VARIATIONS IN QUANTITY AND QUALITY OF GROUNDWATER IN THE SOUTH COAST REGION OF KENYA

A project report

presented to the University of Manitoba

in partial fulfillment of the

requirements for the degree of

Master of Engineering

in

Civil Engineering

by

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Winnipeg, Manitoba

August 1987 ©

ISBN 0-315-37211-7

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ABSTRACT

This paper describes the hydrogeology of the area of Kenya south of Mombasa town, running along the coastal plain from Ukunda in the north towards the Tanzania boarder in the south. The area has a population of around 53,100 (1983 figures) and it is expected that this will rise to about 75,000 by the year 1993. It covers the whole of Diani and Msambweni locations in Kwale district, an area of approximately 300 square kilometres. The climate along the coastal plain is generally hot and humid with a maximum temperature of 33°C and lowest temperature of about 23°C. The mean annual rainfall is 1,200 mm per year with most of the rains coming between April and July. The rain decreases with distance inland parallel to the coast.

The existing water supplies are from boreholes and serve only 10% of the population concentrated in the three commercial centres within the project area. The rest of the people use water from shallow hand-dug wells and other sources including ponds, springs and rivers.

With the objective of improving the sanitation in the area, the government of Kenya undertook to rehabilitate the existing wells (by covering and installing handpumps) as well as drilling new wells to augment the existing water supplies. The project was funded by Swedish International Development Agency (SIDA) under the auspices of United Nations Development Program (UNDP) and with management support from the World Bank.

The first step was to identify the wells which should be rehabilitated and new sites for drilling more wells. This was done by

collecting data from the already existing wells. The information gathered included well depth, well diameter, whether the well is lined or not, whether it has a pump or not and the number of people served by each well. It was found that most of the wells were not lined or covered and this posed a great health hazard. Some wells had been equipped with hand-pumps but due to lack of maintenance none of the pumps were working and people had broken the cement plates covering the wells and reverted to drawing water from the wells using a rope and bucket. Appendix I shows water being drawn from a well using a hand-pump.

The yield from most of the wells were adequate for domestic purposes. Of all the 127 wells drilled only two wells, Mafisini Kibaoni and Mbuani Shamu had very little water (<300 lph). The most productive well was at Msambweni Camp. None of the wells were dry. Chemical analyses were performed for 42 wells and apart from one well (Chalo), which was found to be highly mineralised, all the other wells had reasonably good quality water for drinking.

Electrical conductivity of the water from existing wells was taken in the field. This provided an overall assessment of the total dissolved solids in the wells. The higher the electrical conductance, the more mineralized a well was supposed to be. The actual concentrations were however determined after the water sample was taken to the laboratory and the chemical analysis performed. The local administration was also interviewed in order to identify those villages which were heavily populated and which therefore required more wells. The wells which were found not to have silted up and had relatively clean water were earmarked for rehabilitation while other well sites were identified. The new wells were dug using cable-tool percusion rig to depths between 20 m - 30 m. After drilling the appropriate lengths of casing and screen were installed to prevent the formation from caving in and then a trial test-pumping was carried out using the rig pump (reciprocating pump). During the trial test-pumping drawdown was monitored in the pumping well and where applicable in a nearby observation well(s). During the trial test-pumping a water sample was taken in 2-litre plastic bottles and taken to the laboratory for analysis.

Nearly all the wells drilled had yields between 2 m^3/hr and 3 m^3/hr which is considered adequate for domestic purposes. Quality-wise a number of wells (8 out of 42) were found to be having hard water especially due to the high concentrations of the bicarbonate ion derived from the limestones in which most of the wells are drilled. Hardness is not hazardous to health despite causing scales in pipes and boilers and the difficulty in forming a lather with soap. Because the water from the wells was not intended for industrial purposes, it was recommended that the water was suitable for the expected purposes.

ACKNOWLEDGEMENTS

I am greatly indebted to Professor Goulter, my advisor without whose help and guidance this report could not have been realised. I also acknowledge the assistance provided to me by Mr. Leonard Lye and Ansari Khan during the course of this study. To my colleagues in the 1986/87 Water Resources class, thanks for the many discussions of academic relevance we had.

My special thanks to the Government of Kenya for granting me, through CIDA, the financial support while in Canada. Finally to my parents, thanks for the patience and encouragement given while far away from home.

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ABBREVIATIONS AND SYMBOLS USED

SIDA	Swedish International Development Agency
UNDP	United Nations Development Program
WHO	World Health Organisation
t	Time in minutes since pumping began
r	Distance in metres from the pumping well to the observation well
s	Drawdown in metres
Q	Discharge of the well (appropriate units indicated)
T	The coefficient of transmissibility
S	The coefficient of storativity under artesian conditions
S_y	The coefficient of storativity under water-table conditions
W(u)	Well function of u
TDS	Total dissolved solids
CCE	Carbon chloroform extract
ABS	Alkyl benzl suphonates
LPM	Litres per minute
LPH	Litres per hour
B/H	Borehole
OW	Open well
WRL	Water rest level
WSL	Water struck level
SBH	Shallow borehole

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1. INTRODUCTION

The South Coast Hand Pumps Project is situated in the coastal province of Kenya, Kwale district approximately 500 km SSE of the city of Nairobi and about 40 km south of the port of Mombasa. Figure 1A shows a map of Kenya and the position of the project area, and Figure 1B shows the location of the groundwater wells in the area. The well names are listed in Appendix 2.

The Government of Kenya has realised that the provision of clean potable water to the rural population in general can be achieved mainly by the development of shallow wells which are properly constructed to prevent contamination. Under previous conditions most of the wells in the rural communities were very shallow hand dug wells which were uncovered and rarely provided enough water. In 1982, the South Coast Hand Pumps Project was started with the aim of providing clean water to the rural communities. The project has since been successfully completed and 127 wells have been drilled. Most of the wells were found to have good water of a quality suitable for domestic purposes.

It is the intention of the Government of Kenya's Ministry of Water Development to provide potable water to every community by the turn of the century. Encouraged by the success of South Coast project two more similar projects, the Kwale Hinterland Sanitation Project and the South Nyanza Shallow Wells Project have been started.

This study examines the hydrogeology, quantity and quality of groundwater of the south coast region of Kenya and suggests new measures for assessing quality parameters of groundwater derived from the wells in the region. These measures included the plotting of individual ions

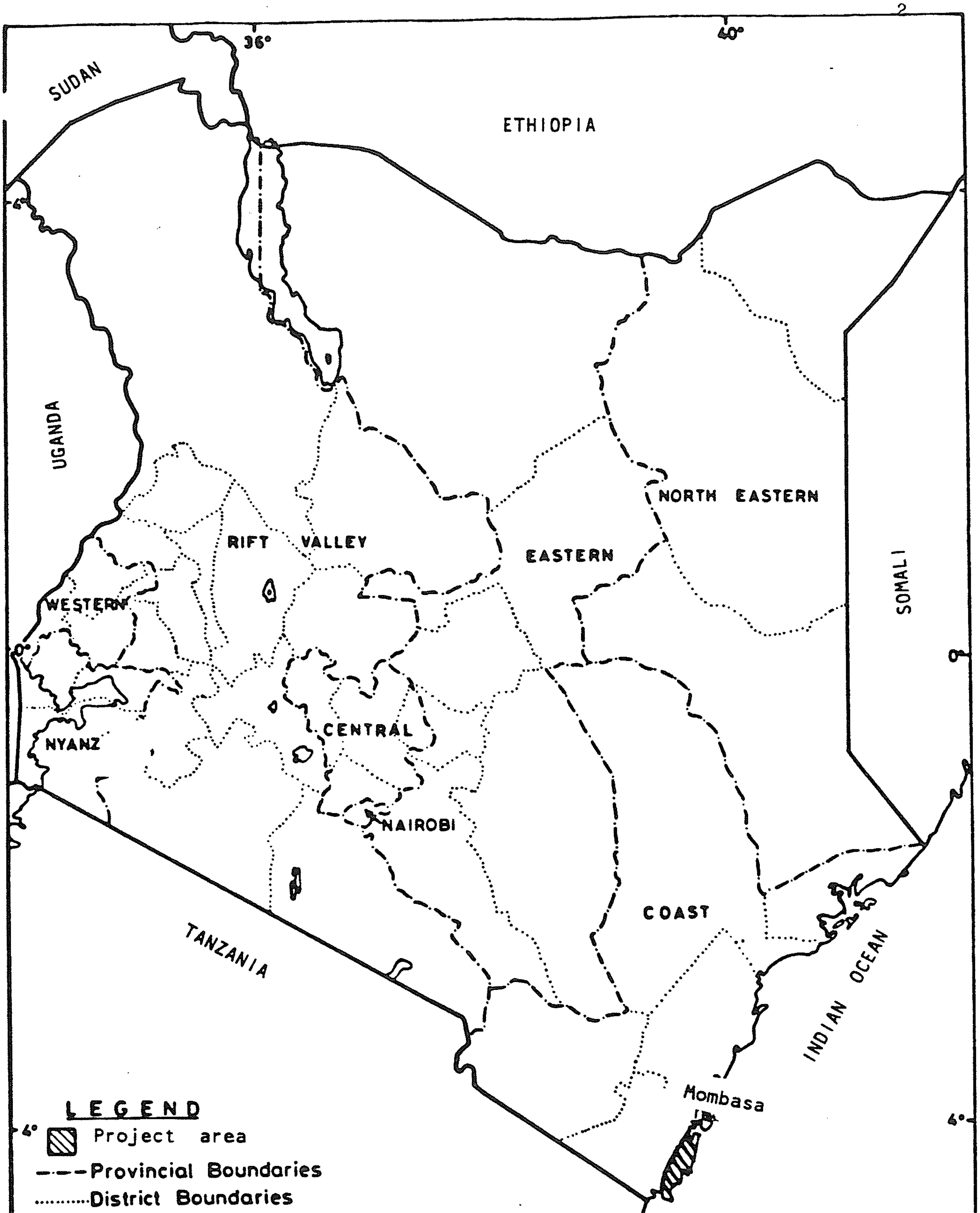

FIGURE 1A: LOCATION OF THE PROJECT AREA

FIELD TESTING AND DEVELOPMENT OF RURAL WATER SUPPLY HAND PUMPS SOUTH COAST PROJECT.

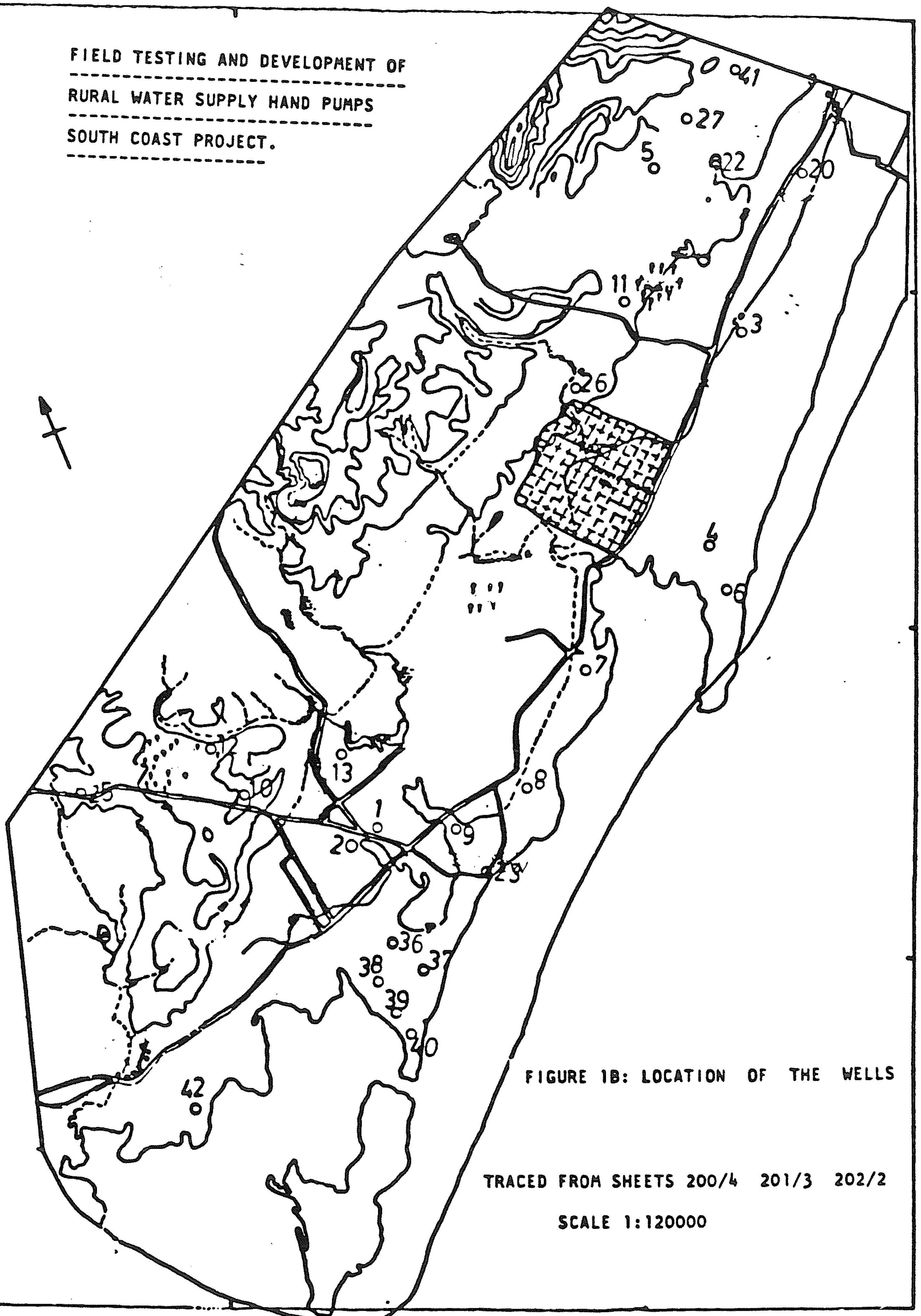

FIGURE 1B: LOCATION OF THE WELLS

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in all the boreholes and defining two limits, the limit of general acceptability and the highest acceptable limit as stipulated by the World Health Organization. The ratio of the concentration of each ion in every well to the difference between the two bands were taken as a quantitative measure of the quality of the water. A ratio of less than 1.0 indicated that the well had potable water as far as the concentration of the particular ion was concerned while a ratio of more than 1.0 indicated that the concentration of the particular ion was excessive.

2. BRIEF DESCRIPTION OF GROUNDWATER, HYDROGEOLOGY AND AQUIFERS

2.1 Hydrogeology of the Project Area

The coastal region has a geology which consists of beach sands, the coral reef complex and sandstones. Interspersed between the sandstones are layers of clays and shales. The area receives about 1200 mm of rainfall annually, mainly from convectional storms, and a fair amount of local recharge takes place through the highly permeable sands to become groundwater. Wells dug into the coral limestones yield hard but potable water mainly confined to solution channels within the rocks. This supply from the coral limestones is however limited by the close proximity of the sea with the consequent risk of contamination by sea water. The sands are highly pervious due to their lack of consolidation and they yield good quality and fair quantities of groundwater at relatively shallow depths. Large diameter boreholes drilled to about 60 m below surface in the Tiwi and Ukunda areas, if properly gravel-packed, can yield large amounts of groundwater (>80 m^3/hr) for municipal supplies. Very deep boreholes in the coastal zone may, however, result in tapping mineralised water from the shales. The wells which are drilled into the sandstone series are liable to be saline due to the fact that these series were deposited in a land-locked basin under conditions of semi-aridity. This led to the evaporation of the water with the consequent precipitation of the mineral salts.

