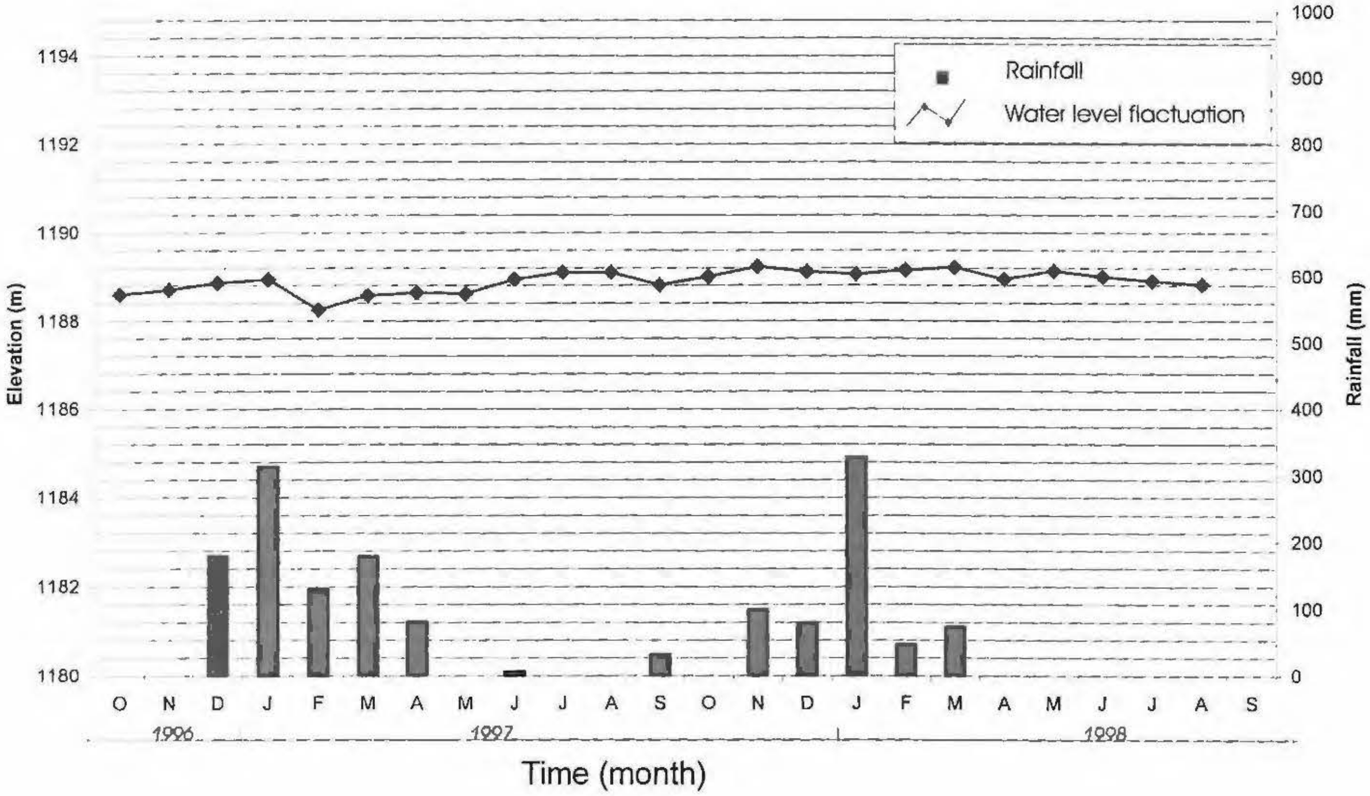
BH-ID	BH-NAME	GRID REF
6-KWEK-279	MABHIDHLI	QK 200268



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96		
Nov-96	27.48	1174.52
Dec-96	27.61	1174.39
Jan-97	27.67	1174.33
Feb-97	27.72	1174.28
Mar-97	27.61	1174.39
Apr-97	27.76	1174.24
May-97	27.78	1174.22
Jun-97	29.25	1172.75
Jul-97	27.79	1174.21
Aug-97	28.22	1173.78
Sep-97	28.31	1173.69
Oct-97	28.1	1173.9
Nov-97	27.94	1174.06
Dec-97	28.1	1173.9
Jan-98	28.4	1173.6
Feb-98	27.5	1174.5
Mar-98	27.44	1174.56
Apr-98	27.76	1174.24
May-98	27.86	1174.14
Jun-98	27.33	1174.67
Jul-98	27.91	1174.09
Aug-98	27.25	1174.75
Sep-98	28.09	1173.91

WELL HYDROGRAPH & WATER LEVEL DATA

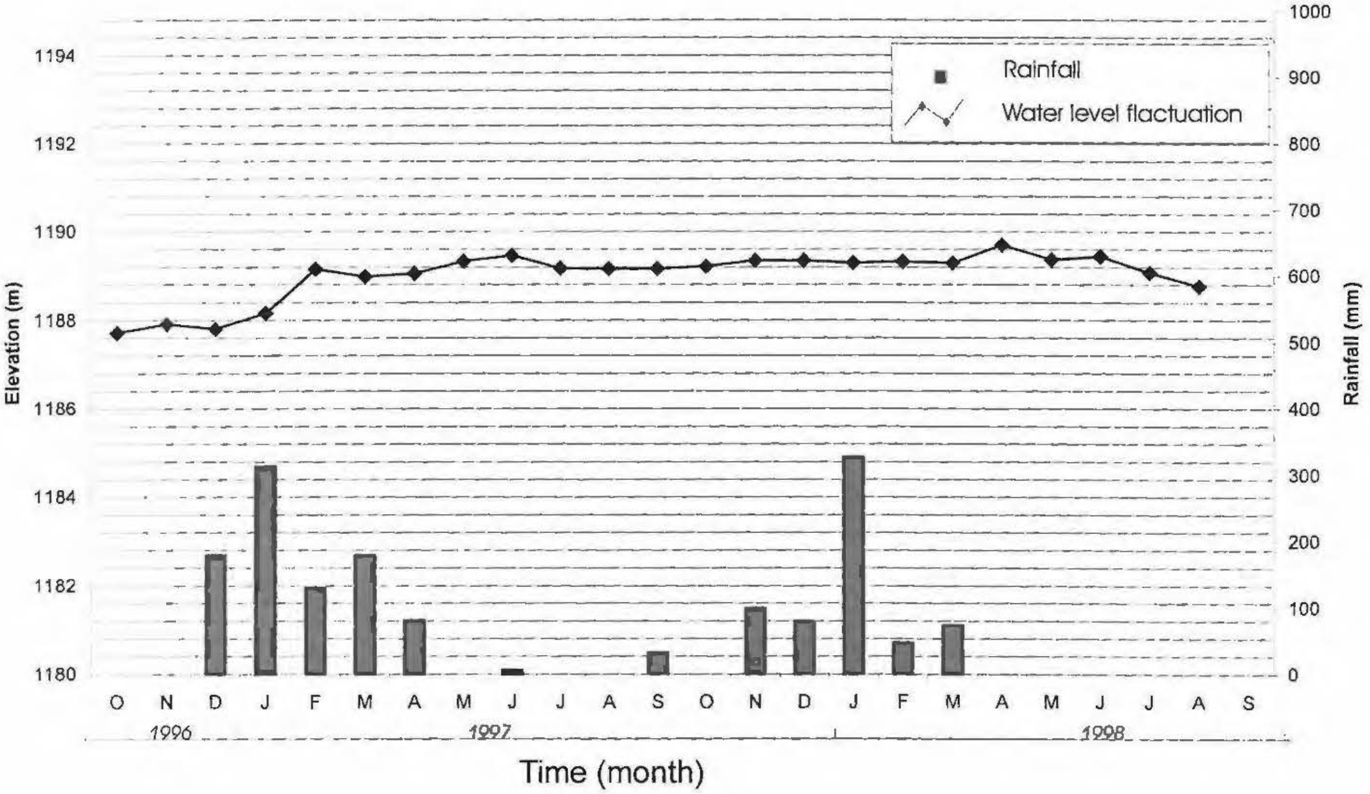
BH-ID	BH-NAME	GRID REF
6-KWEK-289	ST JUDES SC.	QK 355254



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	58.89	1189.11
Nov-96	59.03	1188.97
Dec-96	59.14	1188.86
Jan-97	59.06	1188.94
Feb-97	59.75	1188.25
Mar-97	59.42	1188.58
Apr-97	59.36	1188.64
May-97	59.39	1188.61
Jun-97	59.06	1188.94
Jul-97	58.9	1189.1
Aug-97	58.9	1189.1
Sep-97	59.19	1188.81
Oct-97	59	1189
Nov-97	58.77	1189.23
Dec-97	58.89	1189.11
Jan-98	58.95	1189.05
Feb-98	58.85	1189.15
Mar-98	58.79	1189.21
Apr-98	59.05	1188.95
May-98	58.87	1189.13
Jun-98	59	1189
Jul-98	59.1	1188.9
Aug-98	59.18	1188.82
Sep-98		

WELL HYDROGRAPH & WATER LEVEL DATA

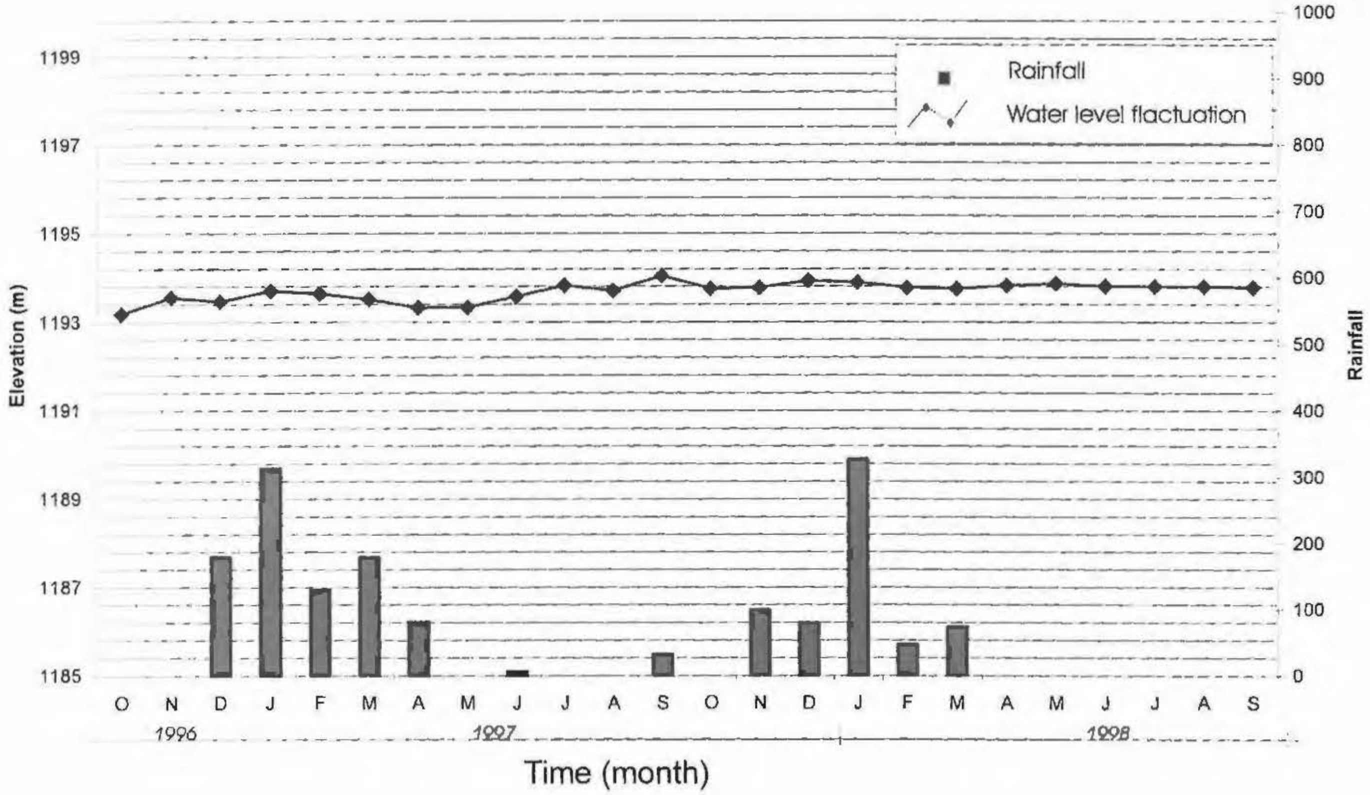
BH-ID	BH-NAME	GRID REF
6-KWEK-288	SALISBURY DIP	QK 363286



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	21.28	1187.72
Nov-96	21.08	1187.92
Dec-96	21.2	1187.8
Jan-97	20.84	1188.16
Feb-97	19.85	1189.15
Mar-97	20.02	1188.98
Apr-97	19.95	1189.05
May-97	19.67	1189.33
Jun-97	19.54	1189.46
Jul-97	19.83	1189.17
Aug-97	19.84	1189.16
Sep-97	19.84	1189.16
Oct-97	19.79	1189.21
Nov-97	19.66	1189.34
Dec-97	19.66	1189.34
Jan-98	19.71	1189.29
Feb-98	19.68	1189.32
Mar-98	19.71	1189.29
Apr-98	19.3	1189.7
May-98	19.63	1189.37
Jun-98	19.56	1189.44
Jul-98	19.92	1189.08
Aug-98	20.23	1188.77
Sep-98		

WELL HYDROGRAPH & WATER LEVEL DATA

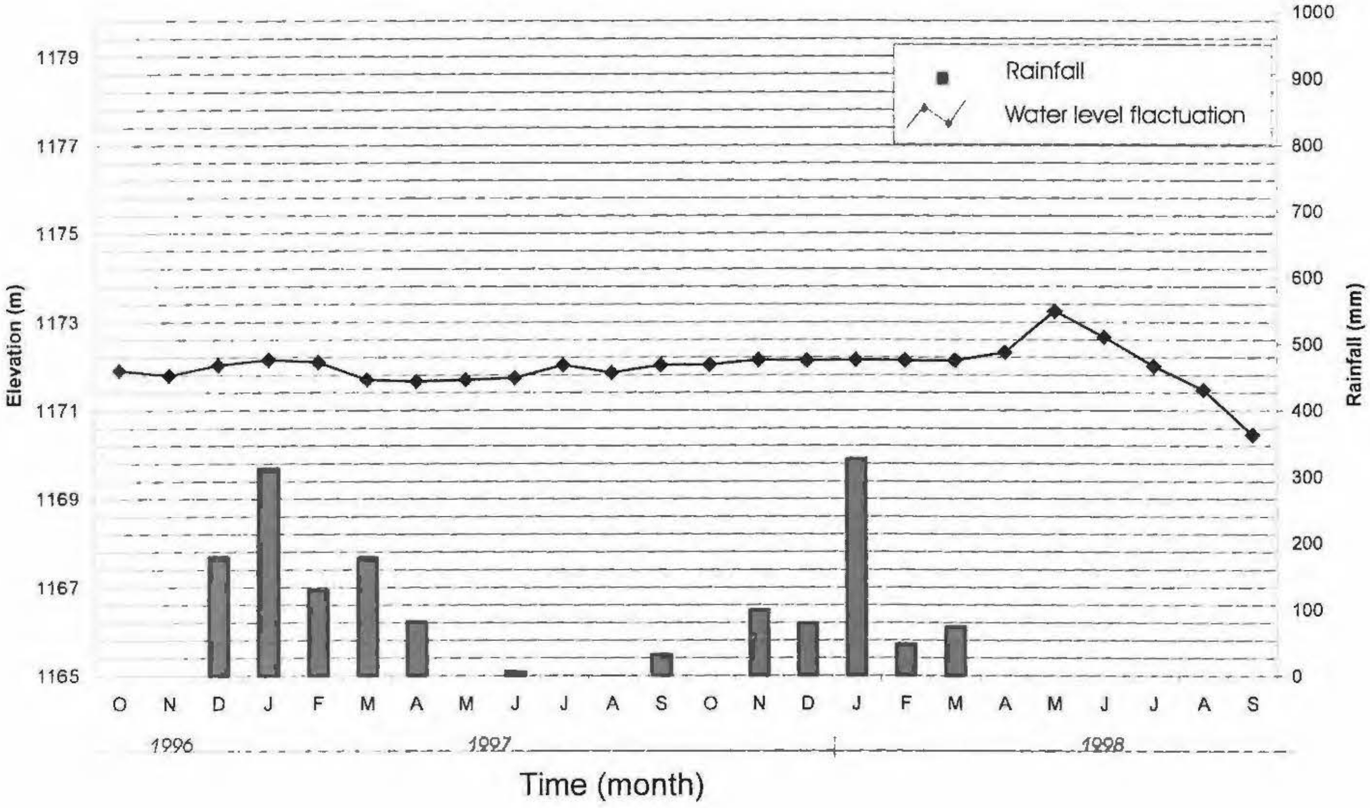
BH-ID	BH-NAME	GRID REF
6-KWEK-169	BHOBHO	QK 293275



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	62.82	1193.18
Nov-96	62.45	1193.55
Dec-96	62.54	1193.46
Jan-97	62.3	1193.7
Feb-97	62.36	1193.64
Mar-97	62.49	1193.51
Apr-97	62.68	1193.32
May-97	62.67	1193.33
Jun-97	62.42	1193.58
Jul-97	62.18	1193.82
Aug-97	62.3	1193.7
Sep-97	61.96	1194.04
Oct-97	62.25	1193.75
Nov-97	62.23	1193.77
Dec-97	62.07	1193.93
Jan-98	62.11	1193.89
Feb-98	62.23	1193.77
Mar-98	62.25	1193.75
Apr-98	62.18	1193.82
May-98	62.13	1193.87
Jun-98	62.19	1193.81
Jul-98	62.2	1193.8
Aug-98	61.98	1194.02
Sep-98	62.22	1193.78