2.2 Groundwater

Water is introduced into the ground by precipitation and streamflow. Once in the ground, water exists in several different environments as illustrated in Figure 2. There are two main zones, the

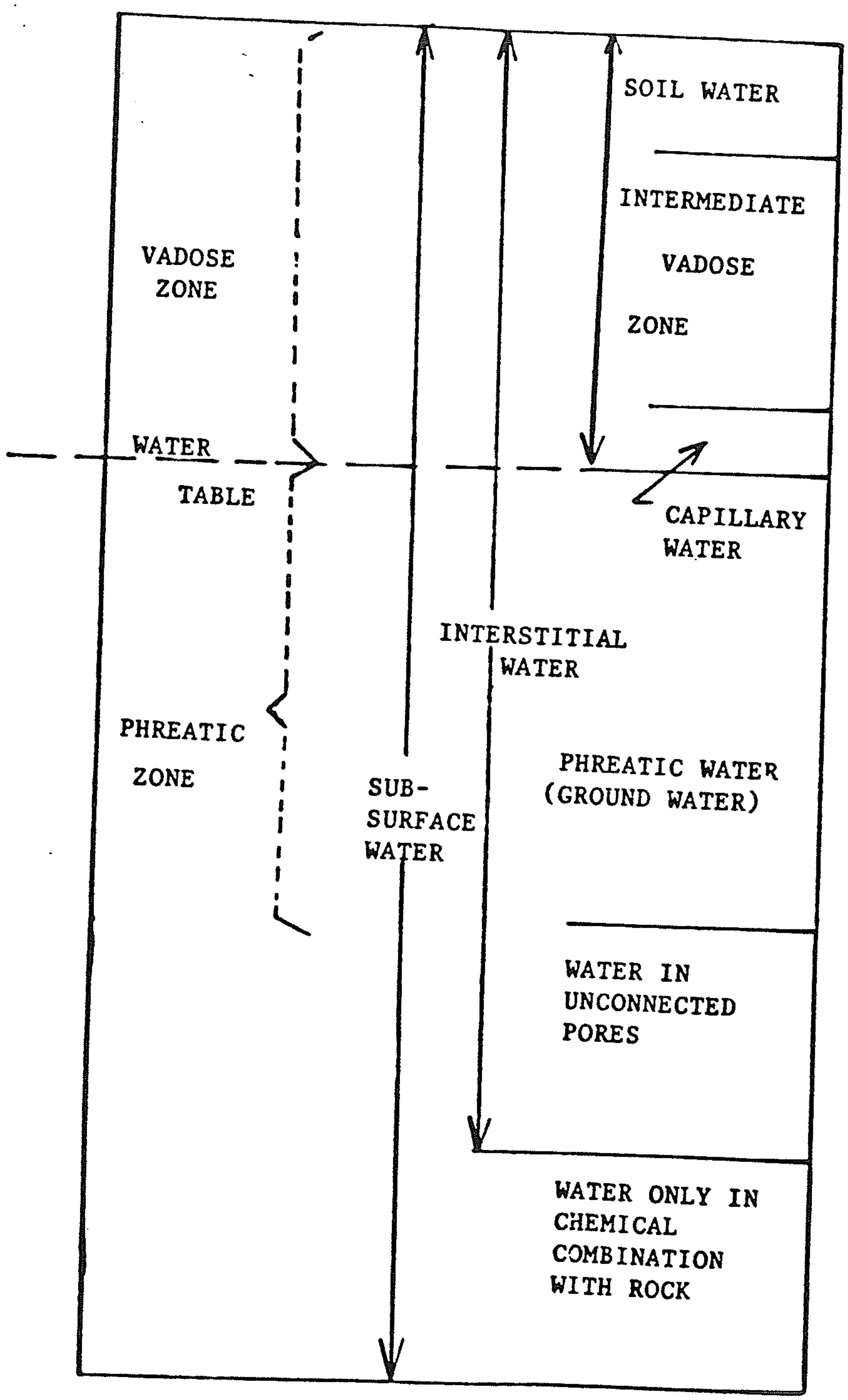

FIGURE 2:CLASSIFICATION OF SUB-SURFACE WATER.

vadose zone and the phreatic zone. In the vadose zone, three separate types of water exist: soil water, intermediate vadose water and capillary water. At the very bottom of the capillary zone lies the groundwater table. The groundwater table is such that, if a number of observation wells are drilled through the capillary zone, the water level standing in each well marks the elevation of the groundwater table. Water below the water table is called groundwater.

The groundwater zone may be imagined as a huge natural reservoir or a system of reservoirs in rocks whose capacity is the total volume of pores or openings that are filled with water. The thickness of the groundwater zone is governed by local geology, availability of pores or openings in the rock formation, recharge and the movement of water from areas of recharge towards points of discharge.

2.3 Aquifers

An aquifer is a saturated bed, formation, or a group of formations, which yields water in sufficient quantities to be economically useful. Water exists in aquifers under two different conditions. The most common condition is when the water table is exposed to the atmosphere through openings in the overlying regolith (loose unconsolidated weathered rock). This type of aquifer is called unconfined aquifer (sometimes called water-table or free aquifer). The second condition occurs when groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations. This type is known as confined aquifer and is generally subject to pressures higher than atmospheric pressure. Unconfined conditions however do occur at the point of recharge in confined aquifers. Confined aquifers occur because the overlying and basal beds are relatively impermeable to water flow.

The functions of an aquifer are four-fold:

i) Gathering: infiltrating rainwater is collected.

ii) Storage: it acts as a water reservoir.

iii) Conduit: it serves as a pipeline to transport the water towards the wells.

iv) Purification: the groundwater is filtered through the sand and thereby cleaned.

The four functions are a characteristic of every aquifer whether it is water-table or confined and are all very important functions of aquifers.

3. ANALYSIS OF AQUIFERS

The non-equilibrium formula developed by Theis (1935) has been widely used with pumping test data for determining the hydraulic properties of an aquifer. The development of the non-equilibrium formula was based partly on the assumptions that the coefficient of storage is constant and that water is released from storage instantaneously with a decline in artesian head. Under water table conditions water is derived from storage by gravity drainage of the interstices above the cone of depression, by compaction of the aquifer and by expansion of the water table itself as pressure on the groundwater is reduced. The important effects of gravity drainage are not considered in the non-equilibrium formula and the application of the formula to the results of pumping tests in unconfined aquifers is not generally justified.

Three distinct segments of the time drawdown curve are recognised under water table conditions. During the initial stages of pumping, the unconfined stratified sediments often react for a short time in the same fashion as an artesian aquifer, i.e. water is released instantaneously from storage by the compaction of the aquifer and the associated beds, and by the expansion of the water itself. Gravity drainage is not a factor at this stage. During the second stage gravity drainage becomes important and its effects are similar to that of leakage from nearby source. In the cases examined in this study, the leakage can be attributed to two sources. About 40 metres south of one pumping well is a seasonal stream and although dry at the time of test pumping, it is possible that the cone of depression spread past the river bed and recharge into the well occurred from water below the river bed. The other possibility of leakage can be attributed to 'reverse flow'. During test pumping water was being spilled about 5 metres from the pumping well, onto the highly permeable sands, from where it permeated back into the well. This is the most probable source of leakage as the analysis by Theis and Jacobs method shows that leakage started at approximately 10 minutes after pumping began, a very short period for the cone of depression to have spread past the river bed.

There is also a decrease in the slope of the time drawdown curve relative to the Theis curve, 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 well. The third segment which may start from several minutes to several days after initial pumping, depending upon aquifer conditions, represents the period during which the time drawdown curves conform closely to the non-equilibrium type curve. Theis (1935) described the third segment of the time drawdown curve under water table conditions: 'In as much as the rate of fall of the water table decreases progressively after a short initial period, it seems probable that as pumping continues the rate of drainage of the sediments tends to catch up with the rate of fall of the water table, and hence that the error in non-equilibrium equation becomes progressively smaller.' Jacob's method (Cooper and Jacob, 1946) is a modification of Theis method and is used in the analysis of aquifer data after the water levels have stabilized. It is much simpler than Theis method as it does not involve a curve matching technique.

4. THEIS NON-EQUILIBRIUM WELL EQUATION

Data collected when 't' is small or 'r' is large do not plot on a straight line using Jacob's method. In certain cases therefore, the Theis method is necessary to obtain the transmissibility and storativity of an aquifer. By use of the Theis equation, the drawdown can be predicted at any time after pumping begins, and this enables the transmissibility and storativity of an aquifer to be determined during the early stages of a pumping test rather than when the water level in the observation wells have stabilized as necessary for Jacob's method. Appendix 3 shows the measurement of drawdown in a typical observation well.

Several assumptions are taken into account in the derivation of the Theis equation:

1. The aquifer is uniform in character and the hydraulic conductivity is the same in all directions.

2. The aquifer is uniform in thickness and infinite in aerial extent.

3. The aquifer receives no recharge.

4. The borehole (well) penetrates and receives water from the full thickness of the aquifer.

5. The water released from storage is discharged instantaneously when the head is lowered.

6. All water removed from the well comes from aquifer storage.

7. Laminar flow exists throughout the vicinity of the well and the aquifer.

8. The water table (or potentiometric surface) has no slope.

These assumptions seem to limit the use of the Theis equation severely but in reality, they do not. The first assumption of uniform hydraulic conductivity is rarely found in a real aquifer but the average hydraulic conductivity determined from pumping tests have proved to be reasonably reliable for predicting well performance. The assumption of no stratification is not a serious limitation in confined aquifers where the well is fully penetrating and open to the formation. The assumption of constant thickness is also not an important limitation because the variation in aquifer thickness within the cone of depression in most situations is relatively small especially in sedimentary rocks. The assumption that the water table or piezometric surface is horizontal before pumping begins is also generally incorrect. However the slope or hydraulic gradient is nearly flat and its effect on calculation of well yield is negligible in most cases. The flow in all regions of an aquifer is considered to be laminar, though there are some departures from laminar flow but this causes only small additional head losses (Mogg, 1959).

In absolute or non-dimensional form, the Theis equation is:

$$s = \frac{Q}{4\pi T} \int_{u}^{\infty} \frac{e^{-u}}{u} du \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where:

u = $r^2S/4Tt$

Q = rate of discharge of the well

T = the coefficient of transmissibility of the aquifer

S = the coefficient of storage of the aquifer

r = distance from the pumped well to the observation well

t = time since pumping began

e = natural logarithm base

In SI units, Equation 1 becomes:

$$s = \frac{1}{4\pi}\frac{Q}{T}\int_{u}^{\infty}\frac{e^{-u}}{u}\,du$$

$$= \frac{1}{4\pi}\frac{Q}{T}\,W(u) \qquad \text{....................(2)}$$

where:

s = drawdown in metres at any point in the vicinity of a well discharging at a constant rate

Q = pumping rate in m^3/day

T = coefficient of transmissibility of the aquifer in m^3/m/day (m^2/day)

W(u)= "well function of u" represents an exponential integral

$$u = \frac{r^2 S}{4Tt} \qquad \text{..................(2a)}$$

where:

r = distance from the centre of the pumping well to the observation well (metres)

S = dimensionless coefficient of storage (storativity)

T = coefficient of transmissivity (m^2/day)

t = time since pumping started (days)

The well function of u, [W(u)] originated as a term to represent the heat distribution in a flat plate with a heating element at its centre. It was recognised that this same concept could be applied to the regular distribution of the groundwater head around a pumping well even though water flows towards a point source rather than away from it. The mathematical principles however remain the same.

Table 1. Values of W(u) for values of u (after Wenzel, 1942).

u	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
u x 1	0.219	0.049	0.013	0.0038	0.0011	0.00036	0.00012	0.000038	0.000012
u x 10^{-1}	1.82	1.2	0.91	0.70	0.56	0.45	0.37	0.31	0.26
u x 10^{-2}	4.04	3.35	2.96	2.68	2.47	2.30	2.15	2.03	1.92
u x 10^{-3}	6.33	5.64	5.22	4.95	4.73	4.54	4.39	4.26	4.14
u x 10^{-4}	8.63	7.94	7.53	7.25	7.02	6.84	6.69	6.55	6.44
u x 10^{-5}	10.94	10.24	9.84	9.55	9.33	9.14	8.99	8.86	8.74
u x 10^{-6}	13.24	12.55	12.14	11.85	11.63	11.45	11.29	11.16	11.04
u x 10^{-7}	15.54	14.85	14.44	14.15	13.93	13.75	13.60	13.46	13.34
u x 10^{-8}	17.84	17.15	16.74	16.46	16.23	16.05	15.90	15.76	15.65
u x 10^{-9}	20.15	19.45	19.05	18.76	18.54	18.35	18.20	18.07	17.95
u x 10^{-10}	22.45	21.76	21.35	21.06	20.84	20.66	20.50	20.37	20.35
u x 10^{-11}	24.75	24.06	23.65	23.36	23.14	22.96	22.81	22.67	22.55
u x 10^{-12}	27.05	26.36	25.96	25.67	25.44	25.26	25.11	24.97	24.86
u x 10^{-13}	29.36	28.66	28.26	27.97	27.75	27.56	27.41	27.28	27.16
u x 10^{-14}	31.66	30.97	30.56	30.27	30.05	29.87	29.71	29.58	29.46
u x 10^{-15}	33.96	33.27	32.86	32.58	32.35	32.17	32.02	31.88	31.77

Example: For u = 4.0 x 10^{-6}, W(u) = 11.85

Equation 2 implies a simple and direct means of solving for T. Unfortunately, however, T is also involved in the W(u) term so that a direct solution is not possible. This problem can be overcome by the use of a graphical solution (type curve) method. In Equation 2, the only variable terms will be the drawdown, s, and the well function, W(u). Similarly in the equation for u the only variable terms will be u, r and t. The significance of these facts will be more apparent if Equations 2 and 2a are rewritten in a slightly different form:

$$W(u) = \left\{\frac{4\pi T}{Q}\right\} s \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\frac{1}{u} = \left\{\frac{4T}{S}\right\} \frac{t}{r^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3a)$$

Equations 3 and 3a suggest that if one ignores the bracketed coefficients, which are constants, the term W(u) should vary with the term 1/u in the same manner as will vary with t/r^2, i.e. if values of W(u) are plotted against corresponding values of 1/u, the resulting curve should resemble that of a plot of s values against t/r^2.

Table 1 gives values of W(u) and u from which 1/u can be determined and the aquifer test data will provide values of s, t, and r. If these two curves are plotted on arithmetic plotting paper they will exhibit a general similarity of shape but they will not be identical due to the fact that the variables in the right of Equations 3 and 3a are multiplied by different constants. However if the two curves are plotted on logarithmic paper, multiplication becomes addition so that the differences in the constant multipliers of Equations 3 and 3a only causes relative displacement in the horizontal and vertical scales of the two plots. The use of logarithmic plotting paper has the added advantage of magnifying the low values in the data array and permitting coverage of large ranges in values on a relatively small area.

$$\log W(u) = \log \frac{4\pi T}{Q} + \log s \qquad \text{....................(4)}$$

$$\log \frac{1}{u} = \log \frac{4T}{s} + \log\left\{\frac{t}{r^2}\right\} \qquad \text{...................(4a)}$$

By preparing a logarithmic plot, with values of W(u) as ordinates and values of 1/u as abscissae, the so called type curve for the Theis equation is developed (see Figure 3).

Use of the Theis equation to determine the transmissivity and storativity from a field pumping test requires measurement of drawdown in at least one observation well. A demonstration of the Theis equation using data from Tiwi borehole No. C4570 shown in Table 2 is given. To calculate T and S using Theis method involves matching the curve plotted from the test data (Figure 4) with the type curve (Figure 3). Both the type curve and the test data curve should be plotted on papers with similar logarithmic scales and cycles. Table 2 shows drawdown data taken at regular intervals from an observation well 32.80 m from the pumping well. The yield of pumping well was 15 m^3 per hour (360 m^3 per day). The test data may be plotted in any of the following ways.

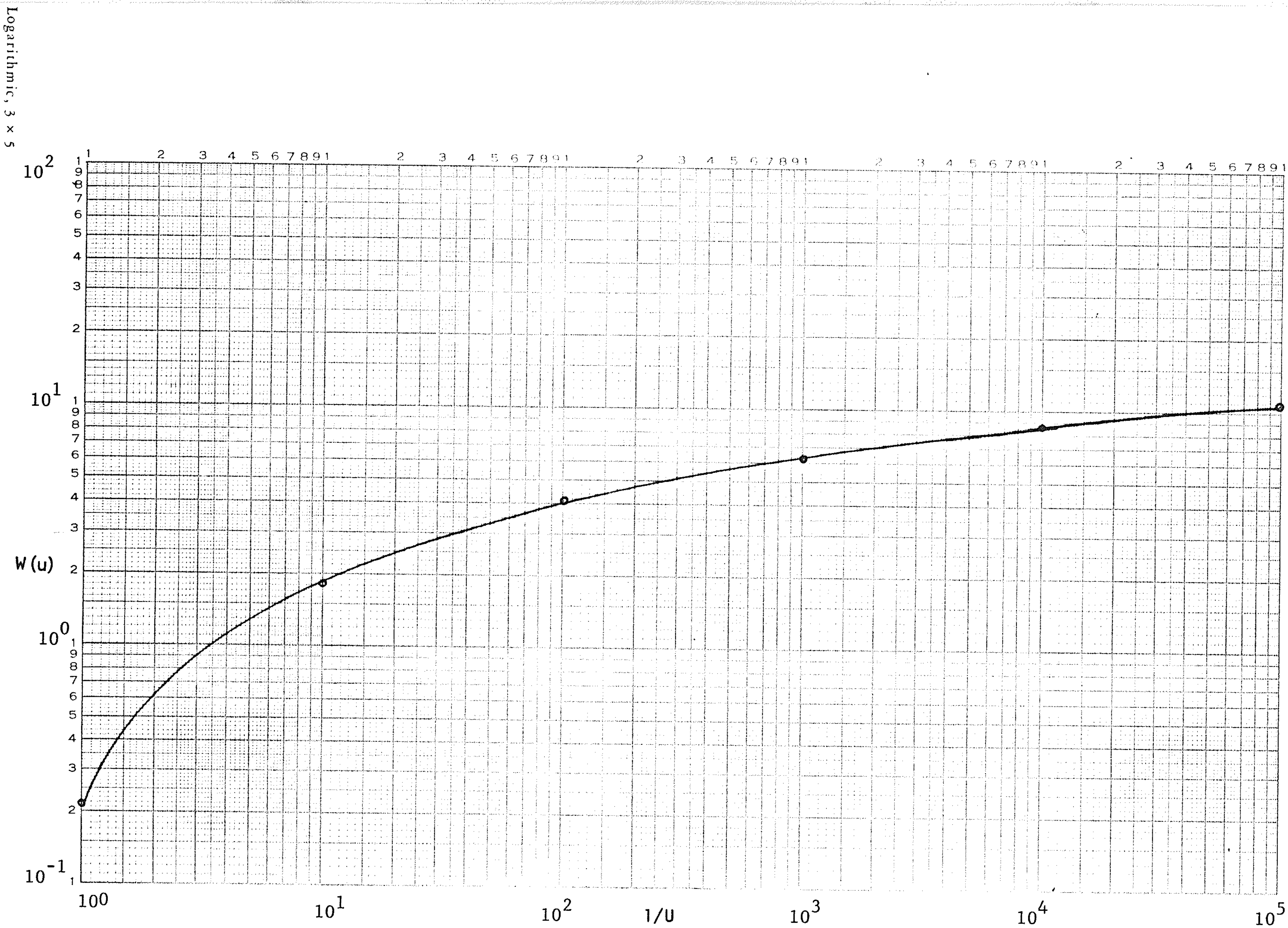

Figure 3: Theis Type Curve (Data from Table 2)

Table 2. Drawdown data in an observation well 32.8 m from pumped well.