WELL HYDROGRAPH & WATER LEVEL DATA

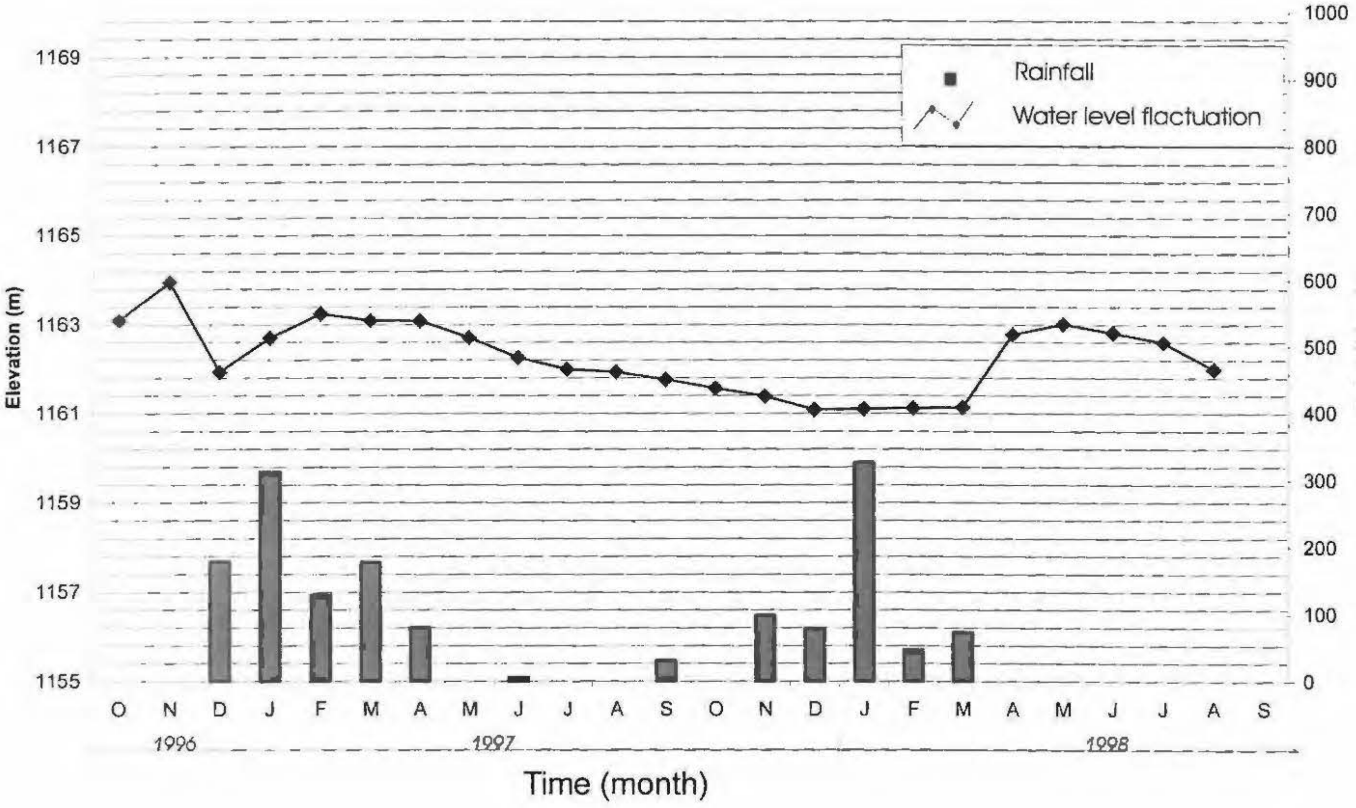
BH-ID	BH-NAME	GRID REF
6-KWEK-165	NTANGWE 3	QK216267



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	43.09	1171.91
Nov-96	43.21	1171.79
Dec-96	42.98	1172.02
Jan-97	42.85	1172.15
Feb-97	42.91	1172.09
Mar-97	43.31	1171.69
Apr-97	43.34	1171.66
May-97	43.31	1171.69
Jun-97	43.27	1171.73
Jul-97	42.98	1172.02
Aug-97	43.15	1171.85
Sep-97	42.98	1172.02
Oct-97	42.97	1172.03
Nov-97	42.86	1172.14
Dec-97	42.87	1172.13
Jan-98	42.86	1172.14
Feb-98	42.87	1172.13
Mar-98	42.87	1172.13
Apr-98	42.69	1172.31
May-98	41.75	1173.25
Jun-98	42.34	1172.66
Jul-98	43	1172
Aug-98	43.53	1171.47
Sep-98	44.55	1170.45

WELL HYDROGRAPH & WATER LEVEL DATA

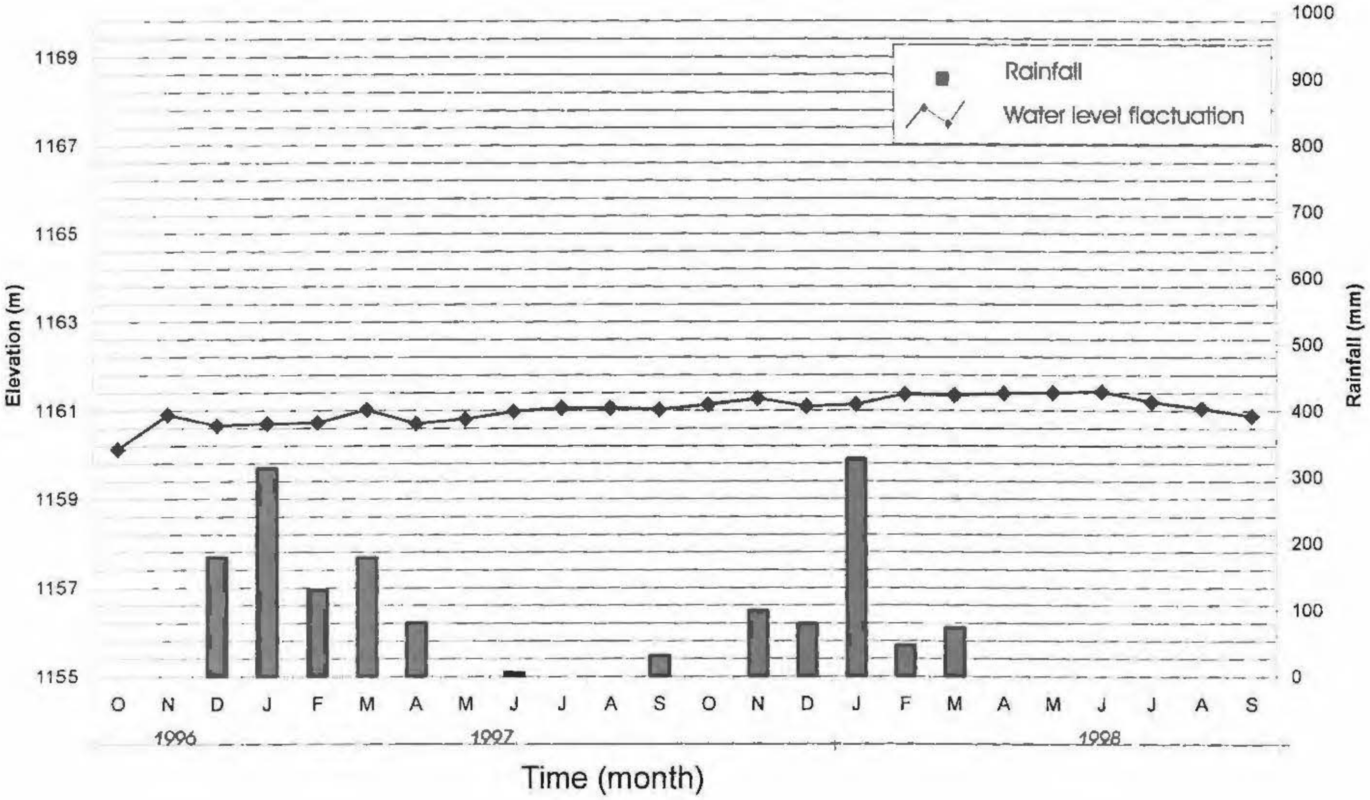
BH-ID	BH-NAME	GRID REF
6-KWEK-168	NTANGWE 1	QK270264



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	64.9	1163.1
Nov-96	64.04	1163.96
Dec-96	66.08	1161.92
Jan-97	65.3	1162.7
Feb-97	64.75	1163.25
Mar-97	64.9	1163.1
Apr-97	64.91	1163.09
May-97	65.29	1162.71
Jun-97	65.75	1162.25
Jul-97	66.01	1161.99
Aug-97	66.07	1161.93
Sep-97	66.24	1161.76
Oct-97	66.44	1161.56
Nov-97	66.62	1161.38
Dec-97	66.92	1161.08
Jan-98	66.9	1161.1
Feb-98	66.88	1161.12
Mar-98	66.86	1161.14
Apr-98	65.22	1162.78
May-98	64.98	1163.02
Jun-98	65.18	1162.82
Jul-98	65.4	1162.6
Aug-98	66.01	1161.99
Sep-98		

WELL HYDROGRAPH & WATER LEVEL DATA

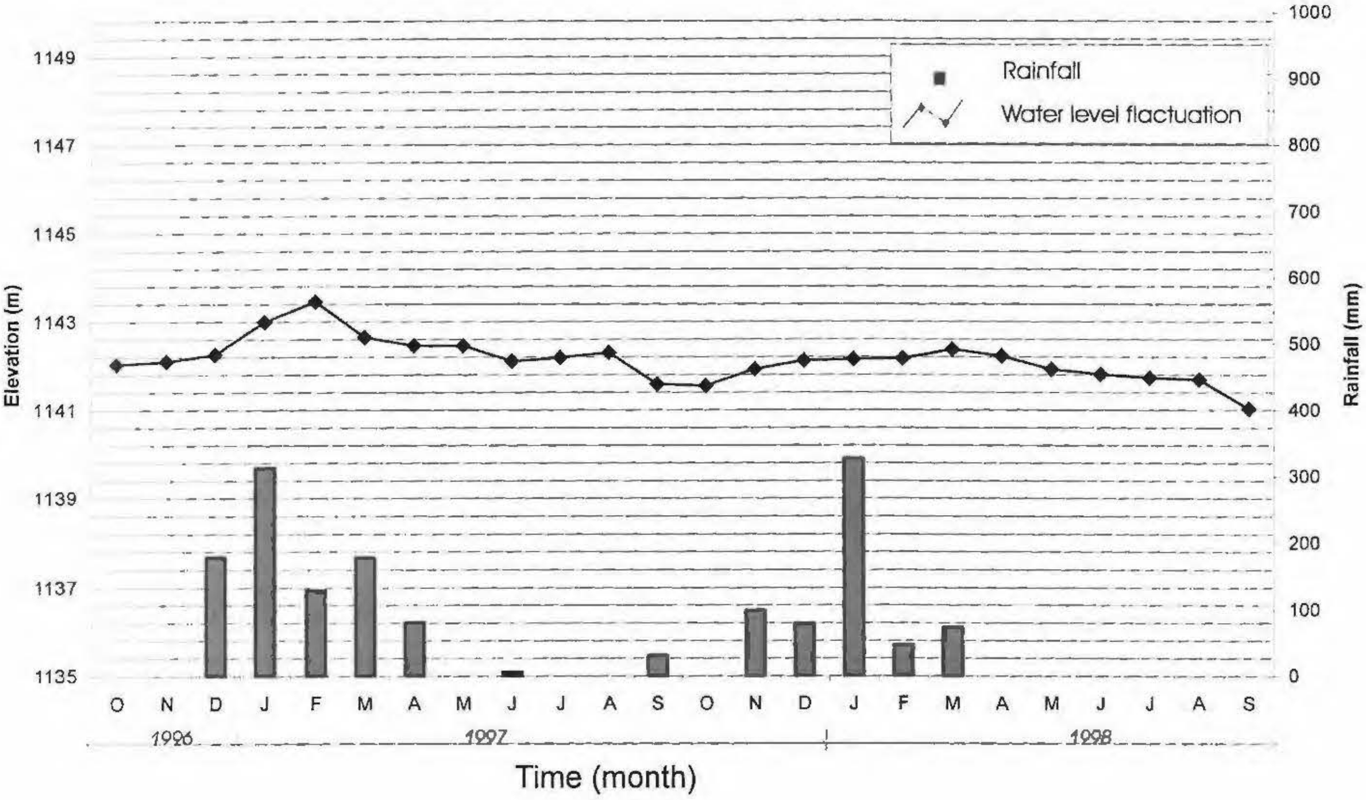
BH-ID	BH-NAME	GRID REF
6-KWEK-173	THUTHUKO	QK166310



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	57.88	1160.12
Nov-96	57.09	1160.91
Dec-96	57.34	1160.66
Jan-97	57.29	1160.71
Feb-97	57.28	1160.72
Mar-97	56.98	1161.02
Apr-97	57.29	1160.71
May-97	57.19	1160.81
Jun-97	57.02	1160.98
Jul-97	56.94	1161.06
Aug-97	56.94	1161.06
Sep-97	56.98	1161.02
Oct-97	56.89	1161.13
Nov-97	56.73	1161.27
Dec-97	56.91	1161.09
Jan-98	56.86	1161.14
Feb-98	56.63	1161.37
Mar-98	56.98	1161.02
Apr-98	56.61	1161.39
May-98	56.6	1161.4
Jun-98	56.57	1161.43
Jul-98	57	1161
Aug-98	56.95	1161.05
Sep-98	57.12	1160.88

WELL HYDROGRAPH & WATER LEVEL DATA

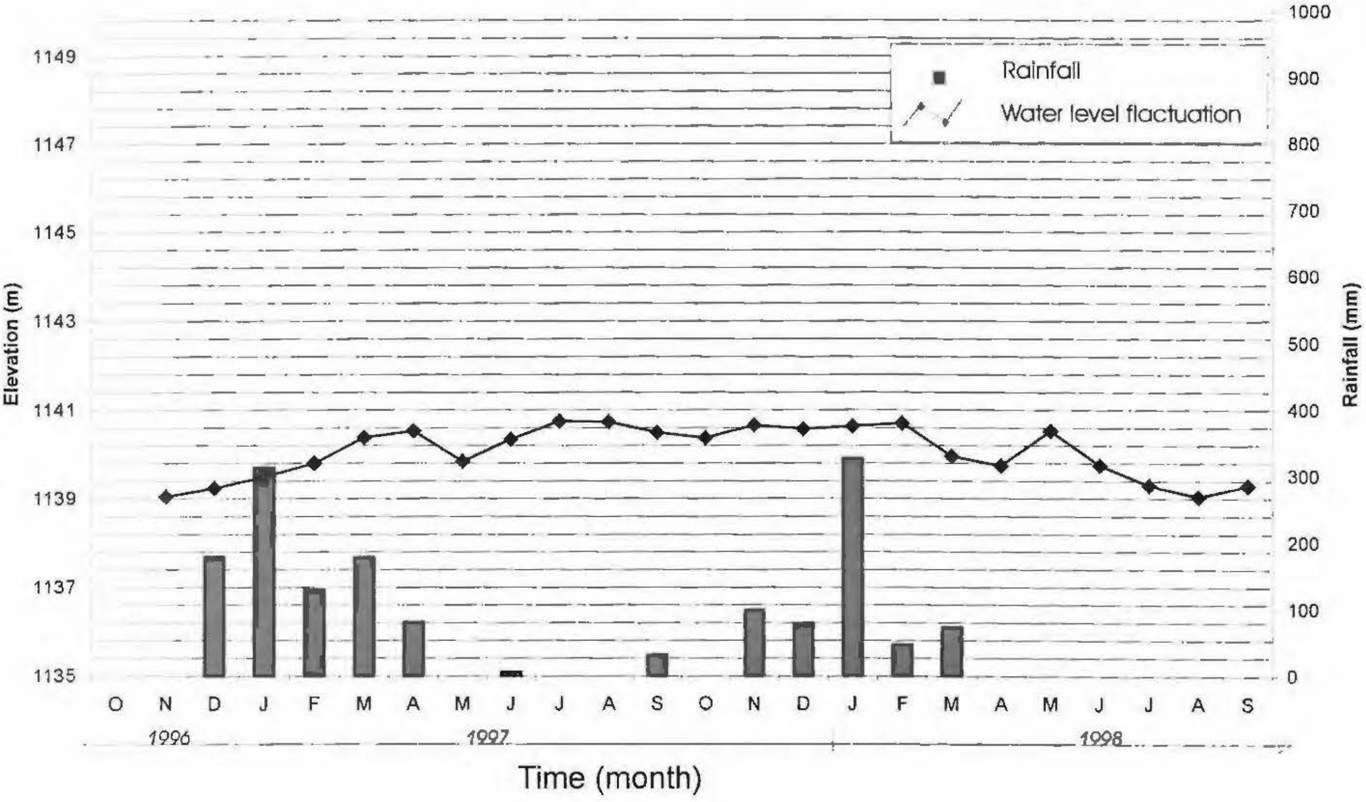
BH-ID	BH-NAME	GRID REF
6-KWEK-174	STOLO	QK124317



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	2.96	1142.04
Nov-96	2.89	1142.11
Dec-96	2.74	1142.26
Jan-97	2	1143
Feb-97	1.54	1143.46
Mar-97	2.35	1142.65
Apr-97	2.54	1142.46
May-97	2.54	1142.46
Jun-97	2.89	1142.11
Jul-97	2.81	1142.19
Aug-97	2.7	1142.3
Sep-97	3.41	1141.59
Oct-97	3.45	1141.55
Nov-97	3.08	1141.92
Dec-97	2.88	1142.12
Jan-98	3.36	1141.64
Feb-98	3.93	1141.07
Mar-98	2.63	1142.37
Apr-98	2.78	1142.22
May-98	3.08	1141.92
Jun-98	2.76	1142.24
Jul-98	3.27	1141.73
Aug-98	3.31	1141.69

WELL HYDROGRAPH & WATER LEVEL DATA

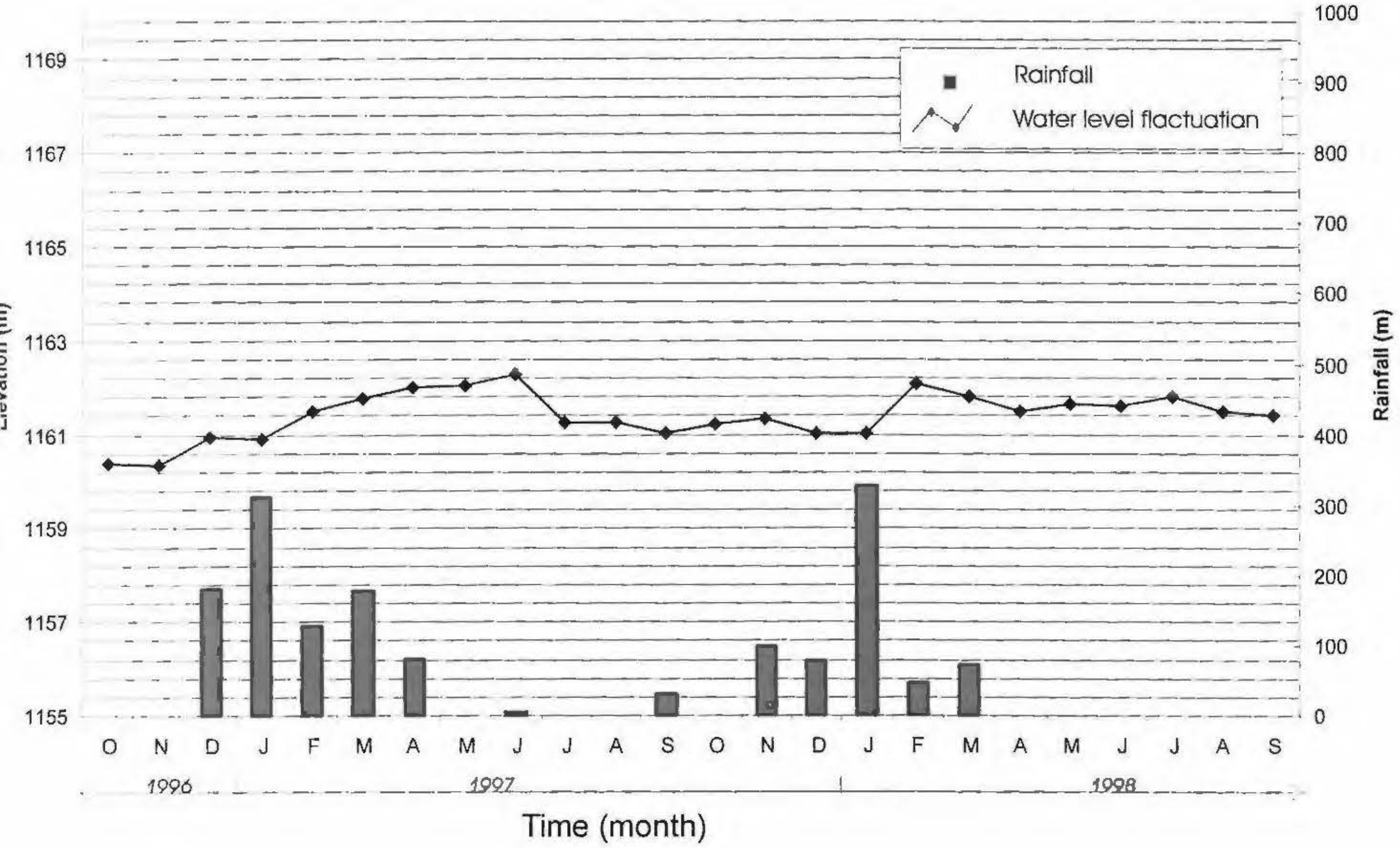
BH-ID	BH-NAME	GRID REF
6-KWEK-175	MATABA	QK104334