Time Since Pumping Started (minutes)	Drawdown (metres)
0	0
1	0.02
2	0.05
3	0.08
4	0.09
5	0.11
6	0.12
7	0.13
8	0.14
9	0.14
10	0.15
15	0.16
25	0.17
30	0.18
35	0.19
40	0.19
50	0.19
60	0.20
70	0.20
80	0.20
90	0.20
100	0.21
110	0.21
130	0.21
150	0.21
160	0.21
170	0.21
180	0.21
200	0.21
240	0.21
300	0.22
420	0.23
480	0.24
600	0.25
660	0.26
720	0.26
780	0.26
840	0.27
900	0.27
960	0.27
1020	0.27
1080	0.27

Table 2 (cont'd ...)

Time Since Pumping Started (minutes)	Drawdown (metres)
1140	0.27
1200	0.27
1260	0.28
1320	0.29
1380	0.29
1440	0.30

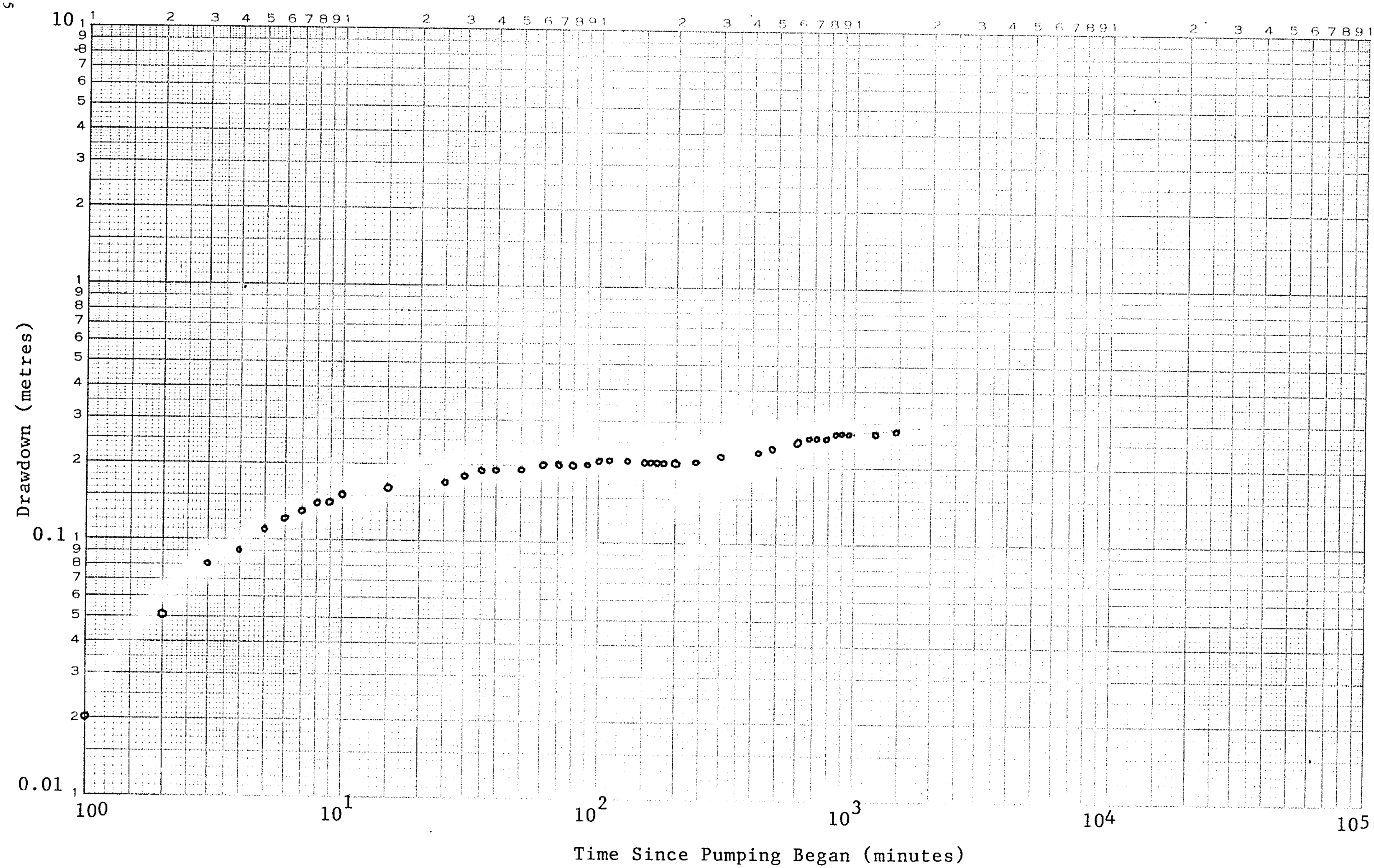

Figure 4: Test Data Plot on LOG-LOG Scale (Data from Table 2)

Table 3. Methods of plotting test data.

Method	Vertical Log Scale	Horizontal Log Scale
(a)	Drawdown, s	t
(b)	Drawdown, s	t/r^2
(c)	Drawdown, s	$1/r^2$

In this analysis, method (a) was used and the plot is shown on Figure 4. Drawdown s is plotted on vertical scale against time since pumping started on the horizontal scale. This plot was then superimposed on the type-curve plot, keeping the axes of both graphs parallel so that the plotted points fall on or fit some portion of the curve. Once a matching position is found, a match point which can be any convenient point on the graphs is selected. Usually a point where W(u) equals 1, 10, or 100 or where s is a whole number is selected for ease of computation.

At the early match point, t = 2.7 minutes (0.001875 days), s = 0.066 metres, u = 0.22 and W(u) = 1.

By using Equations 5 and 6, the transmissibility and storativity of the aquifer can be calculated respectively:

$$T = \frac{1}{4\pi} \frac{Q}{s} W(u) \quad \text{.....................(5)}$$

$$= \frac{1}{4\pi} \frac{360}{0.066}$$

$$= 434 \text{ m}^3 \text{ per day per m}$$

$$S = \frac{4uTt}{r^2} \qquad \text{.....................(6)}$$

$$= \frac{4 \times 0.22 \times 434 \times 0.001875}{(32.8)^2}$$

$$= 6.7 \times 10^{-4}$$

The analysis of pump test data using Theis equation yields transmissibility and storage coefficients for all non-equilibrium situations. However the Theis method is often avoided because the curve matching technique is somewhat laborious.

The Theis method can be avoided in most cases if the pumping test is long enough or the distance from the well to where the drawdown is measured is sufficiently small. In this case the well function W(u) can be replaced by a simpler mathematical function which facilitates the analysis considerably. This function is described in the following chapter.

5. MODIFIED NON-EQUILIBRIUM EQUATION (JACOB'S METHOD)

Cooper and Jacob (1946) developed a method which permits an approximate solution to the Theis non-equilibrium using a straight line graphical approach. The integral expression in the Theis equation is given by the series:

$$\int_u^\infty \frac{e^{-u}}{u} du = W(u)$$

$$= -0.5772 - \log_e u + u - \frac{u^2}{2x2!} + \frac{u^3}{3x3!} - \frac{u^4}{4x4!} + \frac{u^5}{5x5!} \quad \ldots.(7)$$

where:

W(u) = is the well function or exponential integral of u

When the value of u in Equation 7 is small (less than 0.05), i.e., when $\frac{r^2}{t}$ becomes very small ($u = r^2/4Tt$), the terms following the first two terms of Equation 7 may be neglected and Equation 2 becomes:

$$s = \frac{Q}{4\pi T} [\log_e (1/u) - 0.5772)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(8)$$

By solving for the value of u necessary to make the value of s equal to zero Equation 8 can be reduced to:

$$s = \frac{Q}{4\pi T} \log_e \frac{2.25 \ T \ t}{r^2 S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(9)$$

Converting Equation 9 to common logarithms gives:

$$s = \frac{2.3 \ Q}{4\pi T} [\log \frac{2.25 \ T \ t}{r^2 S}] \quad \ldots\ldots\ldots\ldots\ldots\ldots.(10)$$

It can be seen from Equation 10 that a plot of the drawdown s, versus the time t on the log scale or a plot of drawdown taken at same time in three or more observation wells against the distance to the observation well on a log scale will be a straight line. In this analysis one observation well and a plot of drawdown versus time was used. The data for the Tiwi borehole No. C4570 shown in Table 2 are used to demonstrate the procedure. Figure 5 is a plot of drawdown on arithmetic scale and time since pumping began on logarithmic scale. The values of transmissivity, T, and storativity, S, are computed using the following equations:

$$T = \frac{2.30\ Q}{4\pi\Delta s} \qquad \text{..................(11)}$$

$$S = \frac{2.25\ T\ t_o}{r^2} \qquad \text{..................(12)}$$

where:

T = transmissivity in m^3/day/m (m^2/d)

Q = well discharge in m^3/day

Δs = drawdown over one log cycle (m)

t_o = time at zero drawdown intercept (days)

r = distance from the test well to the observation well (m)

From Figure 5, Δs = 0.148 m and t_o = 0.00056 days; therefore:

$$T = \frac{2.3 \times 360\ m^3/day}{4\pi \times 0.148\ m} = 445\ m^3/day/m$$

$$S = \frac{2.25 \times 400\ m^3/day/m \times 0.00056\ day}{(32.8)^2\ m^2}$$

$$= 5.2 \times 10^{-4}$$

By using the Theis method, the value of transmissivity was found to be

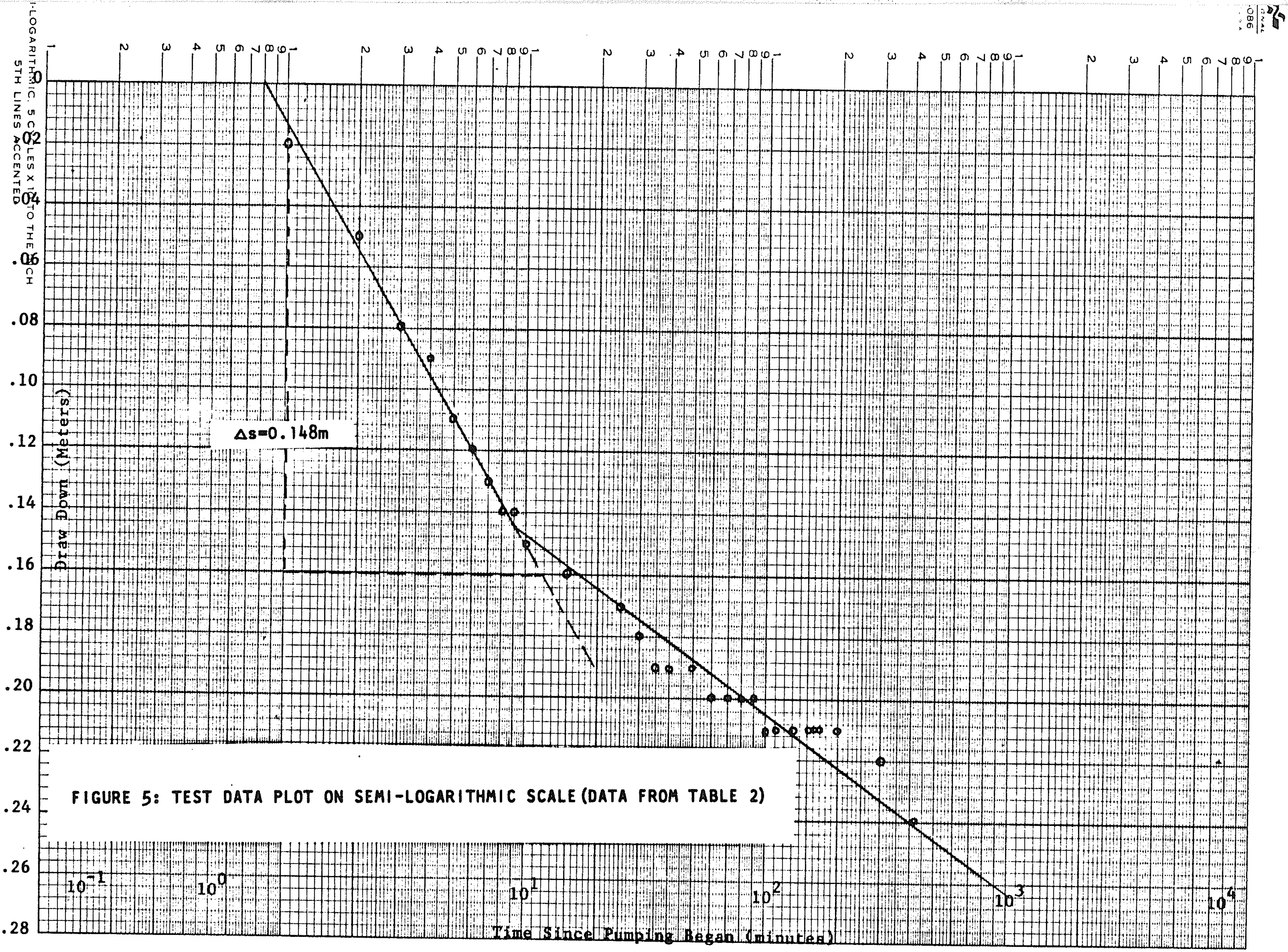

FIGURE 5: TEST DATA PLOT ON SEMI-LOGARITHMIC SCALE (DATA FROM TABLE 2)

434 m^3/day/m and that of storativity was found to be 6.9×10^{-4}. These values do not differ by more than 10% from those calculated using Jacob's method and therefore provide additional support to the values determined by Theis method. Ideally transmissivity and storativity calculated by the Theis non-equilibrium equation and the Cooper/Jacob's approximation method should be the same. However, within the assumptions used, the correspondence between the two values is satisfactory.

6. STEP-DRAWDOWN TESTS

The conventional well hydraulics theory assumes that laminar flow conditions exist in the aquifer during pumping. However turbulent flow occurs in some wells when they are pumped at a relatively high rate. If turbulent flow occurs, the linear relationship between drawdown and pumping rate no longer holds. Step-drawdown tests are developed to examine the performance of wells under turbulent flow. In a step-drawdown test the well is pumped at successively higher pumping rates and the drawdown for each rate is recorded. The pumping times should be the same for each step, usually 2 hours. The data from the step-test can be used to determine the relative proportion of laminar and turbulent flow occuring at any pumping rate. An example of a step-drawdown test for Tiwi borehole number C4142 is given in Table 4.

Table 4. Summary of step-drawdown test in well No. C4142.

Yield, Q (m^3/day)	Drawdown, s (m)	s/Q
492.72 (342 LPM)	2.12	0.0062
685.68 (476 LPM)	5.45	0.00114
990.36 (688 LPM)	10.35	0.0150
1027.92 (714 LPM)	9.64	0.0135

The drawdown s, in a confined aquifer under laminar flow conditions and in a perfectly efficient well is expressed by:

$$s = \frac{2.30\ Q}{4\pi T} \log \frac{2.25\ T\ t}{r^2 S} \qquad \text{..................(13)}$$

The above equation can be written as:

$$s = BQ \qquad \qquad (14)$$

where:

$$B = \frac{2.30}{4\pi T} \log \frac{2.25\ T\ t}{r^2 S} \qquad \qquad (15)$$

The value of B is time dependent but after a period of pumping B changes only slightly and it can be assumed constant under turbulent conditions. Jacob suggested that the drawdown in a well can be correctly expressed as the sum of a first order or laminar component and a second order or turbulent component as follows:

$$s = BQ + CQ^2 \qquad \qquad (16)$$

A graphical method for determining B and C was presented by Bierschank (1964). In this equation,

$$\frac{s}{Q} = B + CQ \qquad \qquad (17)$$

This is a linear equation in s/Q and Q and if s/Q is plotted against Q, a straight line with slope C and intercept B is obtained. If turbulent flow is present the specific capacity, $\frac{Q}{s}$, declines as discharge increases as shown in Equation 18.

$$\frac{Q}{s} = \frac{1}{CQ + B} \qquad \qquad (18)$$

Observing the change in drawdown and specific capacity with increased discharge provides the information required to select a pumping rate which will provide water over a long time without excessive drawdown. The ratio of the laminar headloss to the total headloss can be computed from step-drawdown tests:

$$L_P = \frac{B\,Q}{BQ + CQ^2} \cdot 100 \qquad \text{.....................(19)}$$

where:

L_P = is the percentage of the total headloss that is attributable to laminar flow.

Table 5 shows a discharge and drawdown data from the step drawdown data of Tiwi borehole No. C4142 and Figures 6 and 7 shows the relevant plots. Figure 8 shows a plot of $\frac{s}{Q}$ versus Q. Using Bierschank's method of analysis B = 0.0045 and C = 4.44 x 10^{-5}.

Using Equation 13 the specific capacity can be calculated for any flow rate and the specific capacity and drawdown can also be projected for any discharge rate. Assuming a discharge of 41.3 m^3/hr, L_P (the ratio of laminar to turbulent flow) can be calculated using Equation 19:

$$L_P = \frac{0.045 \times 41.3}{0.0045 \times 41.3 + 4.4 \times 10^{-5} \times (41.3)^2} \times 100\%$$

$$= \frac{0.18585}{0.26090} \times 100\% = 71\%$$

i.e. 71% of the headloss is attributable to laminar flow.

In summary step-drawdown tests can be used to:

1. Determine the specific capacity of the well at various discharge rates and this information can be used to determine the optimum discharge rates.