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96		
Nov-96	6.95	1139.05
Dec-96	6.77	1139.23
Jan-97	6.5	1139.5
Feb-97	6.2	1139.8
Mar-97	5.62	1140.38
Apr-97	5.47	1140.53
May-97	6.16	1139.84
Jun-97	5.66	1140.34
Jul-97	5.25	1140.75
Aug-97	5.27	1140.73
Sep-97	5.51	1140.49
Oct-97	5.63	1140.37
Nov-97	5.34	1140.66
Dec-97	5.43	1140.57
Jan-98	5.36	1140.64
Feb-98	5.3	1140.7
Mar-98	6.04	1139.96
Apr-98	6.26	1139.74
May-98	5.47	1140.53
Jun-98	6.25	1139.75
Jul-98	6.7	1139.3
Aug-98	6.96	1139.04
Sep-98	6.71	1139.29

WELL HYDROGRAPH & WATER LEVEL DATA

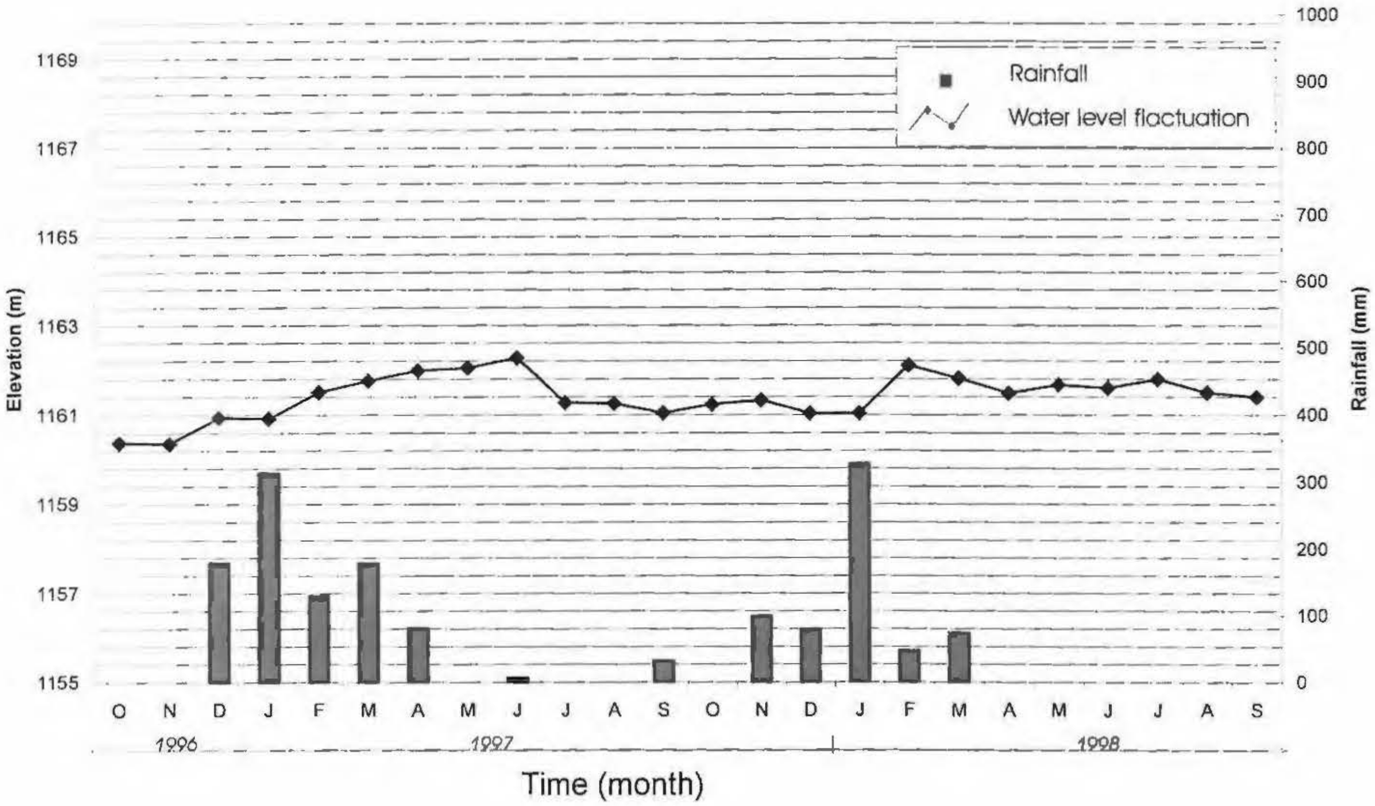
BH-ID	BH-NAME	GRID REF
6-KWEK-178	MKOBOGWE	QK311229



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	8.62	1160.38
Nov-96	8.64	1160.36
Dec-96	8.06	1160.94
Jan-97	8.08	1160.92
Feb-97	7.49	1161.51
Mar-97	7.24	1161.76
Apr-97	7.01	1161.99
May-97	6.95	1162.05
Jun-97	6.73	1162.27
Jul-97	7.73	1161.27
Aug-97	7.75	1161.25
Sep-97	7.96	1161.04
Oct-97	7.77	1161.23
Nov-97	7.68	1161.32
Dec-97	7.97	1161.03
Jan-98	7.97	1161.03
Feb-98	6.9	1162.1
Mar-98	7.19	1161.81
Apr-98	7.52	1161.48
May-98	7.33	1161.67
Jun-98	7.4	1161.6
Jul-98	7.2	1161.8
Aug-98	7.04	1161.96
Sep-98	7.6	1161.4

WELL HYDROGRAPH & WATER LEVEL DATA

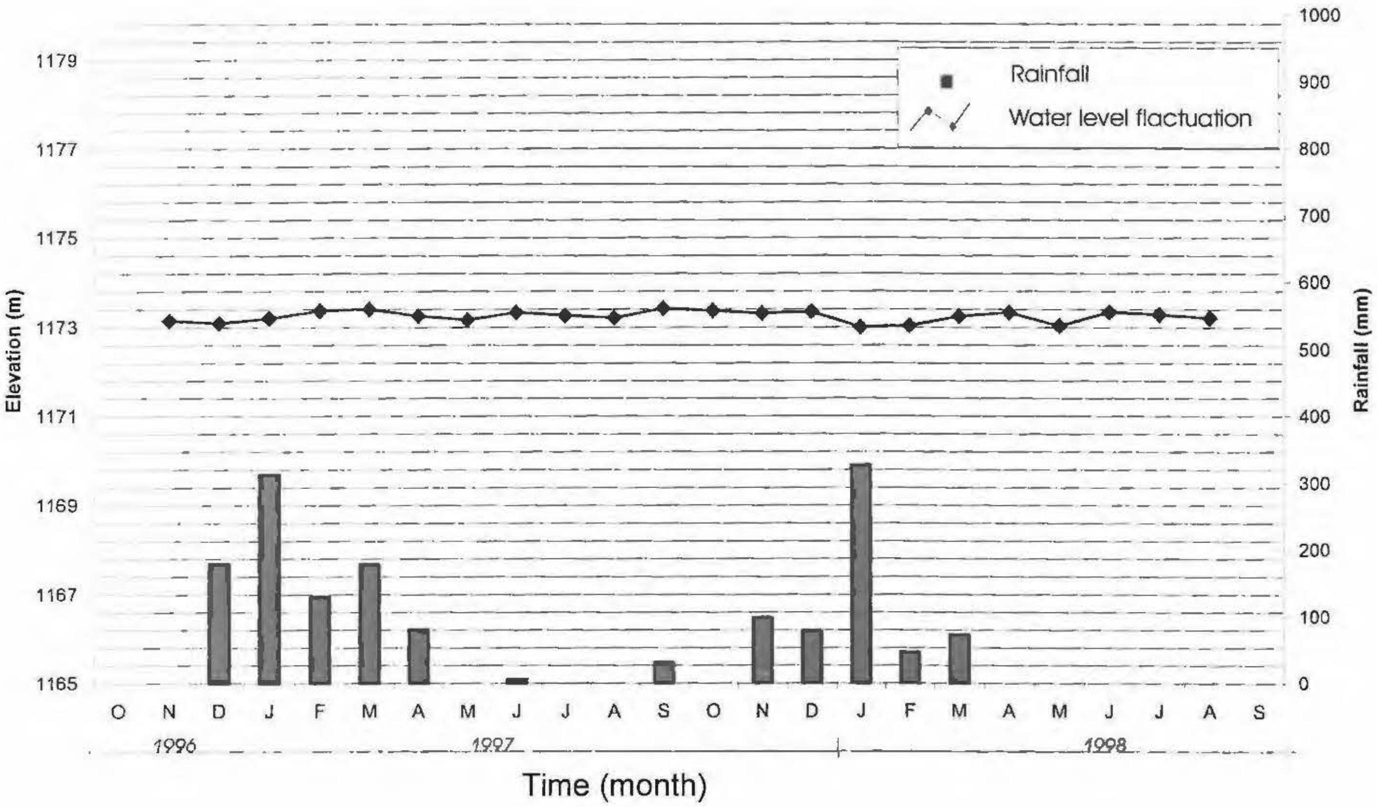
BH-ID	BH-NAME	GRID REF
6-KWEK-255	MKOBOGWE 1	QK149291



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	8.62	1160.38
Nov-96	8.64	1160.36
Dec-96	8.06	1160.94
Jan-97	8.08	1160.92
Feb-97	7.49	1161.51
Mar-97	7.24	1161.76
Apr-97	7.01	1161.99
May-97	6.95	1162.05
Jun-97	6.73	1162.27
Jul-97	7.73	1161.27
Aug-97	7.75	1161.25
Sep-97	7.96	1161.04
Oct-97	7.77	1161.23
Nov-97	7.68	1161.32
Dec-97	7.97	1161.03
Jan-98	7.97	1161.03
Feb-98	6.9	1162.1
Mar-98	7.19	1161.81
Apr-98	7.52	1161.48
May-98	7.33	1161.67
Jun-98	7.4	1161.6
Jul-98	7.2	1161.8
Aug-98	7.04	1161.96
Sep-98	7.6	1161.4

WELL HYDROGRAPH & WATER LEVEL DATA

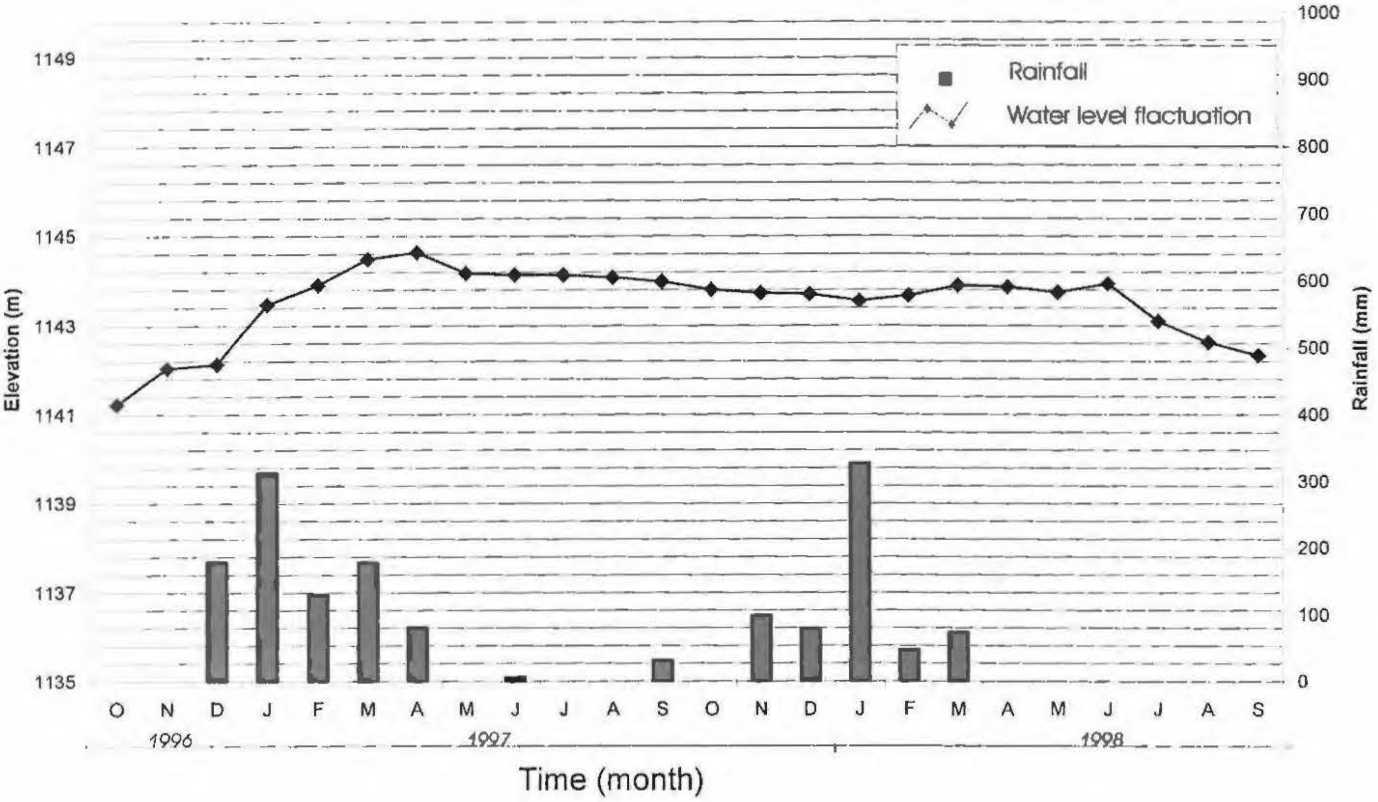
BH-ID	BH-NAME	GRID REF
6-KWEK-184	BUNYWANA	QK308260



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96		
Nov-96	70.85	1173.15
Dec-96	70.91	1173.09
Jan-97	70.8	1173.2
Feb-97	70.63	1173.37
Mar-97	70.6	1173.4
Apr-97	70.75	1173.25
May-97	70.84	1173.16
Jun-97	70.67	1173.33
Jul-97	70.74	1173.26
Aug-97	70.79	1173.21
Sep-97	70.59	1173.41
Oct-97	70.63	1173.37
Nov-97	70.69	1173.31
Dec-97	70.65	1173.35
Jan-98	71	1173
Feb-98	70.97	1173.03
Mar-98	70.76	1173.24
Apr-98	70.67	1173.33
May-98	70.97	1173.03
Jun-98	70.66	1173.34
Jul-98	70.79	1173.21
Aug-98	70.79	1173.21

WELL HYDROGRAPH & WATER LEVEL DATA

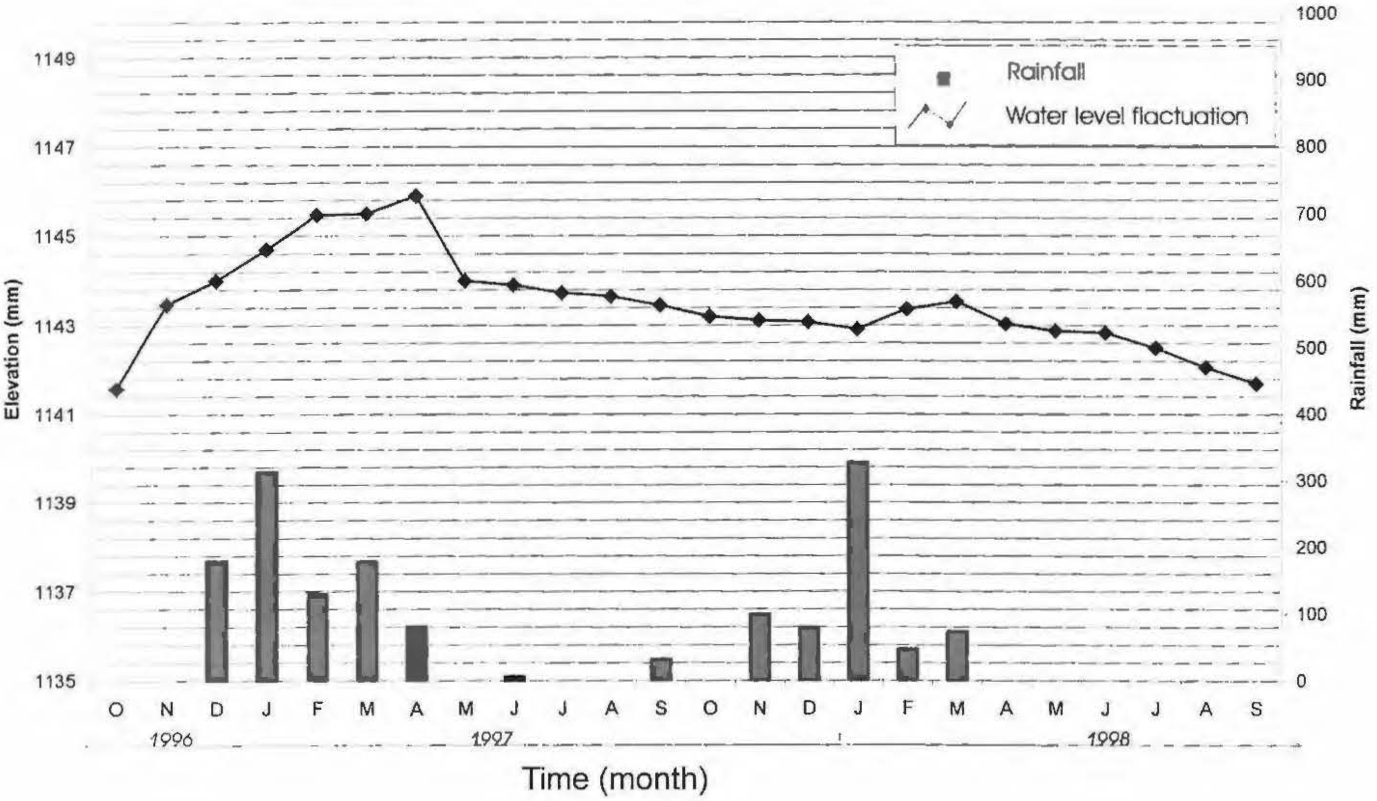
BH-ID	BH-NAME	GRID REF
6-KWEK-187	MUNYAMANA1	QK403307



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	18.77	1141.23
Nov-96	17.96	1142.04
Dec-96	17.87	1142.13
Jan-97	16.53	1143.47
Feb-97	16.09	1143.91
Mar-97	15.51	1144.49
Apr-97	15.36	1144.64
May-97	15.83	1144.17
Jun-97	15.39	1144.61
Jul-97	15.58	1144.42
Aug-97	15.67	1144.33
Sep-97	15.6	1144.4
Oct-97	16.2	1143.8
Nov-97	16.27	1143.73
Dec-97	16.3	1143.7
Jan-98	16.45	1143.55
Feb-98		
Mar-98	16.1	1143.9
Apr-98	16.13	1143.87
May-98	16.25	1143.75
Jun-98	16.06	1143.94
Jul-98	16.9	1143.1
Aug-98	17.38	1142.62
Sep-98	17.67	1142.33

WELL HYDROGRAPH & WATER LEVEL DATA

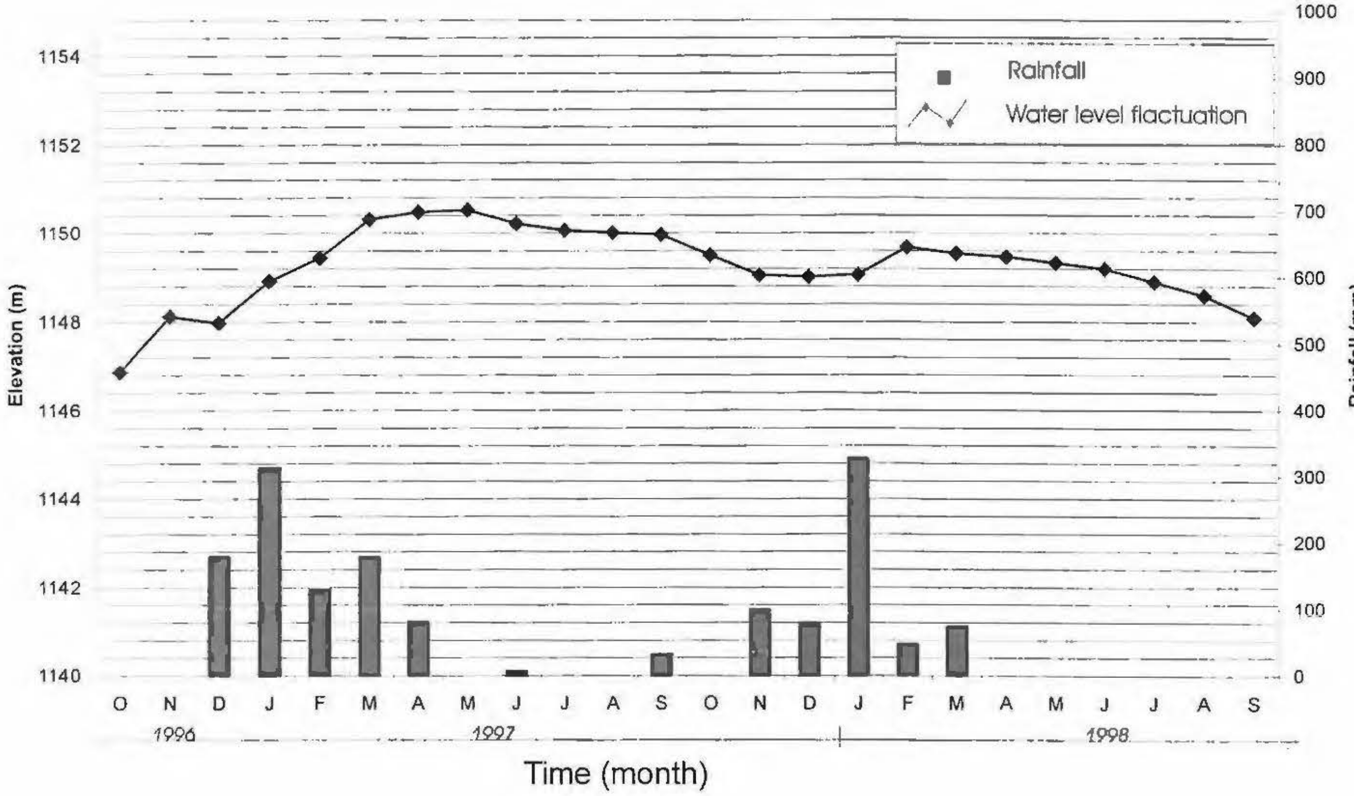
BH-ID	BH-NAME	GRID REF
6-KWEK-188	MUNYAMANA2	QK408302



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	19.42	1141.58
Nov-96	17.53	1143.47
Dec-96	17	1144
Jan-97	16.3	1144.7
Feb-97	15.53	1145.47
Mar-97	15.5	1145.5
Apr-97	15.1	1145.9
May-97	15.21	1145.79
Jun-97	17.09	1143.91
Jul-97	17.27	1143.73
Aug-97	17.35	1143.65
Sep-97	17.55	1143.45
Oct-97	17.8	1143.2
Nov-97	17.89	1143.11
Dec-97	17.92	1143.08
Jan-98	18.09	1142.91
Feb-98	17.64	1143.36
Mar-98	17.46	1143.54
Apr-98	17.96	1143.04
May-98	18.12	1142.88
Jun-98	18.16	1142.84
Jul-98	18.5	1142.5
Aug-98	18.94	1142.06
Sep-98	19.31	1141.69

WELL HYDROGRAPH & WATER LEVEL DATA

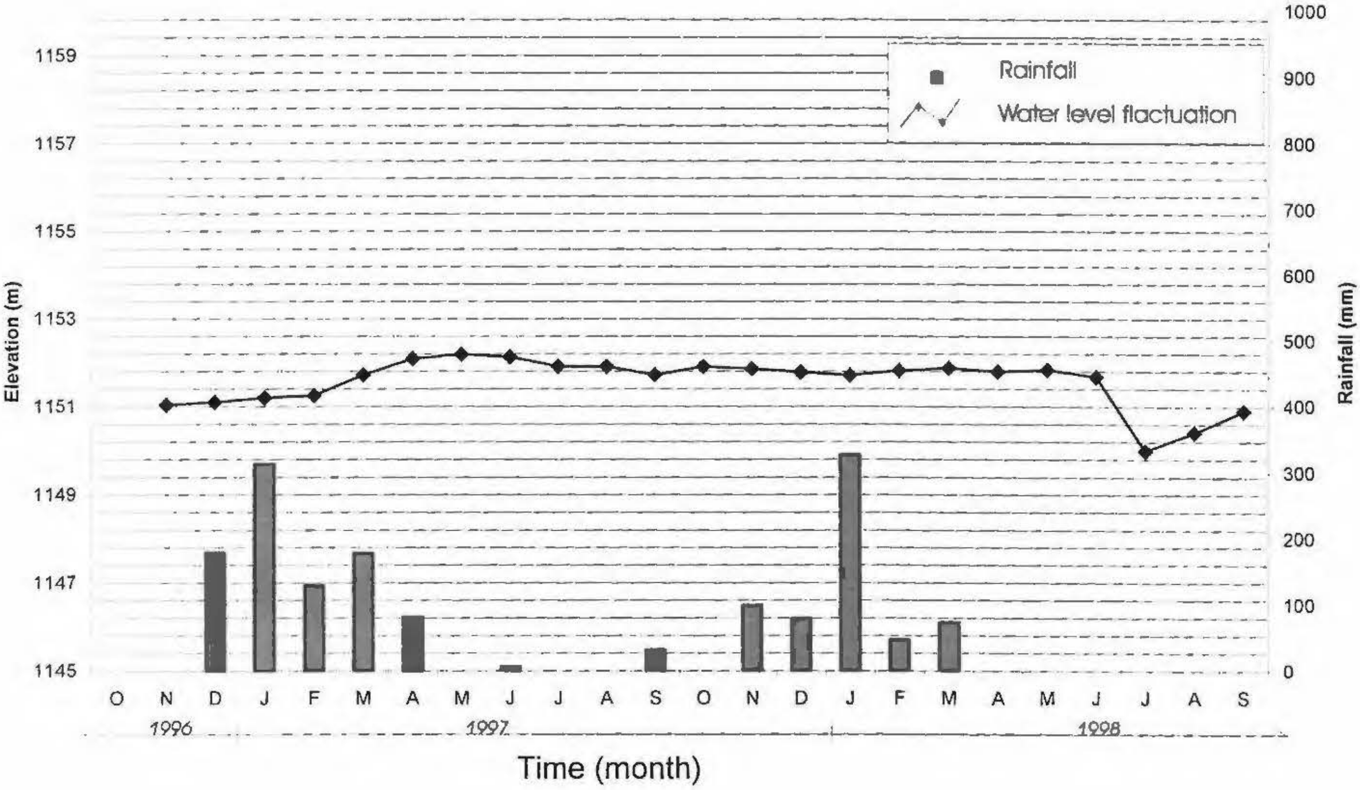
BH-ID	BH-NAME	GRID REF
6-KWEK-189	MBANGWA	QK403296



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	20.13	1146.87
Nov-96	18.88	1148.12
Dec-96	19.02	1147.98
Jan-97	18.08	1148.92
Feb-97	17.56	1149.44
Mar-97	16.69	1150.31
Apr-97	16.52	1150.48
May-97	16.48	1150.52
Jun-97	16.79	1150.21
Jul-97	16.94	1150.06
Aug-97	16.99	1150.01
Sep-97	17.04	1149.96
Oct-97	17.5	1149.5
Nov-97	17.95	1149.05
Dec-97	17.99	1149.01
Jan-98	17.94	1149.06
Feb-98	17.32	1149.68
Mar-98	17.46	1149.54
Apr-98	17.54	1149.46
May-98	17.67	1149.33
Jun-98	17.31	1149.69
Jul-98	18.1	1148.9
Aug-98	19.18	1147.82
Sep-98	18.91	1148.09

WELL HYDROGRAPH & WATER LEVEL DATA

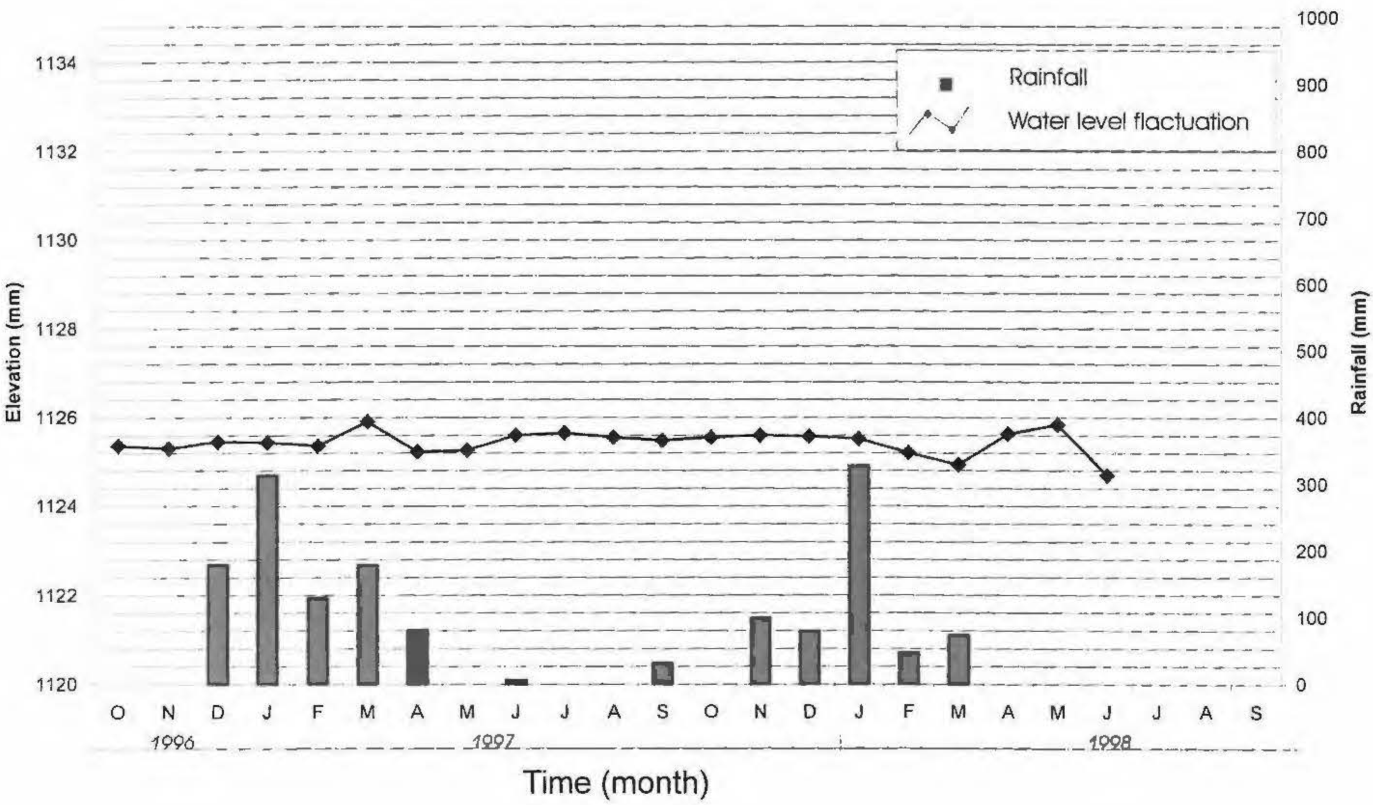
BH-ID	BH-NAME	GRID REF
6-KWEK-210	BAMBANANI	QK370318



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96		
Nov-96	19.96	1151.04
Dec-96	19.9	1151.1
Jan-97	19.8	1151.2
Feb-97	19.75	1151.25
Mar-97	19.28	1151.72
Apr-97	18.91	1152.09
May-97	18.81	1152.19
Jun-97	18.87	1152.13
Jul-97	19.09	1151.91
Aug-97	19.1	1151.9
Sep-97	19.28	1151.72
Oct-97	19.1	1151.9
Nov-97	19.14	1151.86
Dec-97	19.22	1151.78
Jan-98	19.29	1151.71
Feb-98	19.18	1151.82
Mar-98	19.12	1151.88
Apr-98	19.2	1151.8
May-98	19.16	1151.84
Jun-98	19.32	1151.68
Jul-98	21	1150
Aug-98	20.59	1150.41
Sep-98	20.1	1150.9

WELL HYDROGRAPH & WATER LEVEL DATA

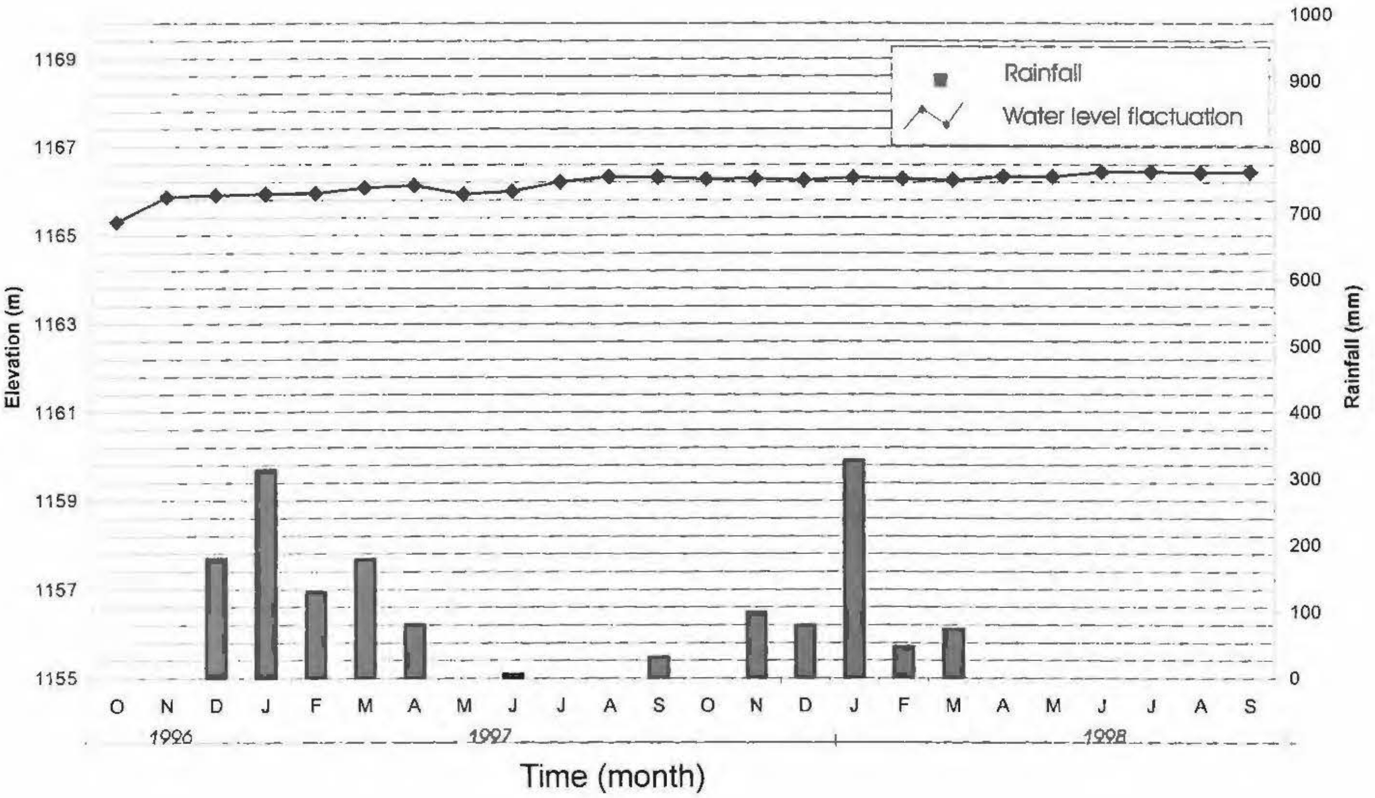
BH-ID	BH-NAME	GRID REF
6-KWEK-244	GWARAZIMBA	QK338352



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	33.63	1125.37
Nov-96	33.69	1125.31
Dec-96	33.55	1125.45
Jan-97	33.56	1125.44
Feb-97	33.64	1125.36
Mar-97	33.09	1125.91
Apr-97	33.77	1125.23
May-97	33.74	1125.26
Jun-97	33.4	1125.6
Jul-97	33.35	1125.65
Aug-97	33.45	1125.55
Sep-97	33.52	1125.48
Oct-97		
Nov-97	33.4	1125.6
Dec-97	33.42	1125.58
Jan-98	33.48	1125.52
Feb-98	33.8	1125.2
Mar-98	34.06	1124.94
Apr-98	33.37	1125.63
May-98	33.16	1125.84
Jun-98	34.3	1124.7
Jul-98		
Aug-98		
Sep-98		