2. Determine the ratio, L_P, denoting the percentage of the total headloss attributable to laminar flow.

Table 5. Step-test data for Tiwi borehole number C4142 (step-test 1 and 3).

Time Since Pumping Started (min)	Drawdown (m)	Discharge (m^3/hr)
0	0	
0.5	1.41	
11	2.09	
13	2.11	
15	2.13	
20	2.14	20.57
25	2.09	
30	2.08	
35	2.08	20.67
40	2.07	
45	2.09	
50	2.09	
55	2.10	
60	2.10	
70	2.13	
80	2.12	
90	2.13	
100	2.09	20.35
110	2.10	
120	2.12	
121	7.13	
122	7.62	
123	8.25	41.07
124	8.44	
125	8.60	
126	8.68	
127	8.73	
128	8.85	
129	8.91	
130	8.95	
135	9.08	
140	9.33	
145	9.45	
150	9.76	
155	9.92	
160	10.08	
165	10.19	
170	10.30	
175	10.30	
180	10.34	41.07
190	10.35	

Table 5. Step-test date for Tiwi borehole number C4142 (step-test 2 and 4).

Time Since Pumping Started (min)	Drawdown (m)	Discharge (m^3/hr)
0.0	0.0	
2.0	4.19	
2.5	4.27	
3.0	4.34	
3.5	4.32	
4.0	4.45	
4.5	4.48	
5.0	4.50	
5.5	4.53	
6.0	4.58	
6.5	4.64	
7.0	4.68	
8.0	4.71	
9.0	4.75	
10	4.85	28.36
15	5.03	
20	5.11	
25	5.17	
30	5.20	28.92
35	5.24	
40	5.28	
45	5.28	
50	5.29	
55	5.31	
60	5.33	
70	5.32	
80	5.37	
90	5.41	
100	5.44	
110	5.45	
120	5.45	
121	8.62	
122	9.11	
123	9.37	
124	9.47	
125	9.56	
135	10.26	43.09
140	10.32	
145	10.42	
150	10.62	
155	10.50	43.54
160	10.49	

Table 5 (cont'd ...)

Time Since Pumping Started (min)	Drawdown (m)	Discharge (m^3/hr)
165	10.51	
170	10.55	
175	10.55	
180	10.56	
190	9.56	
200	9.56	
210	9.61	
220	9.62	41.86
230	9.64	

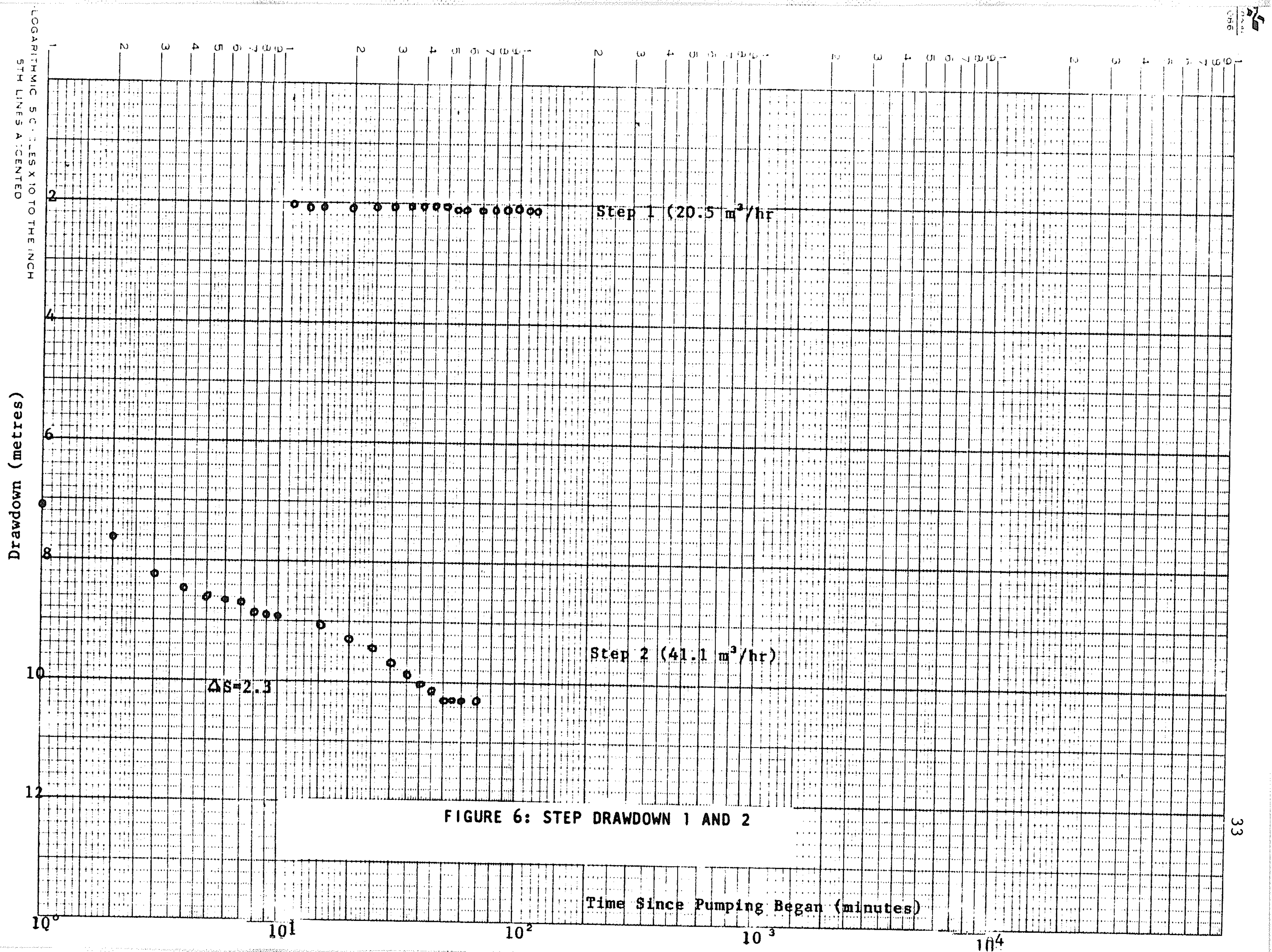

FIGURE 6: STEP DRAWDOWN 1 AND 2

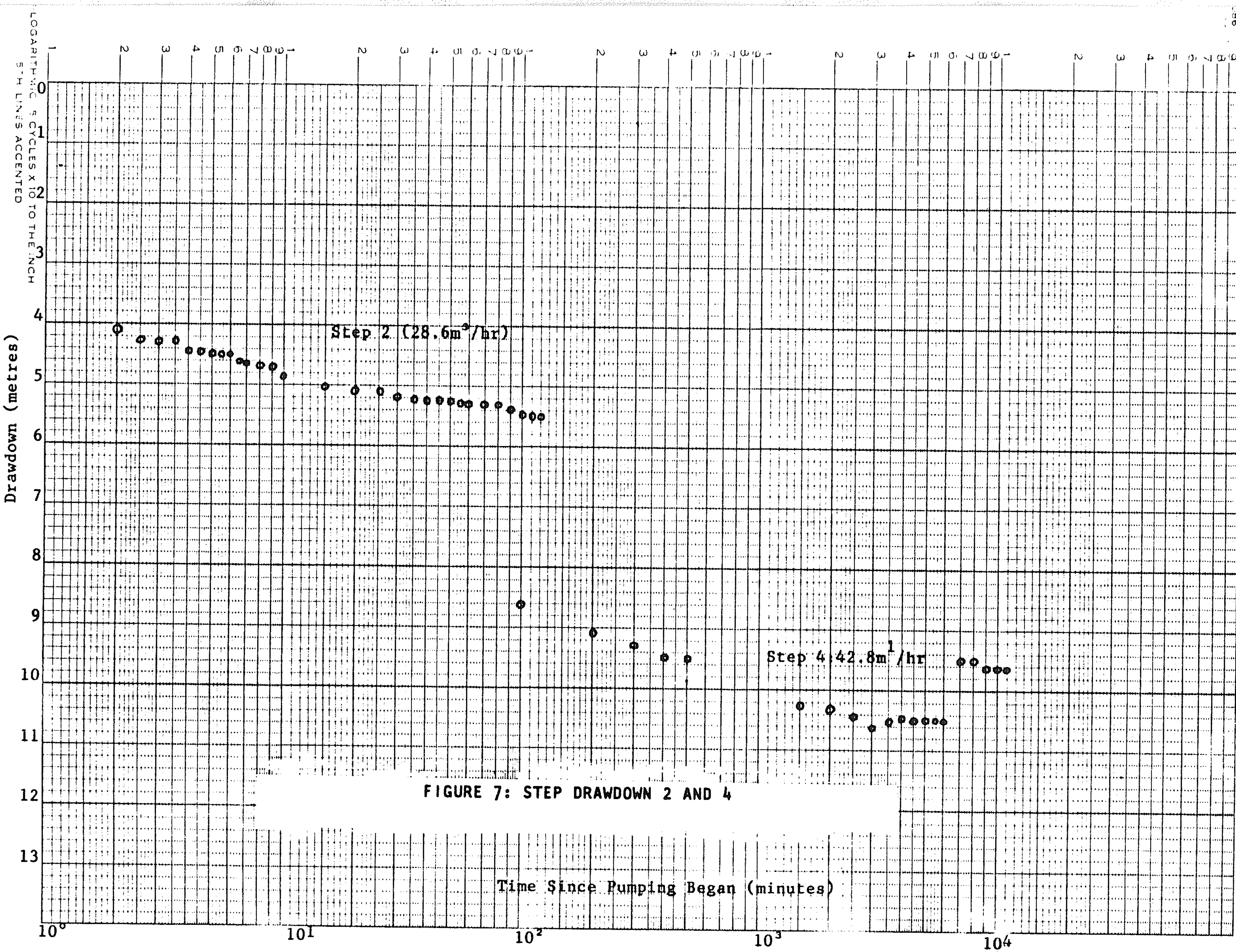

FIGURE 7: STEP DRAWDOWN 2 AND 4

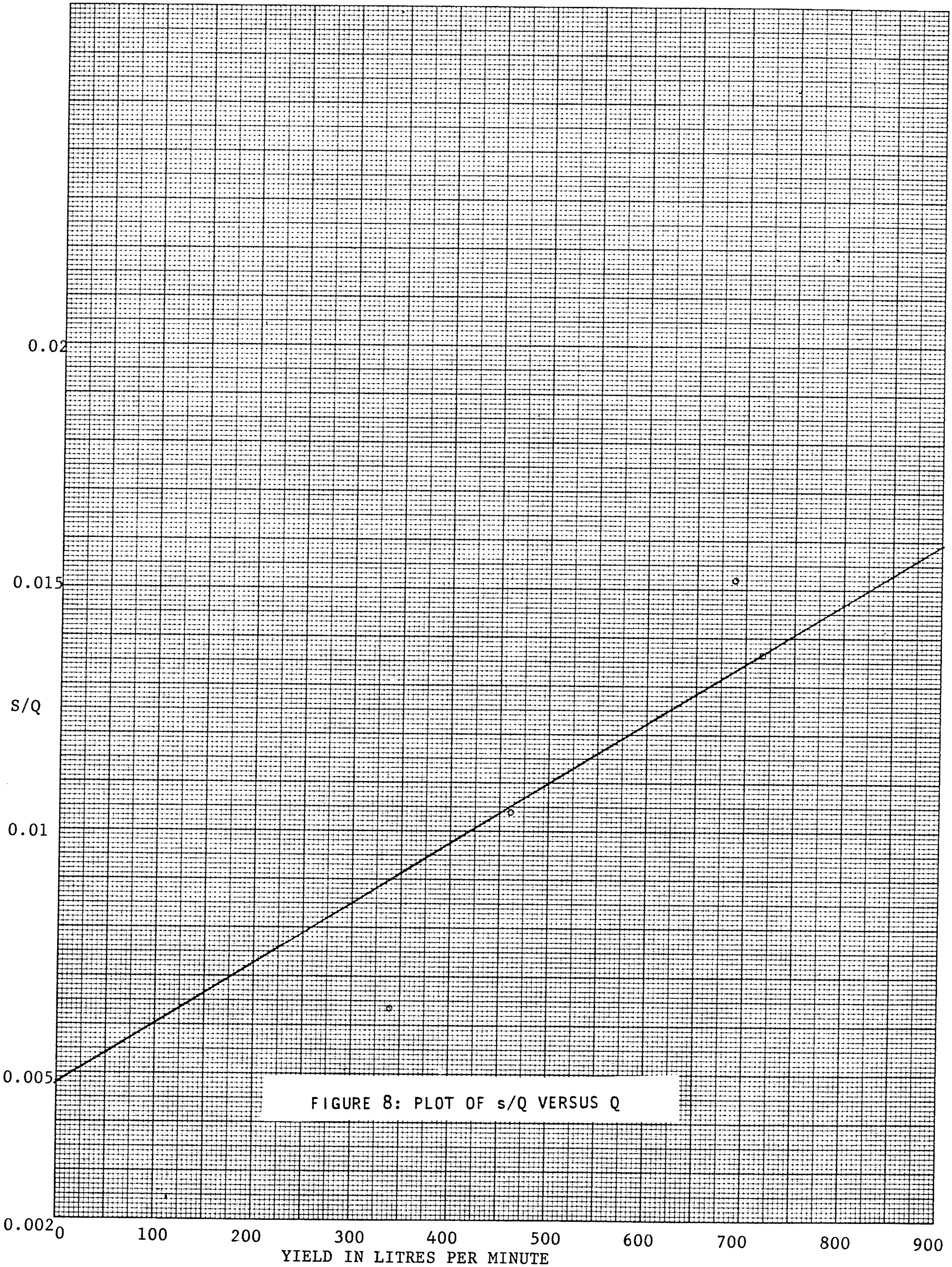

FIGURE 8: PLOT OF s/Q VERSUS Q

3. Determine the transmissivity and storage coefficient values for the aquifer from time-drawdown or distance-drawdown graphs drawn for one of the constant rate pumping tests.

7. WATER LEVEL MONITORING

Water level data provide records of short term changes and long term trends of fluctuations of storage within groundwater reservoirs. Uses of data on groundwater levels include the following:

1. To determine areas of excessively high or low water levels.

2. To enable the estimation of the groundwater outlook in future by showing the time-rate of change in groundwater storage.

3. To provide data for the evaluation of the water yielding properties of aquifers.

4. To appraise the relationship between water level fluctuations and pumping.

5. To aid in base flow estimation of streams.

6. To indicate the status of groundwater in transit.

7. To obtain data for use in research.

Water levels in wells are almost constantly fluctuating and can decline or rise within a relatively short time. Water level fluctuations for six wells over a period of 16 months are shown in Tables 6 to 11 and the water level hydrographs for the same wells shown in Figures 9 to 14. During the 16 month period the highest fluctuation in water levels was 5.84 m at Milalani well which had its highest water level of 8.20 m on 2nd September 1983 and a lowest water level of 14.04 m on 24th April 1983. The lowest water level fluctuation 0.45 m (11.43 cm) was recorded at Mwabungu-Galu well. It had its highest water level of 19.20 m on 3rd June 1983 and a lowest water level of 19.65 m on 11th January 1983. Of all the six wells where the groundwater level fluctuations were recorded, four (Milalani, Msambweni, Gazi and Shamu)

Table 6. Water level fluctuations at Well No. 93, Magutu (total depth of well, 27.10 m).

Date	Static Water Level (m)
14-1-83	22.98
7-2-83	23.67
19-2-83	22.94
31-3-83	23.26
19-4-83	23.34
4-5-83	22.98
22-5-83	22.70
3-6-83	22.65
14-6-83	22.55
30-6-83	22.50
18-7-83	22.47
15-8-83	22.60
2-9-83	22.56
23-9-83	22.63
17-10-83	22.73
13-11-83	22.84
5-12-83	22.95
24-1-84	23.01
17-2-84	23.05
20-3-84	23.10
28-4-84	23.16

Table 7. Water level fluctuations at Well No. 86, Shamu (total depth of well, 20.70 m).

Date	Static Water Level (m)
13-1-83	12.30
7-2-83	12.60
19-2-83	12.65
31-3-83	13.30
19-4-83	13.32
4-5-83	13.34
23-5-83	13.10
3-6-83	13.05
14-6-83	12.97
30-6-83	12.93
18-7-83	12.52
15-8-83	12.11
2-9-83	12.10
23-9-83	12.34
17-10-83	12.39
13-11-83	12.48
5-12-83	12.63
24-1-84	12.78
17-2-84	13.01
20-3-84	13.98
28-4-84	14.64

Table 8. Water level fluctuations at Well No. 55, Munasunga-Galu (total depth of well, 20.70 m).

Date	Static Water Level (m)
11-1-83	19.65
7-2-83	19.57
19-2-83	19.42
31-3-83	19.40
19-4-83	19.49
4-5-83	19.43
23-5-83	19.30
3-6-83	19.20
14-6-83	19.22
30-6-83	19.30
18-7-83	19.32
15-8-83	19.31
2-9-83	19.30
23-9-83	19.35
17-10-83	19.38
13-11-83	19.39
5-12-83	19.40
24-1-84	19.42
17-2-84	19.44
20-3-84	19.44
28-4-84	19.45

Table 9. Water level fluctuations at Well No. 32, Gazi (total depth of well, 20.70 m).

Date	Static Water Level (m)
5-1-83	9.85
7-2-83	10.13
19-2-83	10.26
31-3-83	10.31
19-4-83	10.33
4-5-83	10.20
23-5-83	9.97
3-6-83	9.81
14-6-83	9.51
30-6-83	9.33
17-7-83	9.16
15-8-83	9.24
2-9-83	9.23
23-9-83	9.36
17-10-83	9.57
13-11-83	9.87
5-12-83	10.02
24-1-84	10.39
17-2-84	10.42
20-3-84	10.51
28-4-84	10.58

Table 10. Water level fluctuations at Well No. 6, Milalani 1983/84 (total depth of well, 16.20 m).