WELL HYDROGRAPH & WATER LEVEL DATA

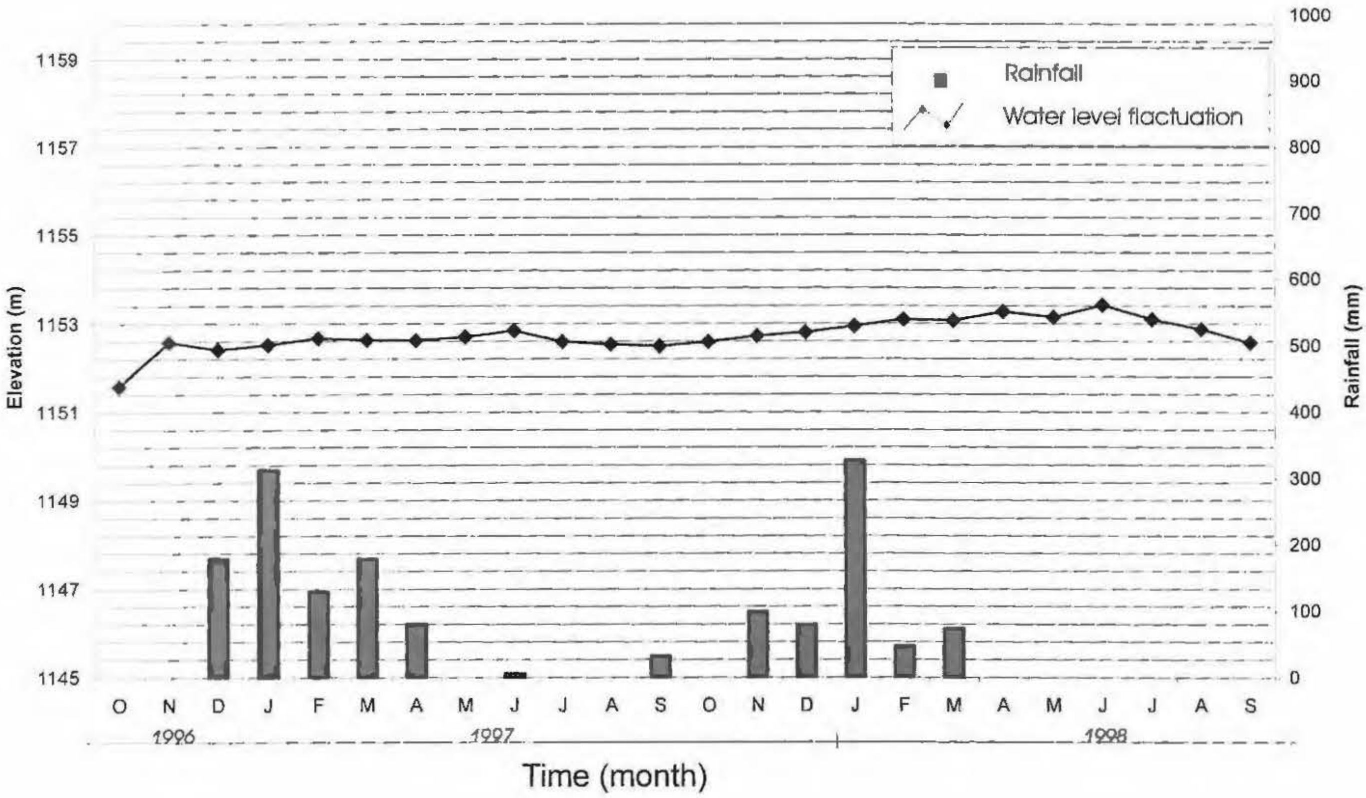
BH-ID	BH-NAME	GRID REF
6-KWEK-221	SINANGENI	QK322309



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	51.69	1165.31
Nov-96	51.13	1165.87
Dec-96	51.09	1165.91
Jan-97	51.06	1165.94
Feb-97	51.05	1165.95
Mar-97	50.92	1166.08
Apr-97	50.87	1166.13
May-97	51.07	1165.93
Jun-97	51	1166
Jul-97	50.79	1166.21
Aug-97	50.68	1166.32
Sep-97	50.69	1166.31
Oct-97	50.73	1166.27
Nov-97	50.72	1166.28
Dec-97	50.76	1166.24
Jan-98	50.7	1166.3
Feb-98	50.72	1166.28
Mar-98	50.75	1166.25
Apr-98	50.67	1166.33
May-98	50.67	1166.33
Jun-98	50.22	1166.78
Jul-98	50.56	1166.44
Aug-98	50.07	1166.93
Sep-98	50.57	1166.43

WELL HYDROGRAPH & WATER LEVEL DATA

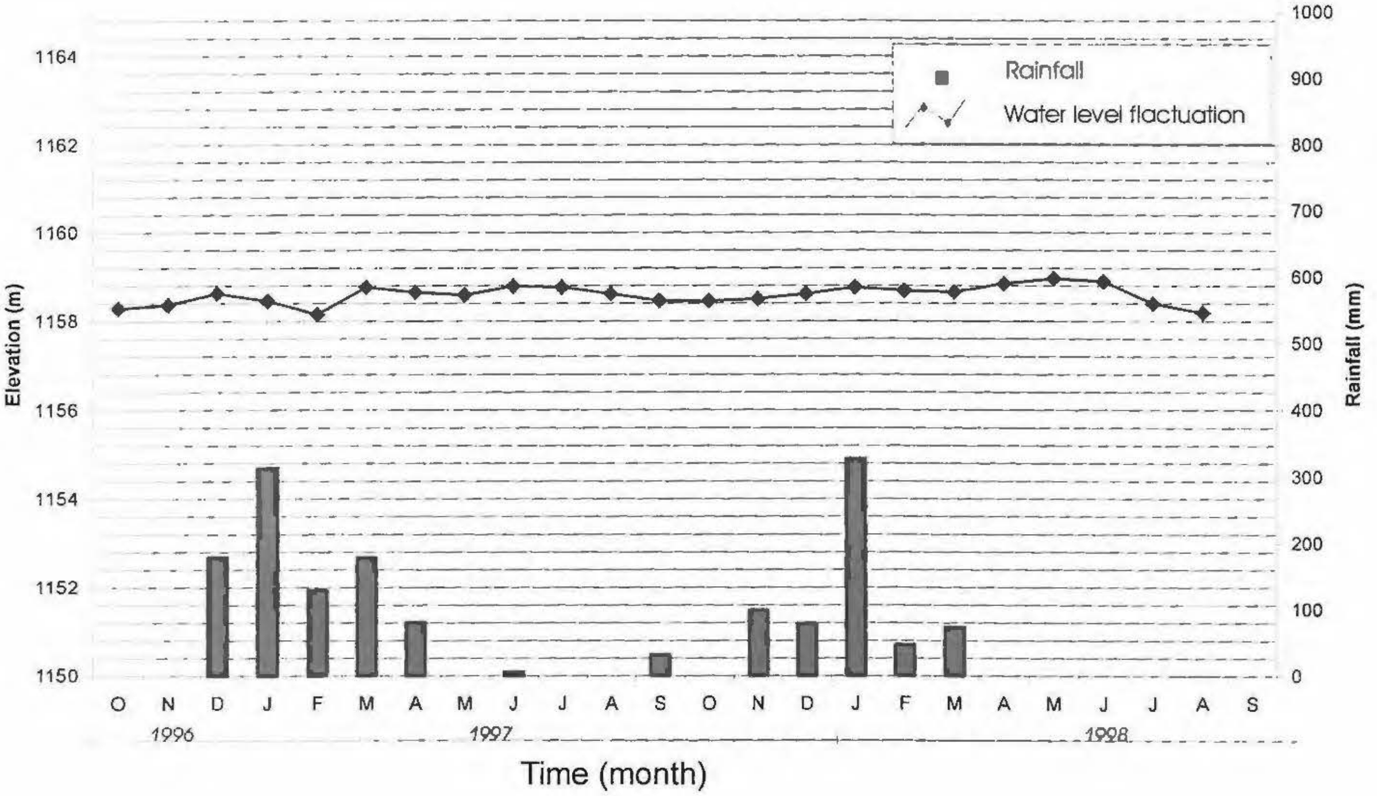
BH-ID	BH-NAME	GRID REF
6-KWEK-207	THABANI	QK365315



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	22.42	1151.58
Nov-96	21.42	1152.58
Dec-96	21.59	1152.41
Jan-97	21.48	1152.52
Feb-97	21.33	1152.67
Mar-97	21.37	1152.63
Apr-97	21.38	1152.62
May-97	21.3	1152.7
Jun-97	21.16	1152.84
Jul-97	21.41	1152.59
Aug-97	21.47	1152.53
Sep-97	21.51	1152.49
Oct-97	21.42	1152.58
Nov-97	21.28	1152.72
Dec-97	21.2	1152.8
Jan-98	21.06	1152.94
Feb-98	20.91	1153.09
Mar-98	20.93	1153.07
Apr-98	20.73	1153.27
May-98	20.86	1153.14
Jun-98	20.58	1153.42
Jul-98	20.9	1153.1
Aug-98	21.13	1152.87
Sep-98	21.43	1152.57

WELL HYDROGRAPH & WATER LEVEL DATA

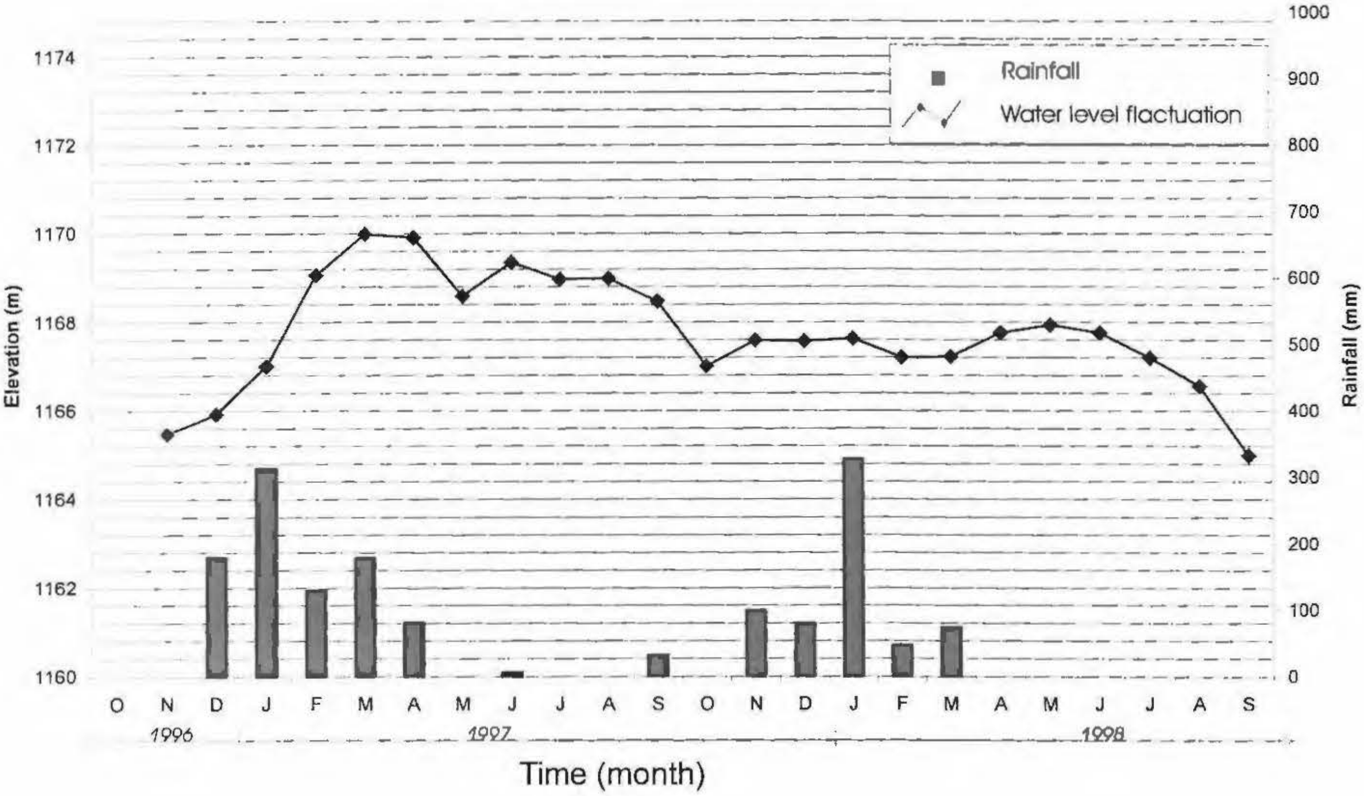
BH-ID	BH-NAME	GRID REF
6-KWEK-190	MAFUSINI	QK409232



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	23.71	1158.29
Nov-96	23.63	1158.37
Dec-96	23.37	1158.63
Jan-97	23.54	1158.46
Feb-97	23.85	1158.15
Mar-97	23.23	1158.77
Apr-97	23.35	1158.65
May-97	23.41	1158.59
Jun-97	23.21	1158.79
Jul-97	23.23	1158.77
Aug-97	23.38	1158.62
Sep-97	23.54	1158.46
Oct-97	23.55	1158.45
Nov-97	22.7	1159.3
Dec-97	22.72	1159.28
Jan-98	23.24	1158.76
Feb-98	23.31	1158.69
Mar-98	23.34	1158.66
Apr-98	23.15	1158.85
May-98	23.03	1158.97
Jun-98	23.1	1158.9
Jul-98	23.6	1158.4
Aug-98	23.81	1158.19
Sep-98		

WELL HYDROGRAPH & WATER LEVEL DATA

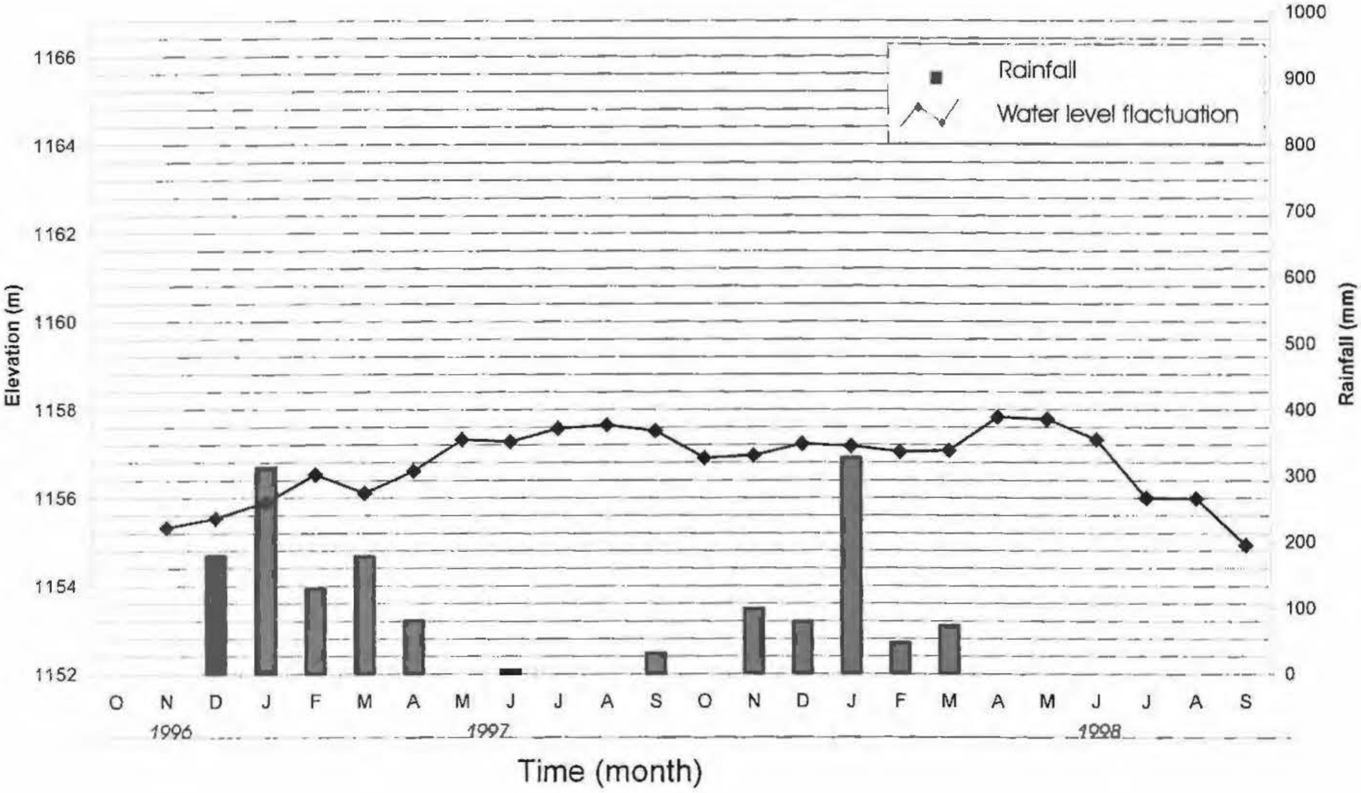
BH-ID	BH-NAME	GRID REF
6-KWEK-196	PHENDUKA	QK409261



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96		
Nov-96	26.53	1165.47
Dec-96	26.08	1165.92
Jan-97	25	1167
Feb-97	22.94	1169.06
Mar-97	22.01	1169.99
Apr-97	22.09	1169.91
May-97	23.41	1168.59
Jun-97	22.65	1169.35
Jul-97	23.03	1168.97
Aug-97	23.01	1168.99
Sep-97	23.53	1168.47
Oct-97	25	1167
Nov-97	24.41	1167.59
Dec-97	24.43	1167.57
Jan-98	24.37	1167.63
Feb-98	24.8	1167.2
Mar-98	24.78	1167.22
Apr-98	24.24	1167.76
May-98	24.06	1167.94
Jun-98	24.24	1167.76
Jul-98	24.8	1167.2
Aug-98	25.44	1166.56
Sep-98	27.01	1164.99

WELL HYDROGRAPH & WATER LEVEL DATA

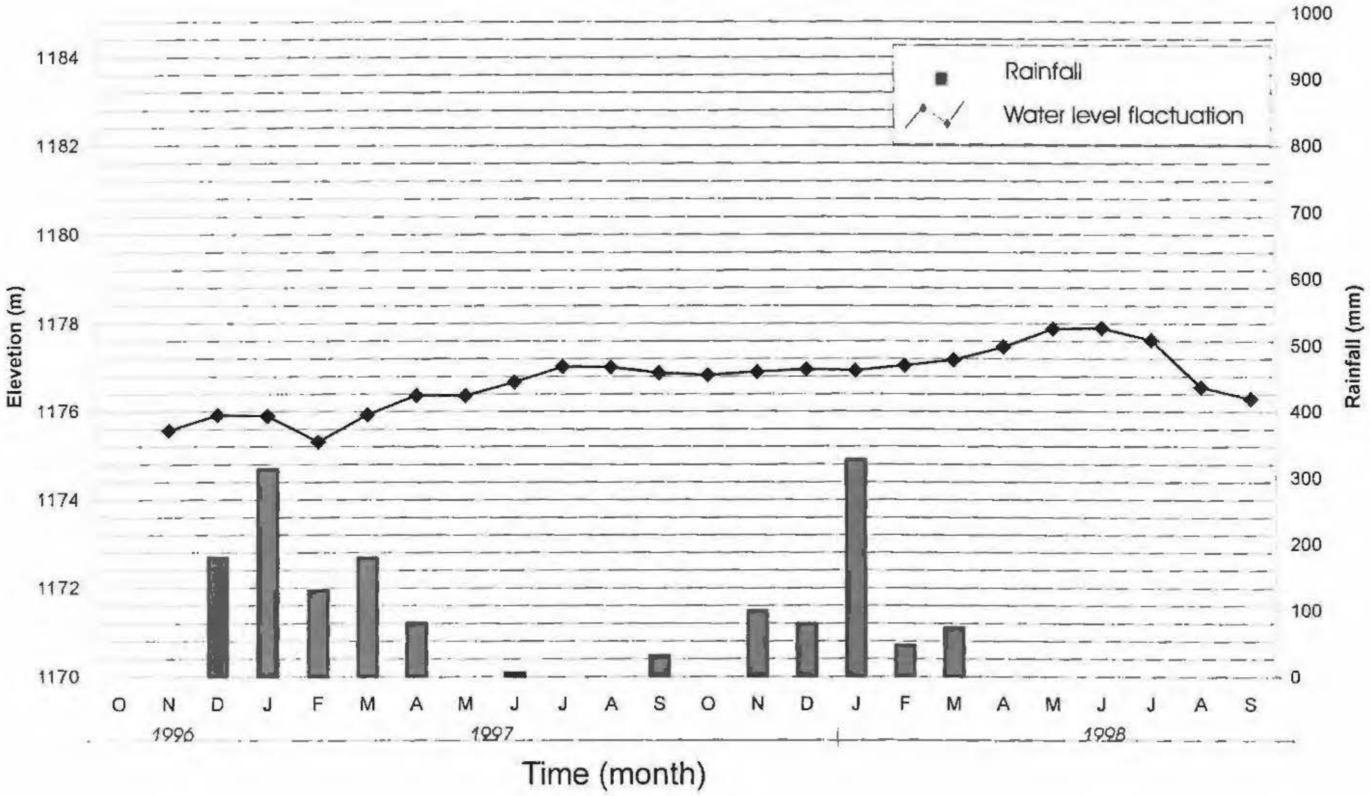
BH-ID: 6-KWEK-197
BH-NAME: MAVULE SCH.
GRID REF: QK433245



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96		
Nov-96	16.67	1155.33
Dec-96	16.46	1155.54
Jan-97	16.1	1155.9
Feb-97	15.47	1156.53
Mar-97	15.89	1156.11
Apr-97	15.39	1156.61
May-97	14.68	1157.32
Jun-97	14.73	1157.27
Jul-97	14.43	1157.57
Aug-97	14.35	1157.65
Sep-97	14.48	1157.52
Oct-97	15.1	1156.9
Nov-97	15.04	1156.96
Dec-97	14.78	1157.22
Jan-98	14.83	1157.17
Feb-98	14.96	1157.04
Mar-98	14.93	1157.07
Apr-98	14.17	1157.83
May-98	14.22	1157.78
Jun-98	14.68	1157.32
Jul-98	16	1156
Aug-98	16.01	1155.99
Sep-98	17.07	1154.93

WELL HYDROGRAPH & WATER LEVEL DATA

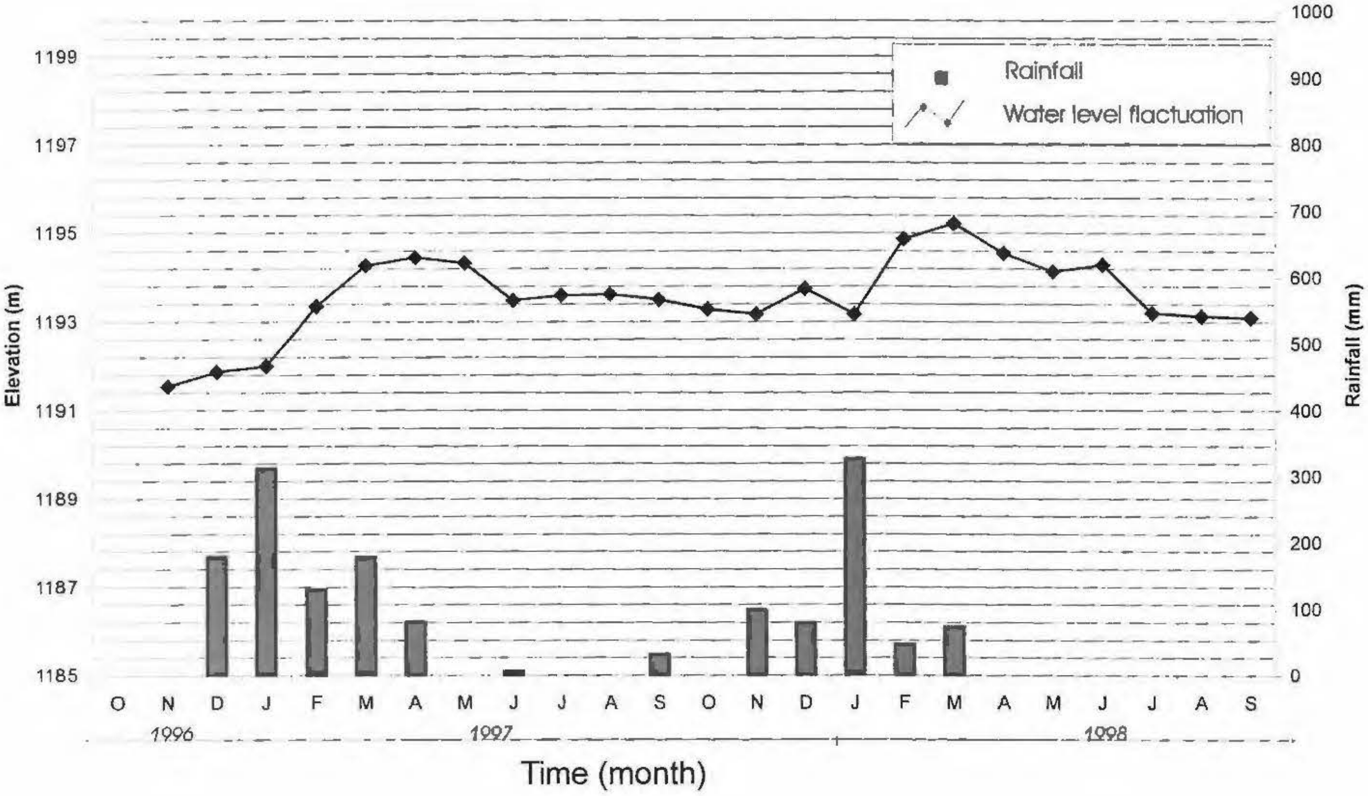
BH-ID	BH-NAME	GRID REF
6-KWEK-198	BULUNGA	QK409232



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96		
Nov-96	15.43	1175.57
Dec-96	15.08	1175.92
Jan-97	15.1	1175.9
Feb-97	15.69	1175.31
Mar-97	15.07	1175.93
Apr-97	14.63	1176.37
May-97	14.64	1176.36
Jun-97	14.33	1176.67
Jul-97	13.98	1177.02
Aug-97	13.99	1177.01
Sep-97	14.12	1176.88
Oct-97	14.17	1176.83
Nov-97	13.94	1177.06
Dec-97	14.04	1176.96
Jan-98	14.07	1176.93
Feb-98	13.95	1177.05
Mar-98	13.82	1177.18
Apr-98	13.53	1177.47
May-98	13.12	1177.88
Jun-98	13.1	1177.9
Jul-98	13.37	1177.63
Aug-98	14.44	1176.56
Sep-98	14.7	1176.3

WELL HYDROGRAPH & WATER LEVEL DATA

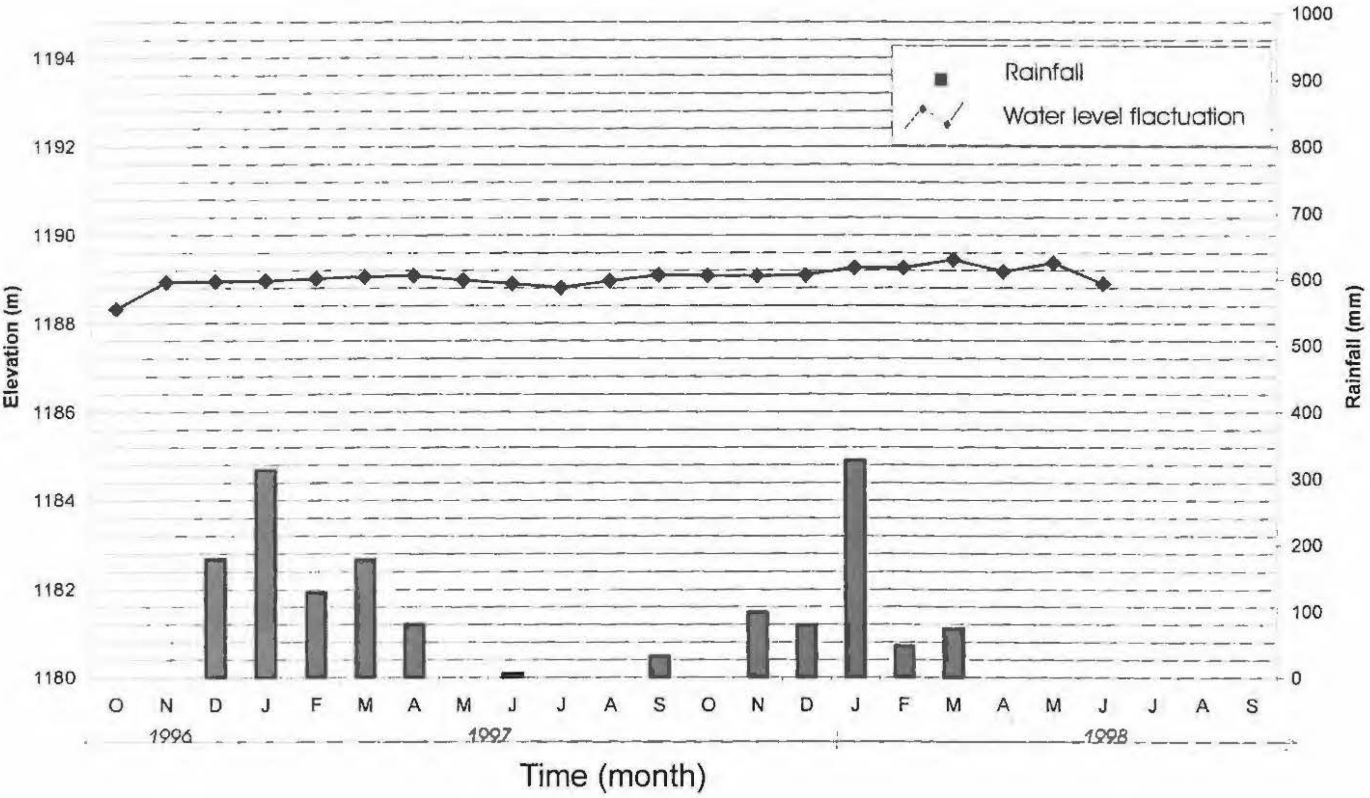
BH-ID	BH-NAME	GRID REF
6-KWEK-200	MDUGULI	QK396224



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96		
Nov-96	11.46	1191.54
Dec-96	11.13	1191.87
Jan-97	11	1192
Feb-97	9.65	1193.35
Mar-97	8.73	1194.27
Apr-97	8.55	1194.45
May-97	8.67	1194.33
Jun-97	9.52	1193.48
Jul-97	9.4	1193.6
Aug-97	9.38	1193.62
Sep-97	9.01	1193.99
Oct-97	9.72	1193.28
Nov-97	9.83	1193.17
Dec-97	9.25	1193.75
Jan-98	9.83	1193.17
Feb-98	8.13	1194.87
Mar-98	7.78	1195.22
Apr-98	8.45	1194.55
May-98	8.86	1194.14
Jun-98	8.71	1194.29
Jul-98	9.8	1193.2
Aug-98	9.87	1193.13
Sep-98	9.5	1193.5

WELL HYDROGRAPH & WATER LEVEL DATA

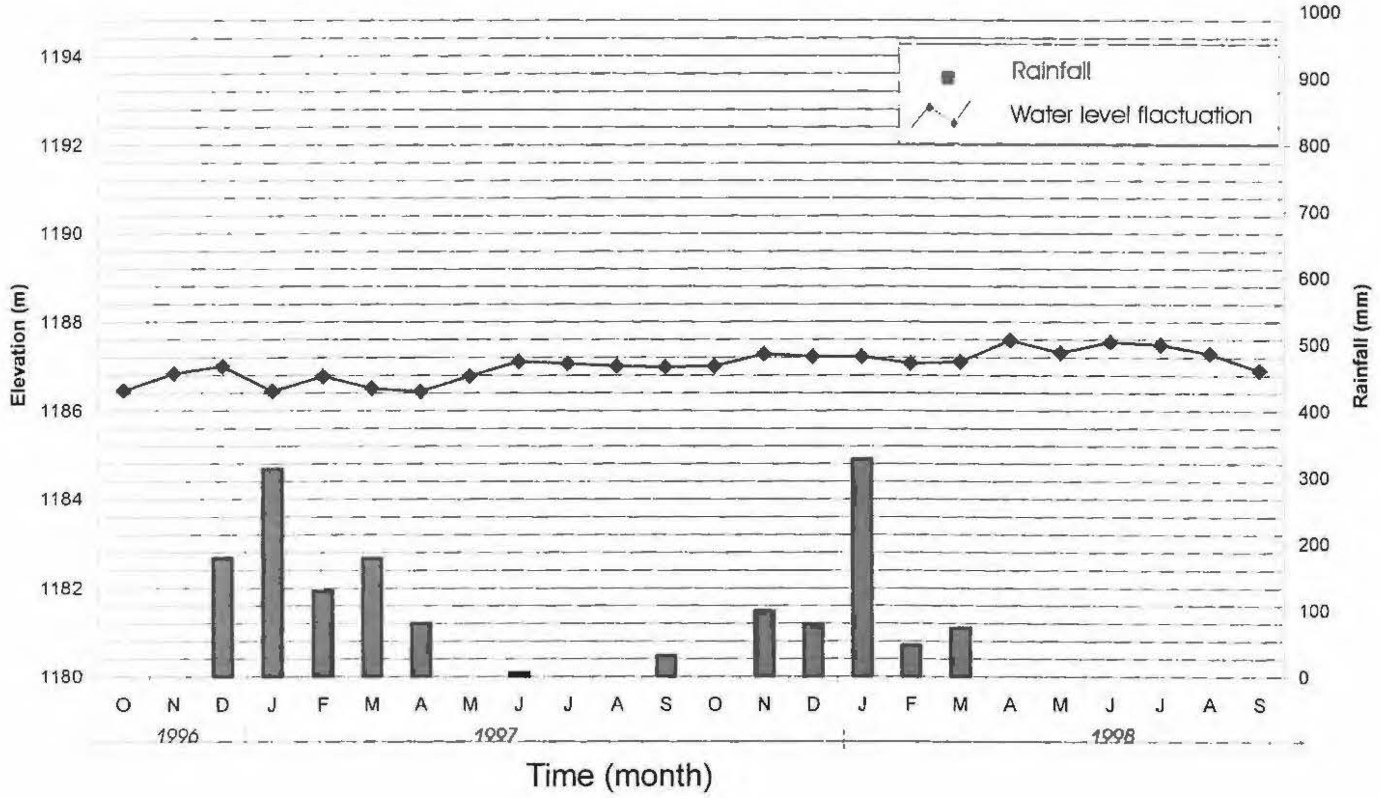
BH-ID	BH-NAME	GRID REF
6-KWEK-203	MTENEZI	QK361255



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96	52.67	1188.33
Nov-96	52.06	1188.94
Dec-96	52.05	1188.95
Jan-97	52.03	1188.97
Feb-97	51.99	1189.01
Mar-97	51.94	1189.06
Apr-97	51.92	1189.08
May-97	52.02	1188.98
Jun-97	52.1	1188.9
Jul-97	52.19	1188.81
Aug-97	52.04	1188.96
Sep-97	51.91	1189.09
Oct-97	51.92	1189.08
Nov-97	51.93	1189.07
Dec-97	51.91	1189.09
Jan-98	51.74	1189.26
Feb-98	51.74	1189.26
Mar-98	51.56	1189.44
Apr-98	51.83	1189.17
May-98	51.63	1189.37
Jun-98	52.1	1188.9
Jul-98	53.13	1187.87
Aug-98		
Sep-98		

WELL HYDROGRAPH & WATER LEVEL DATA

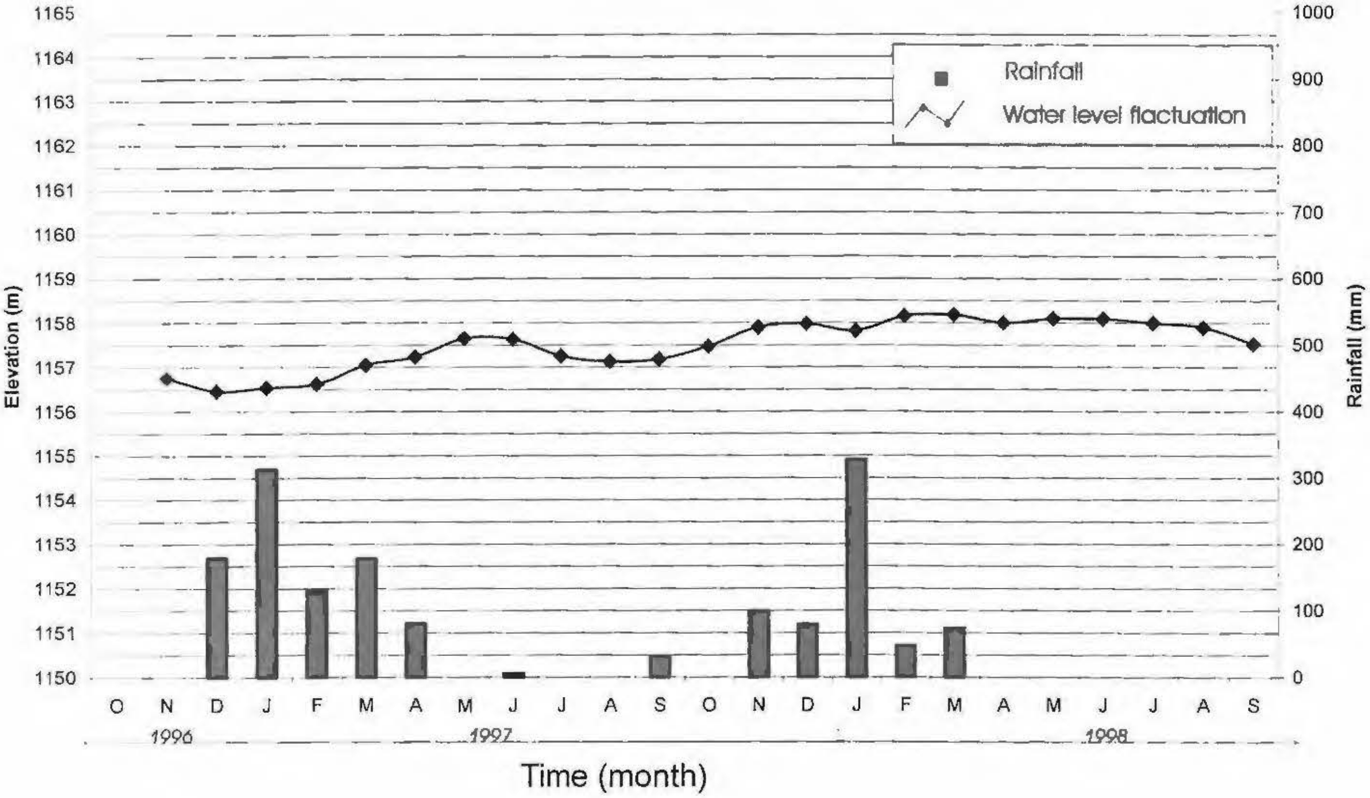
BH-ID	BH-NAME	GRID REF
6-KWEK-205	KUHLELOKU	QK360273



Date	Depth to water level (m)	Eievation of water level (m)
Oct-96	35.54	1186.46
Nov-96	35.16	1186.84
Dec-96	35	1187
Jan-97	35.56	1186.44
Feb-97	35.23	1186.77
Mar-97	35.5	1186.5
Apr-97	35.57	1186.43
May-97	35.22	1186.78
Jun-97	34.89	1187.11
Jul-97	34.94	1187.06
Aug-97	35	1187
Sep-97	35.02	1186.98
Oct-97	35	1187
Nov-97	34.72	1187.28
Dec-97	34.78	1187.22
Jan-98	34.78	1187.22
Feb-98	34.93	1187.07
Mar-98	34.9	1187.1
Apr-98	34.41	1187.59
May-98	34.69	1187.31
Jun-98	34.45	1187.55
Jul-98	34.51	1187.49
Aug-98	34.71	1187.29
Sep-98	35.09	1186.91