Date	Static Water Level (m)
31-12-82	10.60
7-2-83	11.70
19-2-83	11.55
31-3-83	12.35
19-4-83	12.36
4-5-83	12.10
23-5-83	12.20
3-6-83	10.25
14-6-83	9.23
30-6-83	8.5
17-7-83	7.25
15-8-83	8.22
2-9-83	8.20
23-9-83	8.56
17-10-83	8.73
13-11-83	9.3
5-12-83	10.5
24-1-84	10.8
17-2-84	11.90
20-3-84	13.08
24-4-84	14.04

Table 11. Water level fluctations at Well No. 26, Msambweni (total depth 8.50 m)

Date	Static Water Level (m)
3-1-83	3.20
7-2-83	3.95
19-2-83	3.80
31-3-83	4.74
19-4-83	4.76
4-5-83	3.86
23-5-83	2.13
3-6-83	2.30
14-6-83	2.32
30-6-83	2.48
17-7-83	2.60
15-8-83	2.74
2-9-83	2.72
23-9-83	2.89
17-10-83	2.95
13-11-83	3.29
5-12-83	3.59
24-1-84	3.80
17-2-84	3.91
20-3-84	4.02
23-4-84	4.06

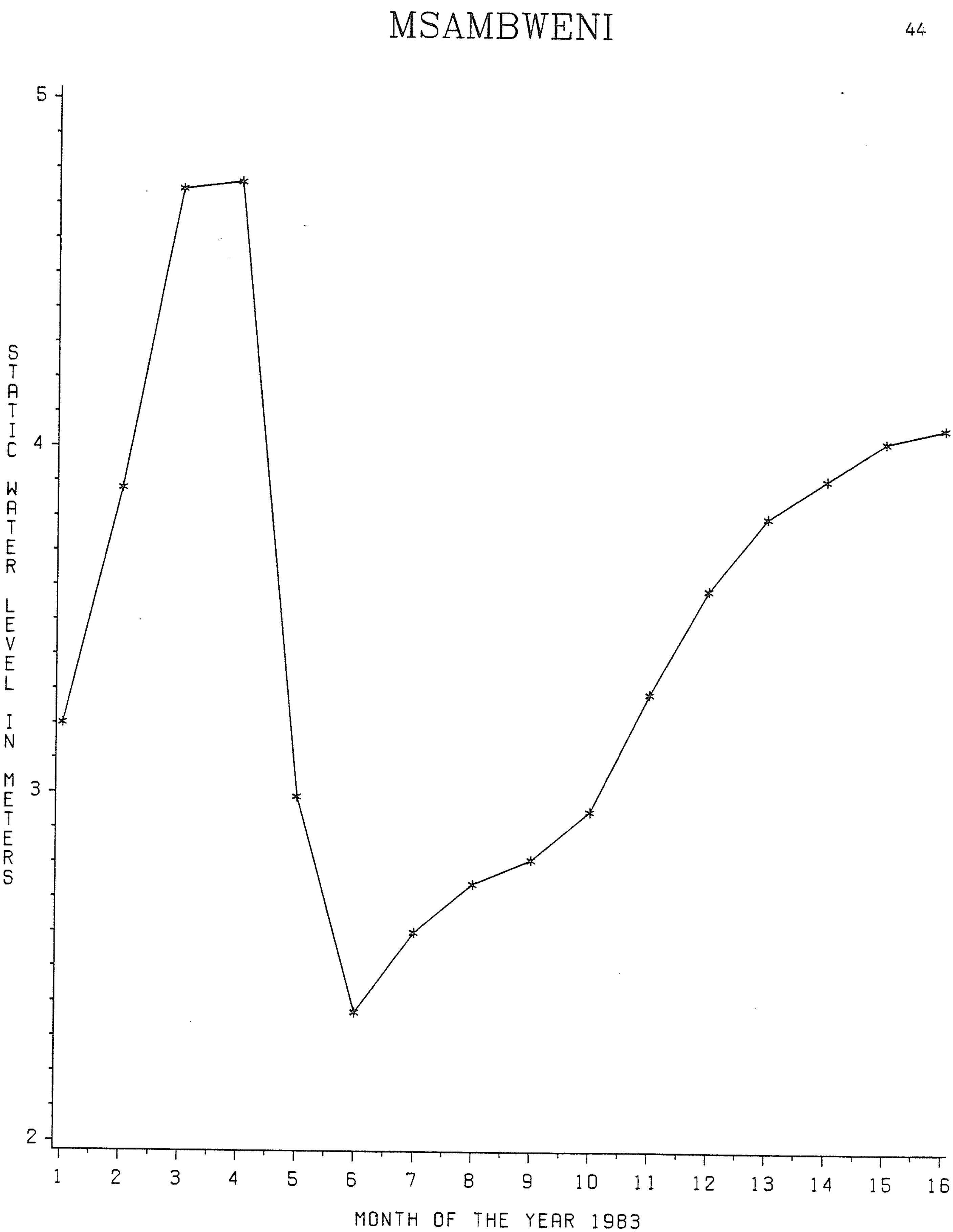

FIGURE 9:WATER LEVEL FLUCTUATIONS AT MSAMBWENI

GAZI

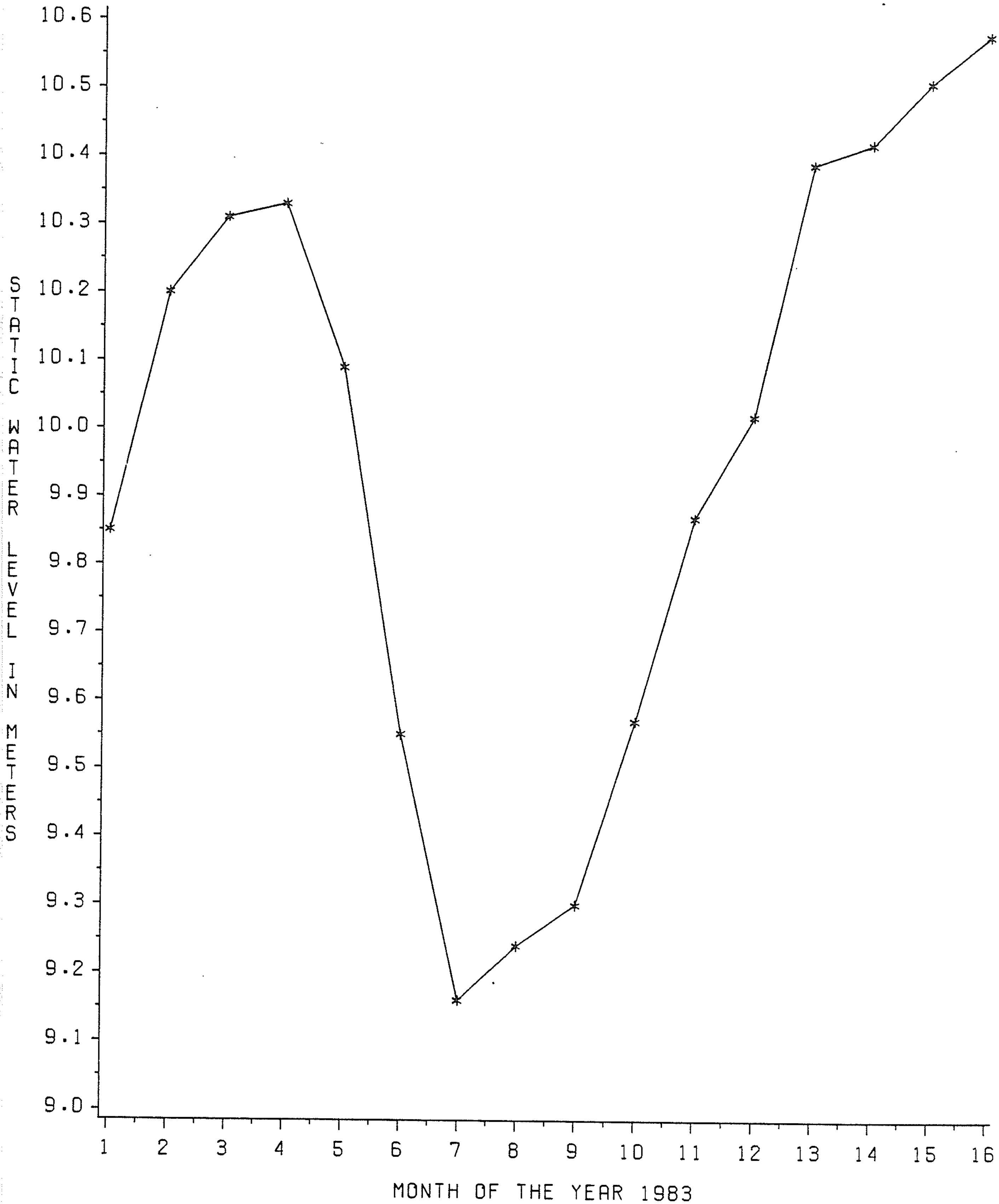

FIGURE 10:WATER LEVEL FLUCTUATIONS AT GAZI

MWABUNGU–GALO

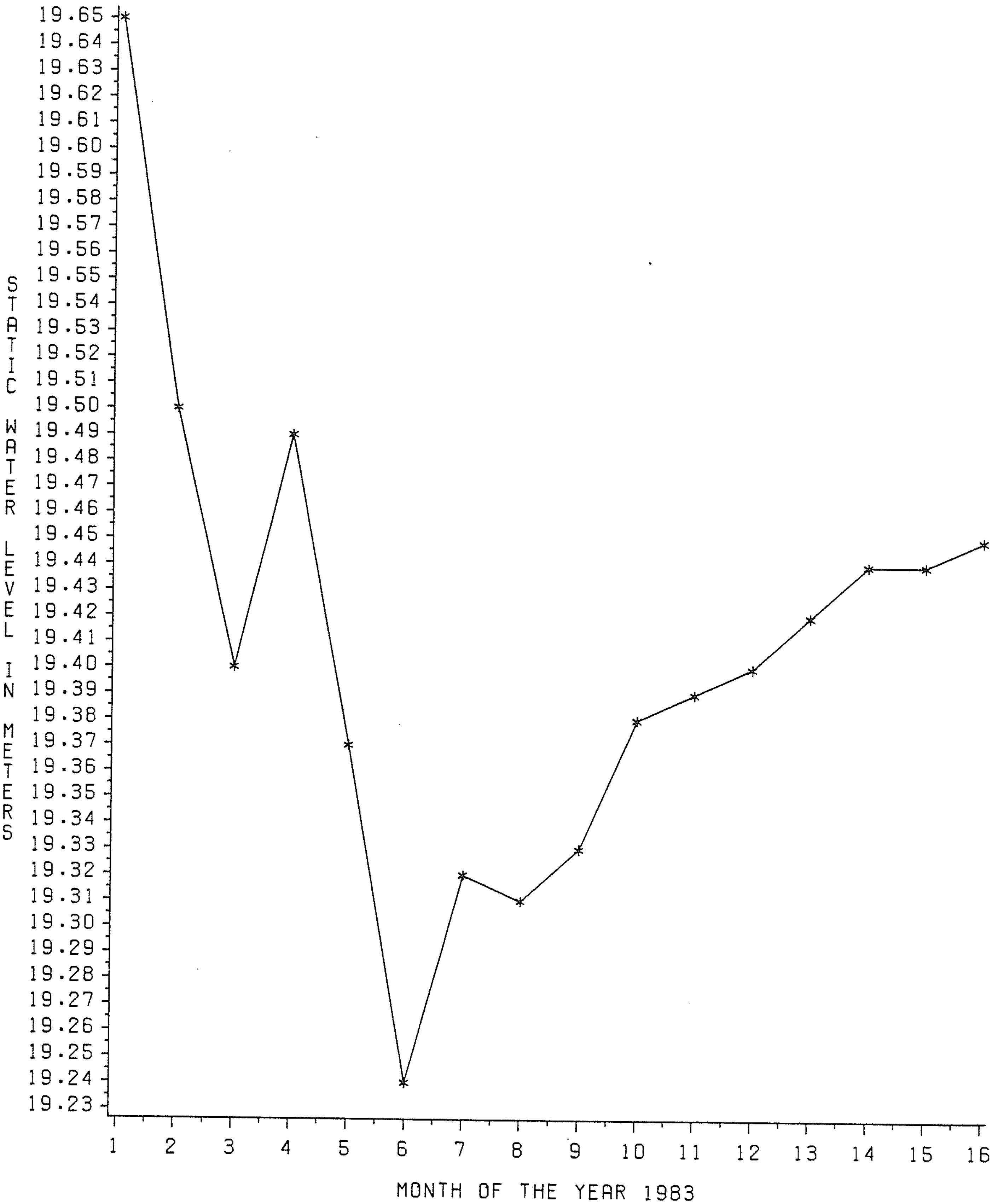

FIGURE 11:WATER LEVEL FLUCTUATIONS AT MWABUNGU-GALO

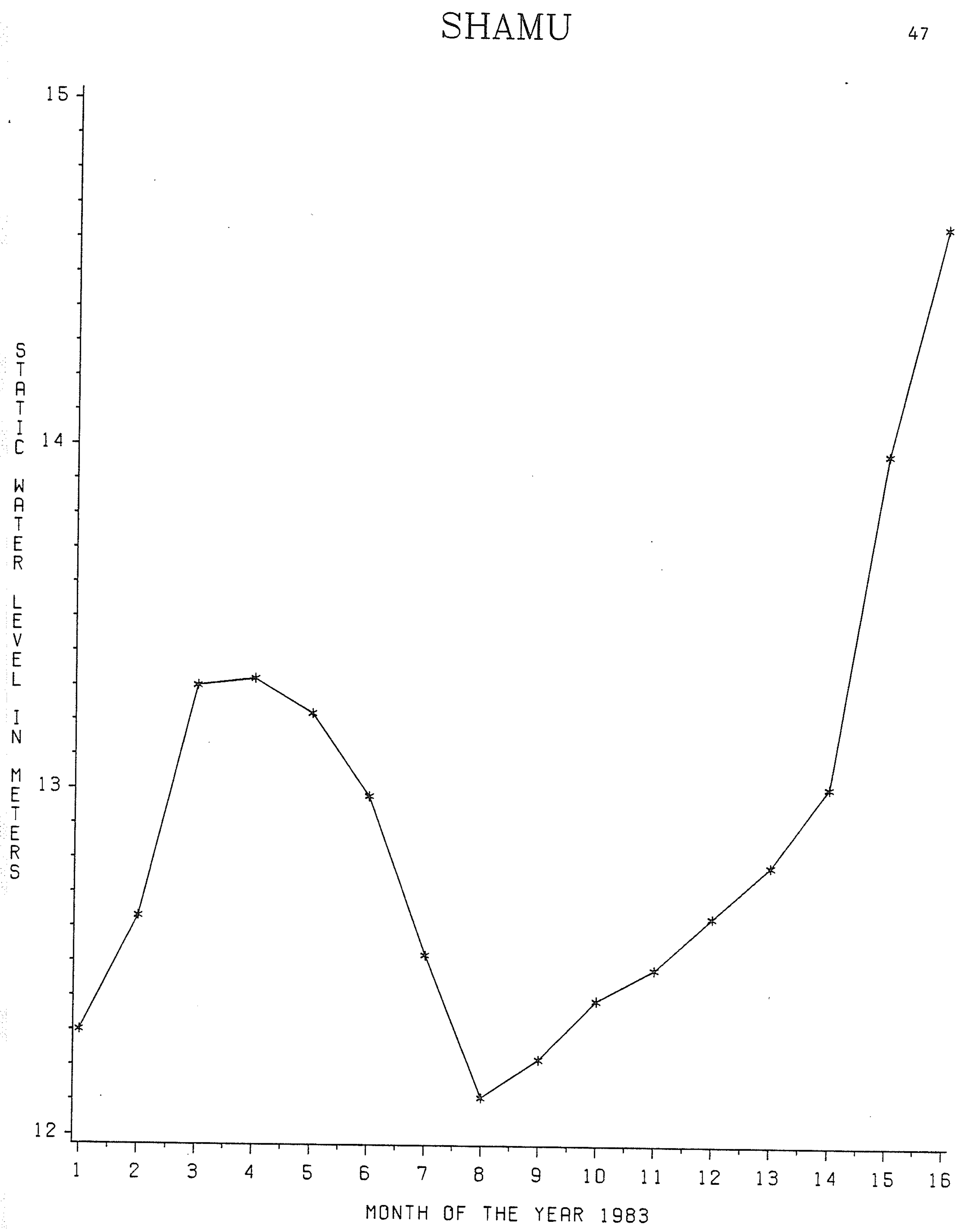

FIGURE 12:WATER LEVEL FLUCTUATIONS AT SHAMU

MAGUTU-NGOMBALO

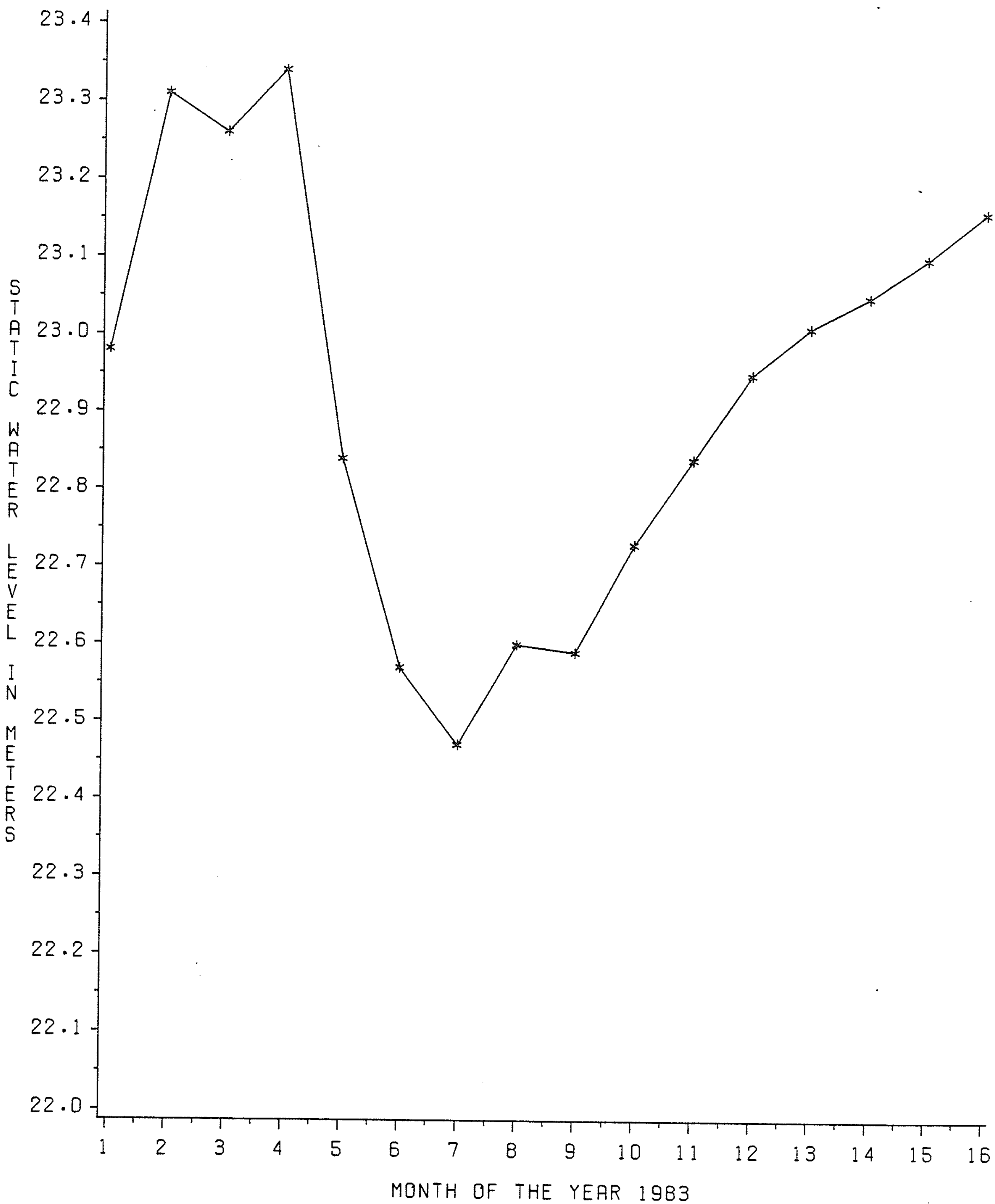

FIGURE 13:WATER LEVEL FLUCTUATIONS AT MAGUTU-NGOMBALO

MILALANI

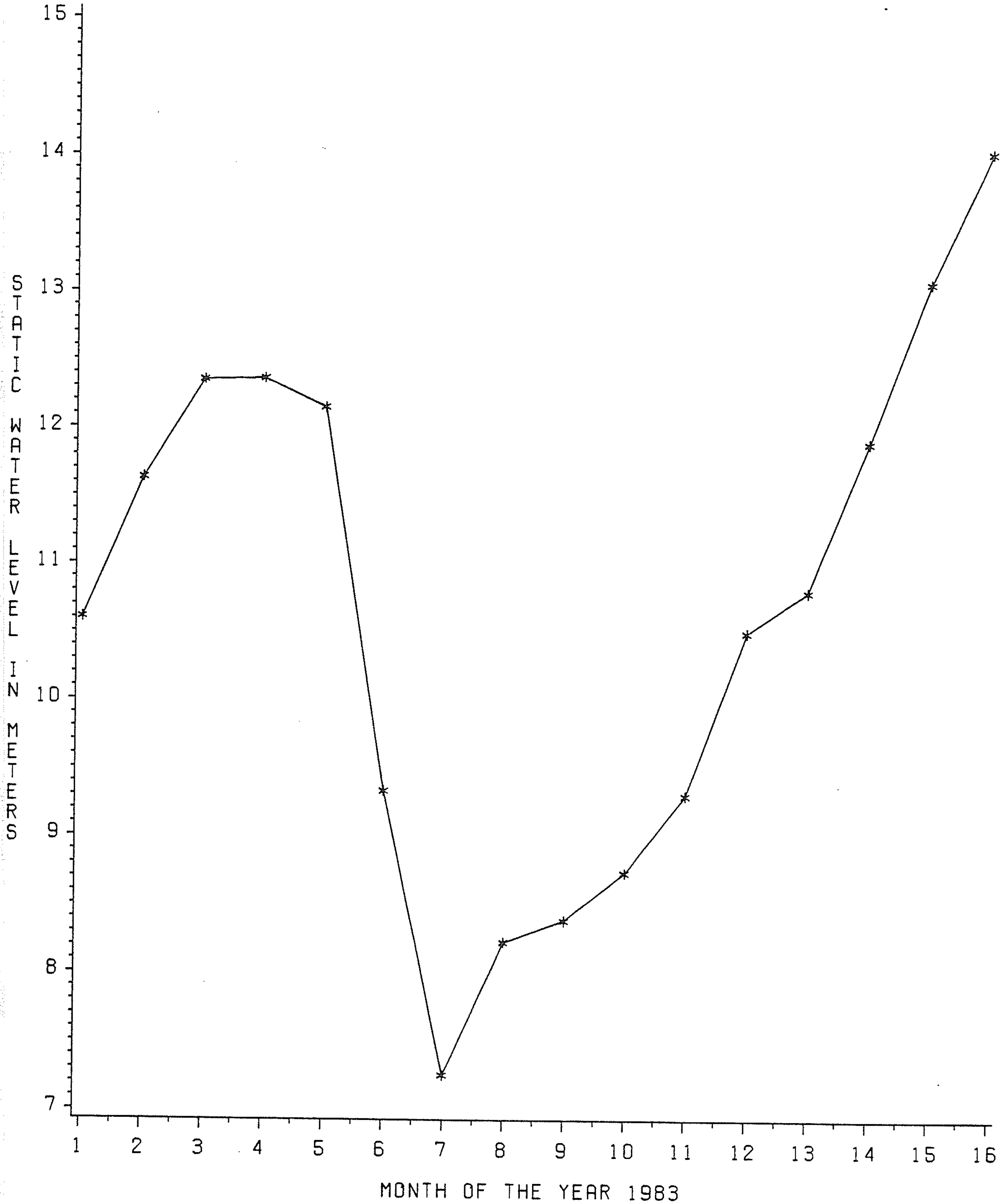

FIGURE 14:WATER LEVEL FLUCTUATIONS AT MILALANI

had the lowest water levels recorded in April. The other two (Mwabungu-Galu and Magutu) had lowest water levels recorded in January and February respectively. This is expected as January through mid-April are the hottest months in the region and groundwater recharge is minimal. The highest water levels were recorded in July in two wells (Magutu and Gazi), September in two other wells (Milalani and Shamu) while the other two wells, Msambweni and Mwabungu-Galu recorded highest water levels in May and June respectively. The long rains in this region come between mid-April and June while the short rains are in September and October. It is therefore in order that the wells register the highest water levels during or immediately after the rains.

It is not clear why differences in the times when the highest (or lowest) water levels occur. One of the possible contributions may be the fact that the water-bearing formation (aquifer) is not continuous. In a sedimentary basin like this one, it is expected that there would be various impermeable clay layers interspersed in between the sands. These clay layers thus creates several localized aquifers instead of one regional aquifer. Because recharge in this area can also be very localized wells within the same 'local' aquifer will tend to show high or low water levels at the same time. Msambweni, Milalani and Gazi wells for example are wells which are close together and they all show the lowest water levels in April. The highest water levels however were registered in May, July and September respectively in the three wells. Whereas these wells should have shown the highest water levels at the same time as expected, the discrepancy would probably be due to the fact that all the three wells are drilled to different depths (Milalani 28m, Msambweni 25m, and Gazi 12m), and some wells would therefore tap deeper aquifers. Another possible reason for the differences between the times of highest and lowest water levels is that the data used was taken over a period of only 16 months. It is possible therefore that should the data have been for several years, most of the wells would have shown the highest and lowest water levels at more or less the same period. Water-level monitoring within the region is still continuing and it is recommended that after enough data have been collected water level graphs be drawn to establish periods of high and low water levels and consequently advise on the withdrawal rates.

Water levels in wells in artesian aquifers under natural conditions generally fluctuate to a much greater extent than water levels in water table aquifers and are sensitive to such factors as earthquakes and earth tides and changes in atmospheric pressure, surface water shape and surface loading (Freeze, 1979). Water levels in artesian wells are also influenced by leakage from water table aquifers (although the effects of recharge are sometimes not noticeable immediately), and by withdrawals from wells and springs. Water levels in water tables are affected by direct recharge from precipitation, evapotranspiration, withdrawals from wells, discharge to streams and sometimes changes in atmospheric pressure (Freeze, 1979).

Fluctuations in water levels indicate changes in the actual quantity of water stored in aquifers and movement of groundwater. A continual decline in water levels results when discharge exceeds recharge; water levels will usually rise when recharge is greater than discharge. The amount of water taken from or added to storage per unit change in water levels under water table conditions is generally many times larger than under artesian conditions ($S_y >> S$).

Changes in storage accounts for the greater part of fluctuations in wells. During the rainy seasons which are in April-June (long rains), and October-November (short rains) in Kenya, the water levels are considerably higher than in the drier months in which there is no recharge but continuous withdrawal. Rapid fluctuations of water levels through vertical distances of several metres are primarily due to pumping. Seasonal trends show several months of rise followed by a fall in response to pumping. Water-level hydrographs are useful for the visual interpretation of water level data. Recharge direct from precipitation and by infiltration of surface water involves the vertical downward movement of groundwater under the influence of vertical head differentials. Thus, recharge involves vertical leakage of water through deposits above the aquifer, the quantity of which varies from place to place and is controlled by the permeability and thickness of the deposits through which leakage occurs. The water in shallow aquifers (15-20 m deep) fluctuates through a wide range in response to periods of above- or below-normal precipitation. In drought years many shallow wells would go dry. However, water stored in thick unconsolidated deposits is available to deeply buried aquifers, so that short drought periods often have little influence on water levels in these aquifers. Artificial recharge techniques have been employed to add water to aquifers but none of the methods has yet been used in Kenya. Artificial methods include water spreading, recharging through pits, excavations, wells and shafts and pumping to induce recharge from surface water bodies. Recharge to aquifer by infiltration of surface waters occur when the water table is below the water surface of a stream and the stream-bed is permeable.

Tables 12 to 14 shows monthly rainfall data for Tiwi, Mwachande and Kikoneni stations and Figures 15 to 17 show their respective histograms for 1983. As shown in these tables most of the rains in this region comes in the months of April to June (long rains) and October-November (short rains). As expected when the rainfall is highest, the groundwater level is also the highest and when there is little rainfall the water level in the wells is low. During this time only wells which are deep enough and which tap good aquifers are left with water while most of the other shallower wells dry up or produce so little water that after pumping for a few hours a wait of several more hours is necessary for the water to trickle down into the well from the surrounding sediments. This latter condition occurs because as most of the wells are water table aquifers which receive recharge directly from local precipitation and because this precipitation is very low the withdrawal from the wells exceed recharge, i.e. the water is being pumped out faster than the entire groundwater reservoir is replenished. Under these conditions, the reservoir is being emptied of water that may have taken sometime to accumulate and there is no possibility of a continuous supply until the next rains.

However for small quantities of water for domestic purposes (20 litres/day), these wells seem to be satisfactory for local needs. In the very dry basins, the groundwater reservoir may not receive any recharge at all in a year of normal precipitation because all the moisture is dissipated from the soil zone into the atmosphere. Recharge

Table 12. Rainfall data for Tiwi Catchment Station Number 60 (mm).

	Year													
Month	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Jan.	-	31.0	31.7	0.0	4.2	41.4	161.5	3.8	7.7	0.0	0.0	0.4	13.8	9.2
Feb.	-	1.2	0.0	0.7	1.4	26.0	77.0	31.4	0.0	0.0	28.3	0.0	57.2	0.0
Mar.	-	4.2	6.5	9.3	53.7	116.6	172.9	12.0	170.0	79.4	40.5	29.7	16.0	17.5
Apr.	-	88.4	271.2	109.5	57.8	201.8	258.9	45.0	47.2	258.9	120.1	281.5	153.6	298.3
May	-	155.4	331.7	154.0	114.4	195.6	480.6	48.6	133.4	518.6	385.1	136.5	196.2	-
June	86.6	197.0	124.6	177.9	81.8	131.5	209.8	21.3	110.6	104.4	146.4	114.3	12.5	-
July	9.2	127.1	94.5	155.1	77.1	45.1	79.6	81.4	60.5	134.9	144.2	98.9	145.2	-
Aug.	76.6	19.7	5.1	12.9	56.8	23.6	56.0	237.0	164.8	48.2	32.3	20.1	28.3	-
Sept.	16.6	36.6	56.1	54.6	116.9	41.0	97.2	21.2	35.7	143.9	66.8	22.8	26.2	-
Oct.	10.7	24.9	17.7	71.1	301.5	53.5	50.5	12.6	190.0	193.7	30.3	194.7	24.4	-
Nov.	28.7	56.8	3.1	1.2	180.3	188.9	59.6	135.3	51.7	139.3	73.7	146.9	108.4	-
Dec.	23.5	3.2	46.2	41.9	82.0	-	36.3	82.7	151.5	28.7	52.2	24.1	37.8	-

year average for Station 603 = 1082.3 mm

Table 13. Rainfall data for Mwachande Station Number 711 (mm)

Month	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Jan.	54.0	0.0	0.7	0.0	0.0	0.0	56.8	18.8
Feb.	23.3	1.9	0.0	0.0	57.0	0.0	20.7	0.0
Mar.	13.1	19.6	13.2	4.8	9.9	7.4	69.0	52.9
Apr.	27.6	21.7	4.5	56.4	75.4	112.0	136.4	187.0
May	-	8.6	19.3	69.4	107.4	253.1	399.2	402.6
June	-	9.5	13.2	29.4	74.5	126.0	83.4	22.7
July	-	32.0	8.3	129.0	34.5	151.2	183.8	-
Aug.	-	2.4	16.4	65.9	23.8	23.0	31.8	-
Sept.	-	0.0	7.2	70.3	28.9	21.1	57.1	-
Oct.	-	10.0	17.9	124.5	13.8	193.0	45.8	-
Nov.	-	1.1	0.9	165.3	2.6	139.4	90.8	-
Dec.	-	-	41.1	62.3	13.2	65.2	72.3	-

Five year average for Station 711 = 739.9 mm

Table 14. Rainfall data for Kikoneni Station Number 619 (mm)

Month	Year												
	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Jan.	120.7	24.4	-	25.9	25.0	208.8	-	22.5	0.0	0.0	0.0	0.4	
Feb.	51.2	0.0	-	46.7	80.0	64.0	-	0.0	0.0	0.0	0.0	19.5	
Mar.	106.4	-	24.2	41.7	151.0	79.5	-	200.4	65.0	6.0	29.8	21.2	
Apr.	52.1	-	117.6	157.3	332.0	237.4	132.3	124.4	197.7	75.6	631.6	95.0	
May	20.1	-	171.5	172.0	151.3	519.1	61.3	137.5	610.4	152.3	168.2	375.6	
June	87.1	-	197.0	39.8	86.0	132.8	86.3	109.9	159.3	59.3	152.5	77.1	
July	15.5	-	117.1	107.8	16.6	136.6	116.0	98.4	154.5	19.5	101.1	140.6	
Aug.	123.4	-	30.8	66.7	39.0	41.2	230.7	188.2	66.9	12.2	-	58.2	
Sept.	13.2	-	62.2	167.5	76.9	42.5	41.0	68.0	183.4	9.7	-	53.5	
Oct.	-	-	89.7	110.0	305.4	79.3	10.0	539.8	248.7	4.7	-	34.0	
Nov.	-	-	46.6	92.9	-	62.0	140.0	58.5	141.1	17.7	-	22.1	
Dec.	-	-	160.7	140.5	89.0	128.9	80.7	261.4	116.5	88.0	-	138.4	