WELL HYDROGRAPH & WATER LEVEL DATA

BH-ID	BH-NAME	GRID REF
6-KWEK-206	KHANGELANI	QK363305



Date	Depth to water level (m)	Elevation of water level (m)
Oct-96		
Nov-96	29.24	1156.76
Dec-96	29.54	1156.46
Jan-97	29.46	1156.54
Feb-97	29.38	1156.62
Mar-97	28.95	1157.05
Apr-97	28.77	1157.23
May-97	28.35	1157.65
Jun-97	28.37	1157.63
Jul-97	28.75	1157.25
Aug-97	28.87	1157.13
Sep-97	28.82	1157.18
Oct-97	28.53	1157.47
Nov-97	28.1	1157.9
Dec-97	28.02	1157.98
Jan-98	28.18	1157.82
Feb-98	27.85	1158.15
Mar-98	27.82	1158.18
Apr-98	28	1158
May-98	27.9	1158.1
Jun-98	27.57	1158.43
Jul-98	28	1158
Aug-98	28.1	1157.9
Sep-98	28.47	1157.53

APPENDIX 5

CHEMICAL ANALYSIS DATA

CHEMICAL ANALYSIS DATA

Well Identification	Location	Grid ref	SO4	Ca	Cl	EC	TDS	F	Fe	Hardness	HCO3	K	Mg	Mn	Na	NO3	pH	Bal.Err.(%)
6-KWEK-165	Ntangwe_3	QK216267	16.1	35.7	14.28	31.5	161	0.6	0.07	136.6	173.1	0.58	8.2	0.36	21	0.3	6.68	3
6-KWEK-166	Mudzingwa	QK169290	10.4	47.7	10.88	40.2	197	0.31	0.14	174	245	0.81	49.6	0.21	6.1	1.2	6.97	19.29
6-KWEK-167	Ntangwe_2	QK236262	7.7	42	8.16	38.8	228	0.65	0.01	182.8	229.8	0.46	10.1	0.08	4.1	1.2	6.59	14.87
6-KWEK-168	Ntangwe_1	QK270264	5.9	32.2	11.29	28.1	154	0.15	0.06	106.9	149.8	0.68	6.6	0.09	1.1	0.4	6.51	13.43
6-KWEK-171	Notice	QK065285	12.4	115	93.84	105.5	706	0.24	0.27	287.75	491.74	19.2	49.24	0.11	112	12.8	7.16	15.13
6-KWEK-172	Mkambeni	QK062279	5.8	56.2	37.14	72.4	427	0.65	0.03	277.2	376.7	0.41	19	0.1	3	16.1	6.62	25.7
6-KWEK-173	Tutuko	QK166310	16.3	22	10.88	27.5	148	1.8	0.05	111.8	416.5	0.6	9.8	0.14	2.1	0.3	6.57	57.91
6-KWEK-174	Stolo	QK124317	14.4	49.6	14.96	46.7	277	0.13	0.12	192.6	257.3	0.67	10	0.02	21	0.4	6.71	7.8
6-KWEK-175	Matamba	QK104334	8.2	45.3	58.5	63.8	310	1.4	0.08	198	248.1	0.7	17.1	0.05	4.5	5.4	7.1	21.75
6-KWEK-176	Njini	QK085327	5	49.5	14.96	71.4	405	1.27	0.15	276.5	410.5	0.31	13.7	0.05	42	2.7	6.68	15.01
6-KWEK-177	Mbukwa	QK136302	40.8	36.4	17	46.9	265	1.87	0.08	172.7	245	0.67	13.5	0.08	1.4	4.2	7.07	29.32
6-KWEK-178	Mkobogwe	QK146292	9.7	51.4	12.24	48.4	256	0.74	0.14	193.7	243.2	0.74	11	0.21	7.3	17.1	6.89	11.84
6-KWEK-179	Short_Line	QK035286	17.2	21.8	7.21	16.2	135	1.15	0.65	46.2	73.6	0.32	11.2	0.08	3.4	0.2	6.58	9.21
6-KWEK-180	Zororo	QK235304	14.7	117.2	37.4	95.7	559.5	0.42	0.6	506.3	652.7	0.9	42	0.3	87	13.8	8.8	3.34
6-KWEK-183	Semisi	QK109279	2.4	37.64	28.28	38.6	255.7	0.74	0.47	148.63	220.65	13	12.46	0.16	34	12.3	7.66	0.47
6-KWEK-184	Bunywana	QK308260	8.9	59.4	21.17	43.3	235	0.06	0.06	184.4	229.8	0.41	25.9	0.08	1.5	0.4	6.38	6.53
6-KWEK-187	Munyamana	QK403307	2.2	67	8.74	70.3	412.3	0.52	0.39	180.29	498.04	13	19.54	0.25	18	1.8	7.12	16.54
6-KWEK-188	Munyamana_2	QK408302	3.4	93.02	18	65.3	261	0.38	0.29	244.92	460.22	11	30.66	0.11	22	2.3	7.16	1.46
6-KWEK-189	Mbangwa	QK403296	2.8	74.75	20.57	59.4	408.7	0.4	0.38	142.48	453.91	13	26.32	0.13	42	3.2	7.1	0.44
6-KWEK-190	Mafusini	QK403282	2.7	72.85	14.78	63.8	368.3	0.57	0.28	215.12	453.91	14	33.62	0.14	30	1.8	7.12	0.7
6-KWEK-191	Sabatha_2	QK385291	2.5	107.5	24.17	50.6	272	0.32	0.17	204.87	334.13	15	62.84	0.07	18	1.4	7.4	30.41
6-KWEK-193	Hube	QK293282	8.4	71.74	26.35	56.3	314	0.41	0.48	152.35	397.17	14	16.52	0.41	22	1.8	7.28	8.6
6-KWEK-194	Phakama_Lin	QK378263	3.8	60.49	17.35	47.5	225.3	0.44	0.28	401.36	312.7	14.2	11.84	0.13	12	0.4	7.15	7.78
6-KWEK-195	Lokuteza	QK396269	1.4	73.8	23.14	64.8	298	0.52	0.41	200.22	472.83	11	18.36	0.22	18	1.3	7.52	14.85
6-KWEK-196	Penduka_	QK409261	3.7	87.72	19.67	56.1	271.3	0.34	0.37	246.96	397.17	13	19.46	0.22	17	0.8	7.43	0.66
6-KWEK-197	Mavula_SC	QK433245	3.5	78.46	17.35	65.5	324	0.34	0.39	204.87	447.61	9.56	21.81	0.21	18	3.6	7.36	8.2
6-KWEK-198	Blunga	QK409232	4.4	106.1	15.17	72.7	349.3	0.51	0.34	230.95	535.87	12	27.88	0.16	18	2.2	7.23	3.67
6-KWEK-199	Donsimoyo	QK365222	1.4	81.57	18	48.5	253.3	0.47	0.48	174.71	353.04	13	12.86	0.2	12	0.5	7.34	2.75
6-KWEK-200	Mdunguli	QK396224	5.9	76.5	134.33	59.2	116.3	0.52	0.41	265.52	441.3	8	35.4	0.23	19	2.1	7.13	17.98
6-KWEK-203	Ntenezi	QK361255	3.7	57.2	13.88	47.3	277	0.3	0.34	227.04	226.96	9.2	24.63	0.14	20	2.7	6.87	17.17
6-KWEK-204	Intandokazu	QK354261	1.9	51.13	10.92	34	201	0.5	0.39	142.28	258.48	13	19.83	0.15	20	4.3	7.51	7.25
6-KWEK-205	Kuhleloku	QK360273	0.18	77.86	17.35	49.6	283.7	0.41	0.17	246.41	340.44	10.1	18.11	0.04	12	6.8	7.24	0.31
6-KWEK-206	Khangelani	QK363305	2.4	60.67	12.85	58.3	325.3	0.31	0.34	244.92	422.39	8.41	34.47	0.2	23	1.8	7.23	1.91
6-KWEK-207	Thabani	QK365315	1.8	73.1	19.28	56	286.7	0.35	0.24	281.32	428.7	14	20.56	0.04	14	1.3	7.39	9.5
6-KWEK-208	Jabulani	QK362306	2.7	65.86	9.64	55.6	339.7	0.25	0.32	169.5	403.48	15	28.14	0.21	24	6.1	7.15	0.01
6-KWEK-209	Zimasko_2	QK369314	7.9	65.57	12.85	62	318	0.23	0.44	189.04	403.48	7.45	24.48	0.13	28	3.5	7.26	3.49
6-KWEK-210	Bambanani	QK088327	2.87	137.9	269.94	58.4	299.3	0.34	0.28	205.8	422.39	15	45.78	0.14	10.7	1.1	7.15	6.23
6-KWEK-211	Zimasko_1	QK367332	6.2	66.47	18.43	45.4	243.7	0.41	0.33	344.56	340.44	9.47	14.23	0.11	18	1.2	7.46	28.65

Well Identification	Location	Grid ref	SO4	Ca	Cl	EC	TDS	F	Fe	Hardness	HCO3	K	Mg	Mn	Na	NO3	pH	Bal.Err.(%)
6-KWEK-212	Qkubekani	QK200268	1.1	137.6	11.05	51.7	238	0.33	0.29	128.14	378.26	12	44.86	0.24	24	4.1	7.65	3.47
6-KWEK-213	Zenjeleni	QK334314	2.1	76.5	19.28	49.3	232	0.98	0.24	216.95	359.35	13	27.64	0.23	14	3.2	7.41	6.31
6-KWEK-215	Gwaraaramba	QK328227	2.5	126.6	16.07	55.6	202.7	0.38	0.28	261.61	419.78	9.24	50.62	0.18	12	0.7	7.38	0.99
6-KWEK-216	Madabu	QK341213	2.4	94.44	18	61	349.3	0.28	0.36	307.81	435	10.6	28.73	0.21	12	2.4	7.29	2.38
6-KWEK-217	Siziba	QK342207	2.8	63.77	12.85	51.6	332	0.28	0.18	239.89	371.96	7.51	27.14	0.15	16	5.8	7.22	6.64
6-KWEK-218	Mancemeza	QK351226	2.9	86.01	23.14	62.3	362.7	0.48	0.46	246.78	409.78	7	43.18	0.37	11	1.3	7.08	3.09
6-KWEK-219	Zanke	QK352238	1.8	92.85	19.92	58.6	288	0.39	4.21	306	447.61	12	23.38	0.03	10	3	7.79	31.22
6-KWEK-220	Ngomambi	QK324298	3.8	84.45	14.14	37.9	224	0.23	0.27	130.93	252.17	14	27.48	0.18	46	1.1	7.09	5.99
6-KWEK-221	Sinangeni	QK322309	1.8	74.3	16.71	50.5	249.3	0.31	0.23	359.46	353.04	14	31.47	0.05	11	1.7	7.44	4.92
6-KWEK-223	Kuwirirana	QK335287	2.3	76.81	20.57	51.3	284	0.23	0.37	311.59	384.57	17.2	32.65	0.22	16	1.1	7.38	21.88
6-KWEK-226	Koria	QK268355	108	66.5	10.7	33.4	195.4	_	0.1	281	248	3.4	8	_	4	0.3	8.8	4.54
6-KWEK-234	Refuse	QK195338	12	24.2	10.7	26.4	154.4	_	_	150.1	78.3	4.5	5	1.6	5	_	8.1	2.21
6-KWEK-235	Chitawara	QK286313	5.8	91.2	11.8	49	286.7	0.1	0.9	367.1	391.6	7.3	18	0.1	8	2.5	7.9	4.68
6-KWEK-236	Sakululwa	QK318369	6	65.9	11.8	35.1	205.3	0.16	6	248.9	261.1	6.9	10	0.3	15	3.5	7.6	5.93
6-KWEK-237	Godweni	QK311307	11	41.1	19.7	27.6	161.5	0.1	0.9	166.7	156.7	5.5	9	0.2	0.8	2.8	7.41	0.07
6-KWEK-238	Manyamana	QK283324	10.7	21	21.4	19.3	112.9	_	0.8	118	104.4	4.4	11.5	0.1	9	0.2	8	0.14
6-KWEK-239	Luka	QK352342	6.7	92.8	11.8	47.7	279	0.06	_	337.6	378.6	6.5	18	0.1	10	3.4	8.2	15.25
6-KWEK-240	Simakani	QK293378	6	9.6	5.9	9.1	53.2	0.1	3.3	48.5	78.3	2.8	1	0.1	8	_	7.4	0.51
6-KWEK-241	Chamatendera	QK145355	6.8	38.3	7.9	25.8	150.9	0.12	2.3	151.9	143.6	5.8	8	0.8	10	38.1	7.6	0.78
6-KWEK-243	Meeting	QK333375	5.7	64.8	7.9	40.7	238.1	0.1	1.5	274.3	326.4	4.9	23	0.1	11	1.7	8	4.45
6-KWEK-244	Gwarazimba	QK338352	6.5	70	17.7	44.9	262.7	0.08	2.4	316.5	326.4	5	26.5	0.2	14	_	8.2	0.22
6-KWEK-247	Ganyani	QK123323	8.1	52.9	39.1	36.7	214.7	0.1	2	206	235	4.3	21.5	0.1	12	_	7.7	2.52
6-KWEK-248	Mukusu	QK156313	5.9	18.4	7.9	12.9	75.5	0.1	0.4	764	91.4	5.8	4.5	0.2	8	3.6	7.3	11.01
6-KWEK-250	Tabisa	QK211335	6.5	24.2	15.8	20.5	119.9	0.1	0.3	116	143.6	6.6	7.5	0.1	9	3.7	7.5	2.28
6-KWEK-251	Makombo	QK223316	6.5	21.9	11.8	16.7	97.7	0.1	0.8	99.2	104.4	6.3	6.5	0.1	7	3.4	7.4	3.07
6-KWEK-253	Budiriro_2	QK190569	6	33.4	11.9	24.3	142.2	0.21	8	145.6	156.6	6.4	8	0.2	11	10.1	7.4	24.02
6-KWEK-256	Ndege	QK120320	12.3	64.3	14.28	51.8	291	1.67	0.12	190.4	291	0.31	10.1	0.07	2.9	4.1	6.83	14.34
6-KWEK-257	Dndera_SC	QK209309	5.9	65.1	5.9	40.8	238.7	0.1	2.8	286.9	300.2	5	24	0.6	11	_	8.7	7.01
6-KWEK-258	Zvaitika	QK214377	5.5	10.6	11.8	12.7	74.3	0.1	3.9	69.6	78.3	4.1	2.5	0.2	10	1.2	7.1	8.18

APPENDIX 6

SUSTAINABLE BOREHOLE YIELDS

DATA ENTRY WORKSHEET

Box A - Borehole Information			
Borehole ID	Inthandokazul	X Coord.	726100
Depth (m)	89	Y Coord.	7935400
Blow yield (l/s)	1	Region	Kwekwe Dist.
Water strikes (m)			
Formation	Upper Karoo Sandstone		
Aquifer lithology	Losely cemented sandstone with clay interbeds		
Type of Tests	24 hour constant rate		
Date	2000		
Interpreted By:	J Njanike		
Comments	Unconfined aquifer		

Box B - Pump Test Data	
Radius (m)	0.0762
Q (m3/d)	86.4
Rest water level	53.1
Main water strike (m)	66
Available drawdown (m)	12.9
pumping time (min)	2490

Box E-Transmissivity and Storativity	
Early T (m2/d)	6.6
t0 (min)	5.2
S	9.2
Late T (m2/d)	2.3
Recov. T (m2/d)	5.2

Box C - Constant Rate Test Pumping Data				Box D - Constant Rate Recovery Data			
Time (min)	Water level (m)	Time (d)	Drawdown (m)	Recovery (min)	Water level (m)	t/t'	Residual Drawd. (m)
7	53.39	0.004861111	0.29	0.5	59	4981	5.9
8	53.5	0.005555556	0.4	1	58.2	2491	5.1
9	53.64	0.00625	0.54	1.5	58.01	1661	4.91
10	53.78	0.006944444	0.68	2	57.86	1246	4.76
12	53.92	0.008333333	0.82	2.5	57.73	997	4.63
14	54.03	0.009722222	0.93	3	57.7	831	4.6
16	54.15	0.011111111	1.05	4	56.83	623.5	3.73
18	54.21	0.0125	1.11	5	55.51	499	2.41
20	54.3	0.013888889	1.2	6	55	416	1.9
25	54.39	0.017361111	1.29	7	54.98	356.7142857	1.88
30	54.48	0.020833333	1.38	8	54.95	312.25	1.85
45	54.59	0.03125	1.49	9	54.94	277.6666667	1.84
60	54.68	0.041666667	1.58	10	54.92	250	1.82
75	54.79	0.052083333	1.69	12	54.89	208.5	1.79
90	54.9	0.0625	1.8	14	54.85	178.8571429	1.75
105	54.99	0.072916667	1.89	16	54.8	156.625	1.7
120	55.02	0.083333333	1.92	18	54.75	139.3333333	1.65
150	55.1	0.104166667	2	20	54.7	125.5	1.6
180	55.16	0.125	2.06	25	53.88	100.6	0.78
210	55.22	0.145833333	2.12	30	53.5	84	0.4
240	55.33	0.166666667	2.23	45	53.17	56.33333333	0.07
280	55.39	0.194444444	2.29	60	53.03	42.5	-0.07
350	55.47	0.243055556	2.37			#DIV/0!	-53.1
410	55.54	0.284722222	2.44			#DIV/0!	-53.1
470	56.1	0.326388889	3			#DIV/0!	-53.1
530	56.42	0.368055556	3.32			#DIV/0!	-53.1
590	56.74	0.409722222	3.64			#DIV/0!	-53.1
650	57.05	0.451388889	3.95			#DIV/0!	-53.1

710	57.39	0.493055556	4.29			#DIV/0!	-53.1
770	57.63	0.534722222	4.53			#DIV/0!	-53.1
830	57.8	0.576388889	4.7			#DIV/0!	-53.1
890	58.02	0.618055556	4.92			#DIV/0!	-53.1
950	58.21	0.659722222	5.11			#DIV/0!	-53.1
1010	58.37	0.701388889	5.27			#DIV/0!	-53.1
1070	58.44	0.743055556	5.34			#DIV/0!	-53.1
1130	58.56	0.784722222	5.46			#DIV/0!	-53.1
1190	58.61	0.826388889	5.51			#DIV/0!	-53.1
1250	58.64	0.868055556	5.54			#DIV/0!	-53.1
1310	58.75	0.909722222	5.65			#DIV/0!	-53.1
1370	58.82	0.951388889	5.72			#DIV/0!	-53.1
1430	58.58	0.993055556	5.48			#DIV/0!	-53.1
1490	58.58	1.034722222	5.48			#DIV/0!	-53.1
1550	58.59	1.076388889	5.49			#DIV/0!	-53.1
1610	58.65	1.118055556	5.55			#DIV/0!	-53.1
1670	58.75	1.159722222	5.65			#DIV/0!	-53.1
1770	58.87	1.229166667	5.77			#DIV/0!	-53.1
1830	58.94	1.270833333	5.84			#DIV/0!	-53.1
1890	59.07	1.3125	5.97			#DIV/0!	-53.1
1950	59.09	1.354166667	5.99			#DIV/0!	-53.1
2010	59.25	1.395833333	6.15			#DIV/0!	-53.1
2070	59.27	1.4375	6.17			#DIV/0!	-53.1
2130	59.33	1.479166667	6.23			#DIV/0!	-53.1
2190	59.33	1.520833333	6.23			#DIV/0!	-53.1
2250	59.33	1.5625	6.23			#DIV/0!	-53.1
2310	59.33	1.604166667	6.23			#DIV/0!	-53.1
2370	59.33	1.645833333	6.23			#DIV/0!	-53.1
2430	59.33	1.6875	6.23			#DIV/0!	-53.1
2490	59.33	1.729166667	6.23			#DIV/0!	-53.1