7 year average = 1355.7 mm

TIWI STATION

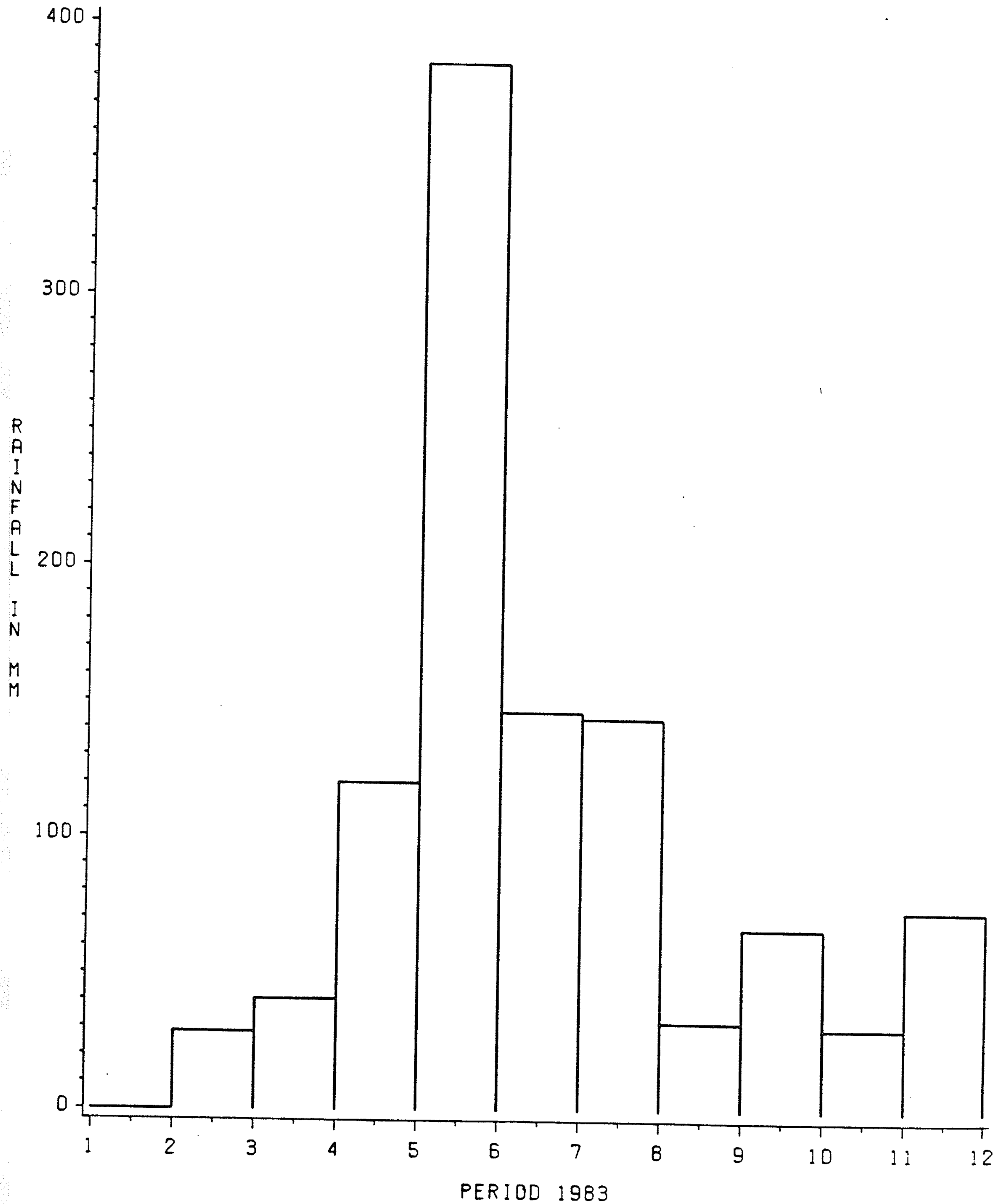

FIGURE 15:RAINFALL FLUCTUATIONS AT TIWI IN 1983

MWACHANDE STATION

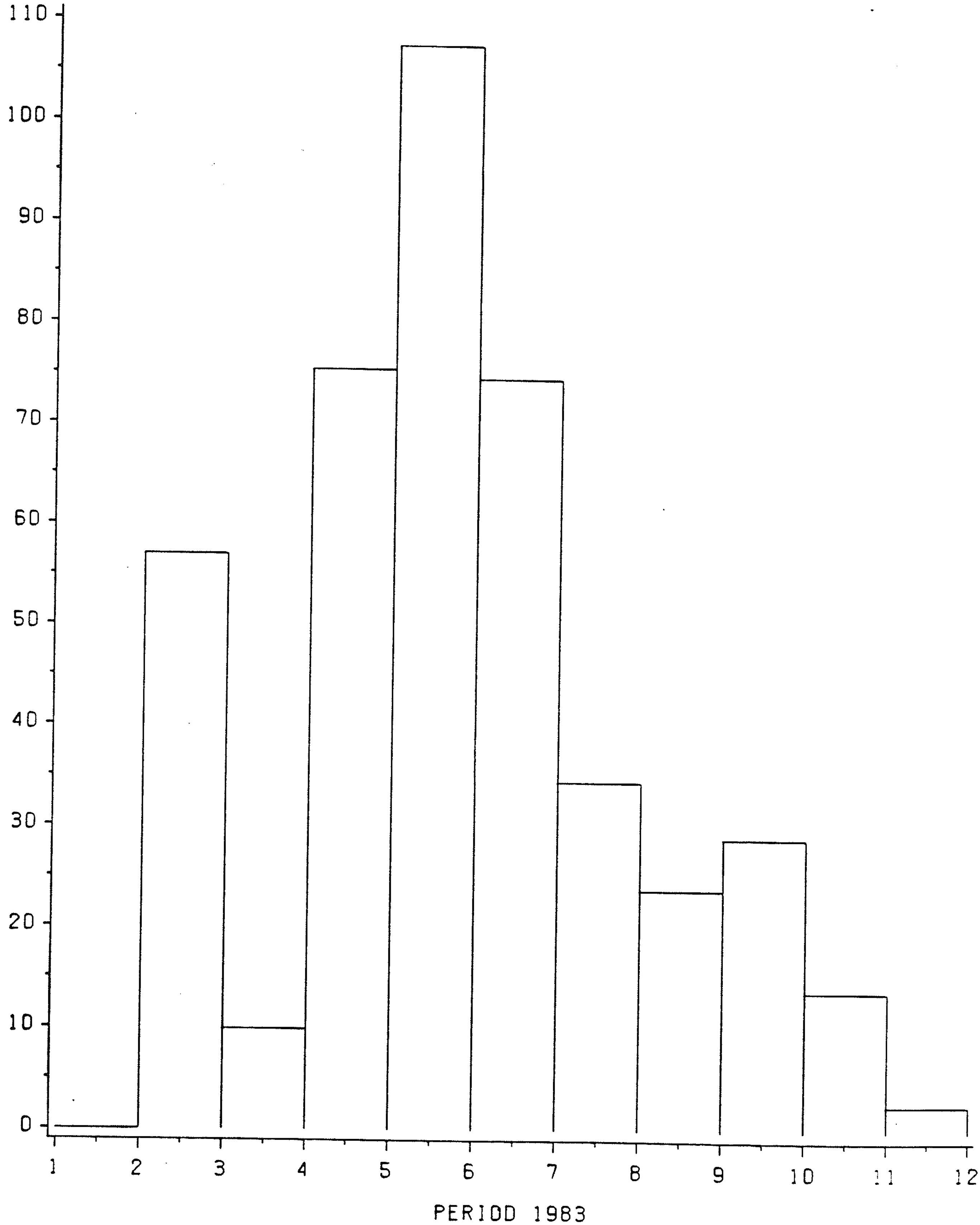

FIGURE 16:RAINFALL FLUCTUATIONS AT MWACHANDE IN 1983

KIKONENI STATION

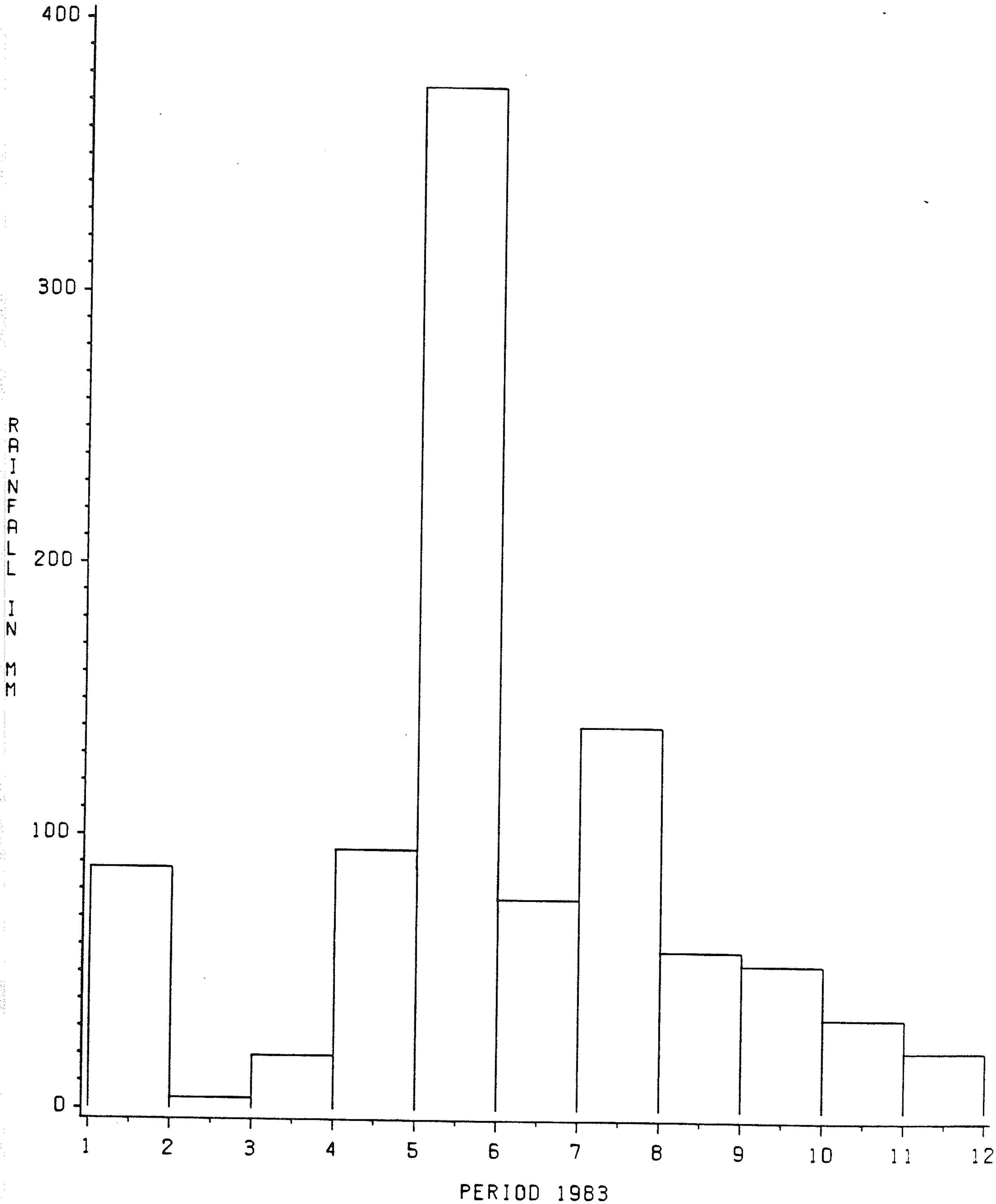

FIGURE 17:RAINFALL FLUCTUATIONS AT KIKONENI IN 1983

to those aquifers occurs only during years of exceptionally heavy rainfall.

Besides the issues associated with aquifer replenishment, the slow movement of water within an aquifer is also a problem. All developed aquifers serve not only as reservoirs to hold water but also as pipelines to carry water to the production wells from the areas where it enters the aquifer. The yield of a production well or group of wells is determined by the quantity of water that can move through the aquifer from recharge areas. If the transmissivity of the aquifer is inadequate, the water levels in production wells will decline whether the aquifer as a whole is adequately recharged or not. Pumping can increase the rate of movement from the recharge areas to production wells by increasing the hydraulic gradient. The terms groundwater recharge and groundwater discharge are used here in their dynamic sense and are restricted to flow processes in the saturated zone. Water-table fluctuations result when the rate of groundwater recharge or discharge is not matched by the unsaturated flow rate created by infiltration or evaporation. Since this equilibrium is seldom realized and also because flow conditions near the surface are extremely transient owing to the intermittent nature of rainfall and evaporation the water table is almost never completely stable.

A summary of the construction data for 127 wells drilled within the south coast region is listed in Appendix 4. 53 of the wells within the region can be considred as 'high' yielding for they produce over $3m^3$ per hour. Apart from Gazi 1, 2 and 3 which are relatively shallow (14m, 17m and 12m respectively) and quite productive (over $6m^3/hr$), all the other wells with a yield of over $3m^3$ per hour have been drilled to depths of 20m to 40m. Yields of between $2m^3$ - $3m^3$ per hour are considered quite adequate for domestic purposes and more than half of the wells (69) have yields greater than $2m^3$ per hour. Eight of the wells (Kingwende Primary School, Msambweni Camp, Mwangundo No. 2, Milalani No. 4, Vingunjini Primary School and Gazi No. 1, 2 and 3) had exceptionally good yields (over $6m^3$ per hour). With an exception of Gazi 1, 2, and 3 where the water was struck between 10-12m, all the other wells had water stuck between 18m and 24m and a water-rest-level of between 10m-15m. The wells at Gazi 1,2, and 3 also had water-rest-levels of around 9m. From the close proximity of these wells and nearly the same water struck and water-rest-levels it would be reasonable to assume that they all tap water from the same aquifer. The Gazi wells shows a discrepancy as far as the 'water struck' levels are concerned but they show more or less the same water rest levels. These wells may have tapped a shallower aquifer at 12m which is underlain by an impervious layer of clay shielding the main aquifer at 18m from the top aquifer. A geoelectrical sounding is however necessary to confirm this and to ascertain the thickness of the clay layer.

The wells in the northern part of the project area seems to be tapping an aquifer which is much more deep seated (Mbuani with a water struck level of 40-44m) but still the yields are reasonable. The further one goes away from the coast, the more deep seated the aquifers become and pumping, using a hand pump may be difficult.

8. CHEMICAL ANALYSIS

Groundwater in Kenya once considered relatively pollution free is being contaminated locally by municipal and industrial wastes. Contamination occurs when soluble or insoluble substances are introduced into the hydrogeologic environment as a result of man's activities. All groundwater originates as rain or snowmelt which infiltrates through the soil into the flow systems in the underlying geologic materials. As groundwater moves along flowlines from recharge to discharge areas, its chemistry is altered by a variety of geochemical processes. Increases of total dissolved solids and most of the major ions normally occur. Shallow groundwater in recharge areas is lower in dissolved solids than the water deeper in the same system and lower in dissolved solids than the water in the shallow zones in the discharge areas.

Once in the aquifer, the primary driving force for contaminant movement is created by the hydraulic gradient that produces groundwater flow. Contaminants are thus carried down gradient forming a contaminant plume as shown in Figure 18. This type of movement is known as advection. Two other hydrodynamic dispersion mechanisms, mechanical mixing and molecular diffusion influence the shape of the plume by causing a spreading of the contaminant over a much larger area than would occur from advection alone and with a consequent dilution of the contaminant away from the source. Mechanical mixing is caused by velocity differences within the pore openings, velocity differences in sizes through which the water moves and the degree of tortuosity (length) of the pore channel.

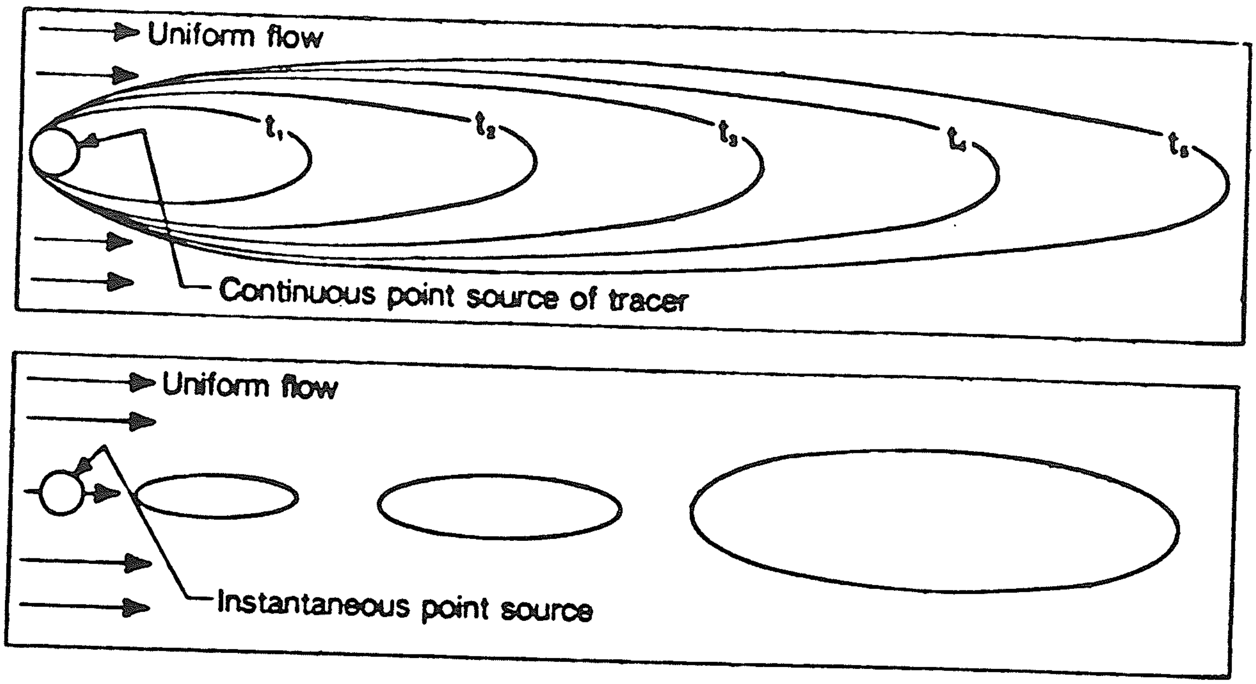

FIGURE 18: SPREADING CHARACTERISTICS OF A TRACER (From Freeze and Cherry, 1979.)