SUSTAINABLE YIELD ESTIMATION WORKSHEET

Box F - Hydraulic Properties

Fracture S (estimated)		0.007
Matrix S (estimated)		0.07
boundary (m)		2.44
Specific capacity (m3/d/m)		35.4
boundary (t)		0.28
delta h (m)		1
Dist. to boundary (m)		24.3098098
t/t' intercept (estimate)		53.7002588
t/t' intercept		50
Discharge rate for max. draw. (m3/d)		17
drawdown at 100 min		1.85
Recovery after 100 min		6.23
delta s (slope of late T curve)		6.78225997
F1-drawdown/recovery		0.29695024
F2 flow factor	F2 Help	3.8

RECOMMENDED BOREHOLE YIELDS

Method	m3/d	hrs at max. pump.rate	l/s @ x h/d			Select Method	Recommended Yield (m3/d)
			10	12			
Recovery	84.7	15.3	2.4	2.0	Guideline	☑	Minimum
Transmissivity	4.6	0.8	0.1	0.1	Guideline	☐	11
Late T	24.6	4.4	0.7	0.6	Guideline	☐	Maximum
Drawdown to boundary	10.8	1.9	0.3	0.2	Guideline	☑	85
Distance to boundary	17.0	3.1	0.5	0.4	Guideline	☑	Mean
Flow characteristic 1	35.8	6.5	1.0	0.8	Guideline	☑	33
Flow characteristic 2	35.9	6.5	1.0	0.8	Guideline		
Maximum drawdown	17	3.1	0.5	0.4	Guideline	☑	

Borehole and Aquifer Hydraulic Properties

Specific capacity m3/d/m (early time)	10.3
Specific capacity m3/d/m (late time)	4.2
Early T m2/d	6.6
Late T m2/d	2.3
S - fractures	0.007
S matrix	0.07
Max. pumping rate l/s	1.5

RECOMMENDED PUMPING SCHEDULE

		Min (m3/d)	Ideal (m3/d)	Max (m3/d)
Daily Discharge		46	69	95
	h/d	Pumping Rate (l/s)		
l/s @	12	1.1	1.6	2.2
l/s @	24	0.5	0.8	1.1
	l/s	Pumping Hours (h/d)		
h/d@Max. pumping rate	1.5	6.3	12.4	17.1

Box A - Borehole Information

Borehole ID	Chitawara	X Coord.	728600
Depth (m)	85	Y Coord.	7931300
Blow yield (l/s)	2.56	Region	Kwekwe Dist
Water strikes (m)	63.5		
Formation	Upper Karoo Sediments		
Aquifer lithology	Loosely cemented sandstone/siltstone		
Type of Tests	10 hrs constant discharge test		
Date	1999		
Interpreted By:	J.T Njanike		
Comments	0-66m Kalahar sands,aeolian mainly fine grained silty sand 66-83m Course grained sst with minor silt fraction 83-90m Red siltstone, sandy to top		

Box B - Pump Test Data

Radius (m)	0.075
Q (m3/d)	129.6
Rest water level	60.4
Main water strike (m)	83
Available drawdown (m)	22.6
pumping time (min)	600

Box E-Transmissivity and Storativity

Early T (m2/d)	16.1
t0 (min)	0.5
S	2.0
Late T (m2/d)	9.3
Recov. T (m2/d)	16.8

Box C - Constant Rate Test Pumping Data				Box D - Constant Rate Recovery Data			
Time (min)	Water level (m)	Time (d)	Drawdown (m)	Recovery (min)	Water level (m)	t/t'	Residual Drawd. (m)
1	60.88	0.000694444	0.48	1	63.39	601	2.99
2	61.22	0.001388889	0.82	2	61.82	301	1.42
4	61.76	0.002777778	1.36	4	61.3	151	0.9
6	62.08	0.004166667	1.68	6	61.02	101	0.62
8	62.29	0.005555556	1.89	8	60.75	76	0.35
10	62.42	0.006944444	2.02	10	60.67	61	0.27
12	62.55	0.008333333	2.15	12	60.61	51	0.21
14	62.59	0.009722222	2.19	14	60.22	43.85714286	-0.18
16	62.67	0.011111111	2.27	16	60.25	38.5	-0.15
18	62.72	0.0125	2.32	18	60.27	34.33333333	-0.13
20	62.81	0.013888889	2.41	20	60.28	31	-0.12
25	62.86	0.017361111	2.46	25	60.3	25	-0.1
30	62.9	0.020833333	2.5			#DIV/0!	-60.4
45	62.96	0.03125	2.56			#DIV/0!	-60.4
60	62.96	0.041666667	2.56			#DIV/0!	-60.4
75	62.97	0.052083333	2.57			#DIV/0!	-60.4
90	62.99	0.0625	2.59			#DIV/0!	-60.4
105	62.99	0.072916667	2.59			#DIV/0!	-60.4
120	63.01	0.083333333	2.61			#DIV/0!	-60.4
150	63.04	0.104166667	2.64			#DIV/0!	-60.4
180	63.11	0.125	2.71			#DIV/0!	-60.4
210	63.13	0.145833333	2.73			#DIV/0!	-60.4
240	63.15	0.166666667	2.75			#DIV/0!	-60.4
270	63.18	0.1875	2.78			#DIV/0!	-60.4
300	63.2	0.208333333	2.8			#DIV/0!	-60.4
360	63.23	0.25	2.83			#DIV/0!	-60.4
420	63.27	0.291666667	2.87			#DIV/0!	-60.4
480	63.29	0.333333333	2.89			#DIV/0!	-60.4
540	63.34	0.375	2.94			#DIV/0!	-60.4
600	63.39	0.416666667	2.99			#DIV/0!	-60.4
0		365				#DIV/0!	-60.4

SUSTAINABLE YIELD ESTIMATION WORKSHEET

Box F - Hydraulic Properties		
Fracture S (estimated)		0.007
Matrix S (estimated)		0.07
boundary (m)		2.9
Specific capacity (m3/d/m)		44.7
boundary (t)		0.33
delta h (m)		1
Dist. to boundary (m)		41.265325
t/t' intercept (estimate)		25.271804
t/t' intercept		45
Discharge rate for max. draw. (m3/d)		95
drawdown at 100 min		2.46
Recovery after 100 min		2.98
delta s (slope of late T curve)		2.5562065
F1-drawdown/recovery		0.8255034
F2 flow factor	F2 Help	2

Borehole and Aquifer Hydraulic Properties	
Specific capacity m3/d/m (early time)	22.6
Specific capacity m3/d/m (late time)	13.9
Early T m2/d	16.1
Late T m2/d	9.3
S - fractures	0.007
S matrix	0.07
Max. pumping rate l/s	5.9

RECOMMENDED BOREHOLE YIELDS

Method	m3/d	hrs at max pump rate	l/s @ x h/d 10	12		Select Method	Recommended Yield (m3/d)
Recovery	126.7	6.0	3.5	2.9	Guideline	☐	Minimum
Transmissivity	25.9	1.2	0.7	0.6	Guideline	☐	30
Late T	157.3	7.4	4.4	3.6	Guideline	☐	Maximum
Drawdown to boundary	29.8	1.4	0.8	0.7	Guideline	☑	155
Distance to boundary	42.9	2.0	1.2	1.0	Guideline	☑	Mean
Flow characteristic 1	154.9	7.3	4.3	3.6	Guideline	☑	81
Flow characteristic 2	155.3	7.3	4.3	3.6	Guideline		
Maximum drawdown	95	4.5	2.6	2.2	Guideline	☑	

RECOMMENDED PUMPING SCHEDULE				
		Min (m3/d)	Ideal (m3/d	Max (m3/d)
Daily Discharge		46	69	95
	h/d	Pumping Rate (l/s)		
l/s @	12	1.1	1.6	2.2
l/s @	24	0.5	0.8	1.1
	l/s	Pumping Hours (h/d)		
h/d@Max. pumping rate	5.9	2.2	3.2	4.5

DATA ENTRY WORKSHEET

Box A - Borehole Information			
Borehole ID	Rufuse	X Coord.	719500
Depth (m)	33	Y Coord.	7933800
Blow yield (l/s)	2.9 l/s	Region	Kwekwe Distric
Water strikes (m)	13.5 m		
Formation	Upper Karoo		
Aquifer lithology	Loosely cemented sandstone/siltstone		
Type of Tests	10 hours constant discharge		
Date	1999		
Interpreted By:	J.Njanike		
Comments	0-7m Recent reditributed sand; 8-18m aeolean Kalahari sands 18-30m Medium grained weakly cemented sst with sandy clays at the bottom 30-33m Silty sandstone - loosely cemented		

Box B - Pump Test Data	
Radius (m)	0.075
Q (m3/d)	156.4
Rest water level	11.64
Main water strike (m)	33
Available drawdown (m)	21.36
pumping time (min)	600

Box E-Transmissivity and Storativity	
Early T (m2/d)	6.1
t0 (min)	0.2
S	0.4
Late T (m2/d)	10.2
Recov. T (m2/d)	1.5

Box C - Constant Rate Test Pumping Data				Box D - Constant Rate Recovery Data			
Time (min)	Water level (m)	Time (d)	Drawdown (m)	Recovery (min)	Water level (m)	t/t'	Residual Drawd. (m)
1	14.66	0.000694444	3.02	2	19.67	301	8.03
2	16.18	0.001388889	4.54	4	14.09	151	2.45
4	17.47	0.002777778	5.83	6	12.75	101	1.11
6	18.61	0.004166667	6.97	8	11.34	76	-0.3
8	19.05	0.005555556	7.41	10	11.47	61	-0.17
10	19.62	0.006944444	7.98			#DIV/0!	-11.64
12	19.83	0.008333333	8.19			#DIV/0!	-11.64
14	19.96	0.009722222	8.32			#DIV/0!	-11.64
16	20.1	0.011111111	8.46			#DIV/0!	-11.64
18	20.2	0.0125	8.56			#DIV/0!	-11.64
20	20.35	0.013888889	8.71			#DIV/0!	-11.64
25	20.46	0.017361111	8.82			#DIV/0!	-11.64
30	20.72	0.020833333	9.08			#DIV/0!	-11.64
45	21.26	0.03125	9.62			#DIV/0!	-11.64
60	21.32	0.041666667	9.68			#DIV/0!	-11.64
75	21.4	0.052083333	9.76			#DIV/0!	-11.64
90	21.45	0.0625	9.81			#DIV/0!	-11.64
105	21.48	0.072916667	9.84			#DIV/0!	-11.64
120	21.5	0.083333333	9.86			#DIV/0!	-11.64
150	21.51	0.104166667	9.87			#DIV/0!	-11.64
180	21.52	0.125	9.88			#DIV/0!	-11.64
210	21.55	0.145833333	9.91			#DIV/0!	-11.64
240	21.58	0.166666667	9.94			#DIV/0!	-11.64
300	21.61	0.208333333	9.97			#DIV/0!	-11.64
360	21.62	0.25	9.98			#DIV/0!	-11.64
420	21.68	0.291666667	10.04			#DIV/0!	-11.64
480	21.73	0.333333333	10.09			#DIV/0!	-11.64
540	21.77	0.375	10.13			#DIV/0!	-11.64
600	21.78	0.416666667	10.14			#DIV/0!	-11.64

SUSTAINABLE YIELD ESTIMATION WORKSHEET

Box F - Hydraulic Properties		
Fracture S (estimated)		0.07
Matrix S (estimated)		0.07
boundary (m)		10
Specific capacity (m3/d/m)		15.6
boundary (t)		0.1
delta h (m)		1
Dist. to boundary (m)		4.4221497
t/t' intercept (estimate)		115.78587
t/t' intercept		85
Discharge rate for max. draw. (m3/d)		50
drawdown at 100 min		9.83
Recovery after 100 min		21.78
delta s (slope of late T curve)		2.7959654
F1-drawdown/recovery		0.4513315
F2 flow factor	F2 Help	1

Borehole and Aquifer Hydraulic Properties	
Specific capacity m3/d/m (early time)	9.6
Specific capacity m3/d/m (late time)	15.2
Early T m2/d	6.1
Late T m2/d	10.2
S - fractures	0.07
S matrix	0.07
Max. pumping rate l/s	2.4

RECOMMENDED BOREHOLE YIELDS

		hrs at max	l/s @ x h/d			Select	Recommended
Method	m3/d	pump rate	10	12		Method	Yield (m3/d)
Recovery	154.6	18.1	4.3	3.6	Guideline	☑	Minimum
Transmissivity	2.2	0.3	0.1	0.1	Guideline	☐	155
Late T	163.1	19.1	4.5	3.8	Guideline	☐	Maximum
Drawdown to boundary	46.8	5.5	1.3	1.1	Guideline	☐	352
Distance to boundary	9.3	1.1	0.3	0.2	Guideline	☐	Mean
Flow characteristic 1	352.2	41.2	9.8	8.2	Guideline	☑	253
Flow characteristic 2	352.9	41.3	9.8	8.2	Guideline		
Maximum drawdown	50	5.8	1.4	1.2	Guideline	☐	

RECOMMENDED PUMPING SCHEDULE

		Min (m3/d)	Ideal (m3/d	Max (m3/d)
Daily Discharge		46	69	95
	h/d	Pumping Rate (l/s)		
l/s @	12	1.1	1.6	2.2
l/s @	24	0.5	0.8	1.1
	l/s	Pumping Hours (h/d)		
h/d@Max. pumping rate	2.4	5.4	8.1	11.1

DATA ENTRY WORKSHEET

Box A - Borehole Information

Borehole ID	Gondweni	X Coord.	731100
Depth (m)	107	Y Coord.	7930700
Blow yield (l/s)	2.82	Region	Kwekwe Distric
Water strikes (m)	71		
Formation	Upper Karoo		
Aquifer lithology	Loosely cemented sandstone/siltstone		
Type of Tests	10 hours constant discharge		
Date	1999		
Interpreted By:	J.Njanike		
Comments	0-57 Kalahari sands - unconsolidated aeolian sand 58-87m Medium grained loosely cemented sst with abundant silt component 88 107m Medium grained loosely cemented sst with sandy siltstone interbeds		

Box B - Pump Test Data

Radius (m)	0.075
Q (m3/d)	190.1
Rest water level	73.7
Main water strike (m)	107
Available drawdown (m)	33.3
pumping time (min)	600

Box E-Transmissivity and Storativity

Early T (m2/d)	15.7
t0 (min)	0.2
S	0.9
Late T (m2/d)	18.0
Recov. T (m2/d)	12.0

Box C - Constant Rate Test Pumping Data				Box D - Constant Rate Recovery Data			
Time (min)	Water level (m)	Time (d)	Drawdown (m)	Recovery (min)	Water level (m)	t/t'	Residual Drawd. (m)
1	75.11	0.000694444	1.41	2	76.57	301	2.87
2	75.75	0.001388889	2.05	4	75.63	151	1.93
4	76.47	0.002777778	2.77	6	75.1	101	1.4
6	77.04	0.004166667	3.34	8	74.63	76	0.93
8	77.21	0.005555556	3.51	10	74.49	61	0.79
10	77.23	0.006944444	3.53	12	74.23	51	0.53
12	77.38	0.008333333	3.68	14	73.99	43.85714286	0.29
14	77.39	0.009722222	3.69	16	73.87	38.5	0.17
16	77.4	0.011111111	3.7	18	73.76	34.33333333	0.06
18	77.42	0.0125	3.72			#DIV/0!	-73.7
20	77.45	0.013888889	3.75			#DIV/0!	-73.7
25	77.49	0.017361111	3.79			#DIV/0!	-73.7
30	77.52	0.020833333	3.82			#DIV/0!	-73.7
45	77.58	0.03125	3.88			#DIV/0!	-73.7
60	77.61	0.041666667	3.91			#DIV/0!	-73.7
75	77.66	0.052083333	3.96			#DIV/0!	-73.7
90	77.67	0.0625	3.97			#DIV/0!	-73.7
105	77.66	0.072916667	3.96			#DIV/0!	-73.7
120	77.68	0.083333333	3.98			#DIV/0!	-73.7
150	77.74	0.104166667	4.04			#DIV/0!	-73.7
180	77.78	0.125	4.08			#DIV/0!	-73.7
210	77.81	0.145833333	4.11			#DIV/0!	-73.7
240	77.85	0.166666667	4.15			#DIV/0!	-73.7
270	77.88	0.1875	4.18			#DIV/0!	-73.7
300	77.89	0.208333333	4.19			#DIV/0!	-73.7
360	77.91	0.25	4.21			#DIV/0!	-73.7
420	77.94	0.291666667	4.24			#DIV/0!	-73.7
480	77.96	0.333333333	4.26			#DIV/0!	-73.7
540	77.99	0.375	4.29			#DIV/0!	-73.7
600	78.03	0.416666667	4.33			#DIV/0!	-73.7

SUSTAINABLE YIELD ESTIMATION WORKSHEET

Box F - Hydraulic Properties		
Fracture S (estimated)		0.007
Matrix S (estimated)		0.07
boundary (m)		4.3
Specific capacity (m3/d/m)		44.2
boundary (t)		0.33
delta h (m)		0.7
Dist. to boundary (m)		40.7618488
t/t' intercept (estimate)		32.7784235
t/t' intercept		32
Discharge rate for max. draw. (m3/d)		95
drawdown at 100 min		3.7
Recovery after 100 min		4.3
delta s (slope of late T curve)		1.83564881
F1-drawdown/recovery		0.86046512
F2 flow factor	F2 Help	2

Borehole and Aquifer Hydraulic Properties	
Specific capacity m3/d/m (early time)	22.1
Specific capacity m3/d/m (late time)	25.0
Early T m2/d	15.7
Late T m2/d	18.0
S - fractures	0.007
S matrix	0.07
Max. pumping rate l/s	8.5

RECOMMENDED BOREHOLE YIELDS

Method	m3/d	hrs at max. pump rate	l/s @ x h/d 10	 12		Select Method	Recommend Yield (m3/d)
Recovery	184.2	6.0	5.1	4.3	Guideline	☐	Minimum
Transmissivity	27.1	0.9	0.8	0.6	Guideline	☐	29
Late T	432.1	14.1	12.0	10.0	Guideline	☐	Maximum
Drawdown to boundary	43.2	1.4	1.2	1.0	Guideline	☑	383
Distance to boundary	29.3	1.0	0.8	0.7	Guideline	☑	Mean
Flow characteristic 1	383.5	12.5	10.7	8.9	Guideline	☑	138
Flow characteristic 2	384.5	12.5	10.7	8.9	Guideline		
Maximum drawdown	95	3.1	2.6	2.2	Guideline	☑	

RECOMMENDED PUMPING SCHEDULE

		Min (m3/d)	Ideal (m3/d)	Max.(m3/d)
Daily Discharge		46	69	95
	h/d	Pumping Rate (l/s)		
l/s @	12	1.1	1.6	2.2
l/s @	24	0.5	0.8	1.1
	l/s	Pumping Hours (h/d)		
h/d@Max. pumping rate	8.5	1.6	2.2	3.1