In the absence of any groundwater movement, a slug of highly concentrated chemical will move outwards from its origin towards points of lower concentration through diffusion. The effect of molecular diffusion on contaminant dispersion is, however, much less than the effect of mechanical mixing processes and except in cases of no groundwater movement at all (very rare) it can be ignored in the estimation of the spread of contaminant plumes.

Table 15 shows the chemical analysis data for 42 wells in the project area and Table 16 the recommended chemical concentrations in drinking water by World Health Organization (WHO).

The determinations to establish water quality most often utilised are hardness, iron, chlorides, total dissolved solids, specific electrical conductance and hydrogen ion concentration or the pH.

According to its total dissolved solids (TDS) groundwater is classified as follows:

Fresh	< 1000 mg/l
Moderately saline (brackish)	1000 - 10000 mg/l
Very saline	10000 - 35000 mg/l
Briny	> 35000 mg/l

For most groundwater, the specific conductance multiplied by a factor of 0.55 to 0.75 gives a reasonable estimate of the total dissolved solids (TDS).

8.1 Numerical Presentation

Chemical analysis can be expressed in many different ways. Since most of the solids in water are in solution, their concentration in ionic form is presented as milligrams per litre (mg/l) or in milliequivalents per litre (meq/l). An example of the numerical

Table 15. Chemical analysis data.

Well No.	Name	Substances Concentration mg/L													Remarks
		NO_3	HCO_3	CL	SO_4	F	Na	Ca	Mg	Mn	Fe	Zn	PH	TDS	
1	C5420 Milalani II B/H	1.25	246.0	21.4	Nil	0.58	16.0	96.0	1.96	Nil	Nil	0.05	7.7	286	Free from organic pollution
2	Milalani III B/H	0.35	290.0	35.7	10.0	0.58	32.4	30.4	44.16	Nil	Nil	0.25	7.3	322	Neutral and soft
3	Vidungeni B/H	0.54	92.0	28.6	8.00	0.60	20.0	23.1	13.92	Nil	Nil	0.20	6.8	102	Free from organic pollution
4	SBH 5 B/H	0.30	312.0	28.6	9.00	0.65	28.0	54.4	32.64	Nil	Nil	0.12	7.2	345	Free from organic pollution
5	Mbuani (ow 83)	*	45.6	170.	1.00	0.03	?	6.1	5.00	1.7	1.0	*	5.9	54	(calcuated)
6	Kibarani (ow 76)	-?	187.2	29.0	3.00	0.30	?	132	21.00	0.1	2.2	*	8.2	162	Organic matter present, hard
7	Mwangoloko (ow 67)	-?	341.0	50.0	16.00	0.20	-?	114.	43.00	0.1	0.6	*	7.7	360	Moderately mineralised
8	Kiberani (ow 66)	-?	305.0	0.10	12.0	-	-?	99.	34.00	0.1	0.3	*	7.5	330	Hard with organic matter
9	Kiberani (ow 77)	-?	14.4	11.0	1.50	0.06	-?	3.1	2.50	0.1	0.3	*	6.7	30	Low mineral and organic matter
10	Mkuakwani (ow 92)	-?	441.6	61.0	2.50	0.20	-?	140.0	56.0	0.1	0.2	*	7.9	480	Slightly hard and alkaline
11	Mtambwe Muhaka (ow 81	-?	12.2	13.0	0.38	0.04	-?	55.	3.90	0.8	0.5	*	5.5	42	Slightly acid and corrosive
12	Kibarani (ow 75)	-?	385.2	5.7	1.12	0.20	-?	138.	30.0	0.1	2.5	*	7.5	420	Hard slightly
13	Kibarani (ow 69)	-?	307.2	99.0	11.3	0.20	-?	112.	44.0	0.3	0.3	*	7.9	420	- do -

Table 15. Chemical analysis data.

Well No.	Name	Substances Concentration mg/L													
		NO_3	HCO_3	CL	SO_4	F	Na	Ca	Mg	Mn	Fe	Zn	PH	TDS	Remarks
14	Kibarani (ow 73)	-?	348.6	22.0	1.75	0.17	-?	127.	9.0	0.1	0.6	*	7.5	360	Okay
15	Bongwe (ow 87)	-?	441.6	32.0	1.25	0.20	-?	118.	56.0	0.1	0.1	*	7.9	420	Slightly hard and alkaline
16	Kibarani borehole	-?	19.2	23.0	3.35	.2	-?	110.	60.	0.1	0.1	*	6.2	360	Good quality
17	Chalo (ow 42)	-?	448.6	0.39	165.	-	-?	380.	-	124	0.1	*	8.2	3300	Highly saline and hard source
18	Mwalibema (ow 71)	-?	273.0	66.0	9.25	0.2	-?	118.	33	0.1	0.6	*	8.5	384	Mildly hard and tyrbid organic matter
19	Lunga Lunga B/H2	-?	429.1	-	144	.42	-?	186	225	1.0	0.5	*	7.9	480	Hard, high concentration of sulphates
20	Mugutu (ow 93)	-?	326.7	22.0	1.5	.20	-?	100	39	0.1	0.4	*	7.8	300	Slightly hard water
21	Mwamaguo (ow 2)	-?	21.94	19.0	5.0	.04	-?	1.3	.9	0.3	1.6	*	5.8	48	Slightly acidic - needs filteration
22	Shamu (ow)	-?	4.87	39.0	0.8	.04	-?	1.7	1.1	0.1	1.0	*	5.4	72	Slightly acidic - needs filteration

Table 15 (cont'd ...)

Table 15. Chemical analysis data.

Well No.	Name	Substances Concentration mg/L													
		NO_3	HCO_3	CL	SO_4	F	Na	Ca	Mg	Mn	Fe	Zn	PH	TDS	Remarks
23	Msambweni (I)	0.06	192.0	60.0	Nil	0.65	51	50.4	22.6	Nil	Nil	0.06	7.5	610	Moderate mineral constituent
24	(ow 03) ?	0.51	130.0	34.0	3.0	0.65	19	84.0	Nil	Nil	Nil	0.07	7.6	382	Chemically suitable
25	(ow 4) Bomani	0.02	130.0	48.0	29.	0.65	26	94.0	8.6	Nil	Nil	0.2	7.4	268	Free from organic pollution
26	Ngaja Village (ow 5)	.007	160.0	104.	27.	0.40	49	113.0	8.6	Nil	Nil	0.14	7.3	812	Fairly mineralised
27	Milalani (ow 6)	0.3	130.0	34.0	Nil	0.65	24	88.0	.96	Nil	Nil	0.14	7.9	220	Soft and neutral
28	Munge (ow 8)	Nil	116	28	Nil	0.7	20	62	10.56	Nil	Nil	0.1	7.8	174	Soft and neutral
29	Munge (ow 9)	0.12	148	32	Nil	0.7	24	85	10.56	Nil	Nil	0.14	7.5	256	Chemically suitable
30	Munge (ow)	0.2	168	100	28	0.3	114	36.8	17.3	Nil	Nil	0.1	7.6	476	Moderate mineral composition
31	Ndzovuni (ow 11)	0.12	138	32	Nil	0.3	19	43	3.8	Nil	Nil	0.08	7.6	120	Neutral and soft
32	Kingwende (ow 12)	0.05	128	26	Nil	0.6	18	85	1.9	Nil	Nil	0.08	7.8	234	Moderate with favourable mineral concentration

Table 15 (cont'd ...)

Table 15. Chemical analysis data.

Well No.	Name	Substances Concentration mg/L													
		NO_3	HCO_3	CL	SO_4	F	Na	Ca	Mg	Mn	Fe	Zn	PH	TDS	Remarks
33	Msambweni (ow 13)	0.5	50	28	33	0.85	22	24	Nil	Nil	Nil	0.02	7.5	150	Slight organic pollution
34	Milalani (ow 15)	0.02	136	16	Nil	0.2	18	39	5.8	Nil	Nil	0.11	7.8	132	Favourable mineral constituent
35	Mabatani (ow 16)	0.1	156	22	Nil	0.65	16	94	7.68	Nil	Nil	0.1	7.2	368	Fit for domestic use
36	Kingwende (ow 17)	0.03	150	40	Nil	0.30	25	58.4	3.8	Nil	Nil	0.07	7.4	376	- do -
37	Kingwende (ow 18)	0.3	140	20	Nil	0.35	18	48	4.8	Nil	Nil	0.07	7.5	462	- do -
38	Kingwende (ow 20)	0.15	140	42	1	0.75	28	83	35.5	Nil	Nil	0.02	7.8	392	- do -
39	Munge (ow 21)	0.1	150	92	Nil	0.3	51	47	15.4	Nil	Nil	0.1	7.3	446	- do -
40	Munge (ow 23)	Nil	180	148	Nil	0.75	91	99	17.2	Nil	Nil	0.13	7.5	408	- do - fairly mineralised
41	Kiriogo (ow 24)	0.28	144	22	Nil	0.2	26	48.8	1.4	Nil	Nil	0.08	7.4	138	Soft and suitable
42	Shirazi (ow 26)	0.06	156	54	16	0.6	7.8	26.4	14.8	Nil	Nil	0.05	7.6	462	Soft and suitable

Key: -? ... not indicated
* ... not analysed

Table 16. International standards for drinking water (W.H.O).

Substance	Maximum Allowable Concentration (mg/L)
Toxic Substances	
Lead	0.05
Arsenic	0.05
Selenium	0.01
Chromium (Cr Hexavalent)	0.05
Cyanide	0.20
Cadmium	0.01
Barium	1.00
Radionuclides (Gross beta activity)	$10\mu\mu/1$
Components Hazardous to Health	
Nitrate as NO_3	45.0
Fluoride	1.5

Chemical Substances Affecting the Potability of Water

Substance	Limit of General Acceptability	Maximum Allowable Concentration
Total dissolved solid	500 mg/l	1500 mg/l
Colour	5 units*	50 units*
Turbidity	5 units**	25 units**
Taste	Unobjectionable	-
Odour	Unobjectionable	-
Iron (Fe)	0.3 mg/l	1.0 mg/l
Manganese (Mn)	0.1 mg/l	0.5 mg/l
Copper (Cu)	1.0 mg/l	1.5 mg/l
Zinc (Zn)	5.0 mg/l	15 mg/l
Calcium (Ca)	75 mg/l	200 mg/l
Magnesium (Mg)	50 mg/l	150 mg/l
Sulphate (SO_4^{2-})	200 mg/l	400 mg/l
Chloride (Cl-)	200 mg/l	600 mg/l
PH range	7-8.5	>6.5 & <9.2

Table 16 (cont'd ...)

Substance	Maximum Allowable Concentration	Maximum Allowable Concentration
Magnesium + sodium sulphate	500 mg/l	1000 mg/l
Phenolic substances (as Phenol)	0.001 mg/l	0.002 mg/l
Carbon chloroform extract (CCE) (Organic Pollutant)	0.2 mg/l	0.5 mg/l***
Alkyl benzl suphonates (ABS) (Surfactants)	0.5 mg/l	1.0 mg/l

* Platinum-cobalt scale

** Nephelometric turbidity units

*** Concentrations greater than 0.2 mg/l indicate the necessity for further analysis to determine the causative agent.

presentation using chemical analysis data from Table 15 is shown on Table 17, in which the ions are expressed in milligrams per liter, milliequivalents per litre and in milliequivalents per cent. The choice of presentation will usually depend on the analyst.

8.2 Pictorial Diagrams

Pictorial diagrams can be used to present the data of a particular well in bars or circular diagrams. While it is not possible to present data from many wells (aquifers) by means of pictorial diagrams, they are able to illustrate graphically the major ions in a water sample and serve as a simple, visual comparison of groundwater samples. The most commonly used type of pictorial diagram is the bar graph which shows the fractional content of anions and cations as fractions of the total column length. Conventionally cations are plotted on the left of the bar and anions on the right. Figure 19 illustrates the presentation of data using a bar graph of data for Milalani well taken from Table 17. These types of figures are not believed to be as clear and useful for this analysis as those proposed and discussed in the following sections. Consequently comparable graphs for the other wells in the area are not developed here.

8.3 Graphical Presentation

Graphical presentation of chemical analysis data is intended to simplify comparison and evaluation of different analyses. One of the methods which was used was to plot the concentration of a particular cation or anion in different boreholes. By defining two limits, the lower limit being the limit of general acceptability and the upper limit being the maximum allowable limit as stipulated by World Health

Table 17. Numerical presentation of chemical data.

Name of Well	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
Milalani II	Na^+	16	0.70	12.4	NO_3^-	1.25	0.02	0.42
	Ca^{2+}	96	4.8	84.8	HCO_3^-	246	4.03	86.1
	Mg^{2+}	1.96	0.16	2.8	Cl^-	21.4	0.60	12.8
	Mn^{2+}	Nil	-	-	SO_4^2	Nil	-	-
	Fe^{2+}	Nil	-	-	F^-	0.58	0.03	0.64
	Zn^{2+}	0.05	0.0015	0.09				
	Total		5.66	100.09			4.68	99.3
Milalani III	Na^+	32.4	1.41	21.3	NO_3^-	0.35	.0056	0.09
	Ca^{2+}	30.4	1.52	23.0	HCO_3^-	290	4.75	79.3
	Mg^{2+}	44.16	3.68	55.6	Cl^-	35.7	1.00	16.7
	Mn^{2+}	Nil	-	-	SO_4^{2-}	10	0.21	3.5
	Fe^{2+}	Nil	-	-	F^-	0.58	0.030	0.5
	Zn^{2+}	0.25	.0076	0.11				
	Total		6.62	99.9			5.99	99.6
Vindungeni	Na^+	20.0	0.87	27.2	NO_3^-	0.54	.0086	0.3
	Ca^{2+}	23.1	1.16	36.3	HCO_3^-	92.0	1.51	59.7
	Mg^{2+}	13.92	1.16	36.3	Cl^-	28.6	0.81	32.0
	Mn^{2+}	-	-	-	SO_4^-	8.0	0.17	6.7
	Fe^{2+}	-	-	-	F^-	0.6	0.03	1.2
	Zn^{2+}	0.2	0.006	0.18				
	Total		3.196	99.9			2.53	99.9
SBH 5 B/H	Na^+	28	1.22	18.32	NO_3^-	0.32	.0048	.078
	Ca^+	54.4	2.72	40.8	HCO_3^-	312	5.11	83.9
	Mg^{2+}	32.64	2.72	40.8	Cl^-	26.6	0.75	12.3
	Mn^{2+}	-	-	-	SO_4^{2-}	9.0	0.19	3.1
	Fe^{2+}	-	-	-	F^-	0.65	0.34	5.5
	Zn^{2+}	0.12	.0037	0.56				
	Total		6.66	99.9			6.09	99.4

Table 17 (cont'd)

Name of Well	Concentration (units shown)							
	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
Mbuani	Na^+	?	–		NO_3^-	*	–	
	Ca^{2+}	6.1	0.31	37.8	HCO_3^-	45.6	0.75	13.5
	Mg^{2+}	5.0	0.42	51.2	Cl^-	170.0	4.79	86.2
	Mn^{2+}	1.7	0.06	7.3	SO_4^{2}	1.0	0.02	0.36
	Fe^{2+}	1.0	0.03	3.7	F^-	0.03	0.0016	.029
	Zn^{2+}	*	–	–				
	Total		0.82	100			5.56	100
Kibarani (OW76)	Na^+	?	–	–	NO_3^-	?	–	–
	Ca^{2+}	132.0	6.6	78.3	HCO_3^-	187.2	3.07	77.3
	Mg^{2+}	21.0	1.75	20.8	Cl^-	29.0	0.82	20.7
	Mn^{2+}	0.1	0.0036	0.043	SO_4^{2-}	3.0	0.063	1.59
	Fe^{2+}	2.2	0.078	0.93	F^-	0.3	0.016	0.40
	Zn^{2+}	*						
	Total		8.43	99.2			3.97	99.6
Mwangoloko	Na^+	?	–	–	NO_3^-	?	–	
	Ca^{2+}	114.0	5.70	61.3	HCO_3^-	341.0	5.59	76.2
	Mg^{2+}	43.0	3.58	38.5	Cl^-	50.0	1.41	19.2
	Mn^{2+}	0.1	0.0036	0.039	SO_4^{2-}	16.0	0.33	4.5
	Fe^{2+}	0.6	0.021	0.23	F^-	0.20	0.015	0.20
	Zn^{2+}	*						
	Total		9.3	99.8			7.34	99.9
Kibarani (OW66)	Na^+	?	–	–	NO_3^-	?	–	–
	Ca^{2+}	99.0	4.95	63.2	HCO_3^-	305	5.0	95.2
	Mg^{2+}	34.0	2.83	36.1	Cl^-	0.10	0.0028	0.053
	Mn^{2+}	0.1	0.036	0.46	SO_4^{2-}	12	0.25	4.8
	Fe^{2+}	0.3	0.011	0.14	F^-	–	–	–
	Zn^{2+}	*	–					
	Total		7.83	99.8			5.25	100.05

Table 17 (cont'd)

Name of Well	Concentration (units shown)							
	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
Kibarani (OW77)	Na^+	?	-	-	NO_3^-	*	-	
	Ca^{2+}	3.1	0.15	41.7	HCO_3^-	14.4	0.24	43.1
	Mg^{2+}	2.5	0.20	55.6	Cl^-	11.0	0.31	53.4
	Mn^{2+}	0.1	0.0036	1.0	SO_4^{2}	1.50	0.03	5.1
	Fe^{2+}	0.3	0.011	3.1	F^-	0.06	0.003	0.5
	Zn^{2+}	*						
	Total		0.36	101			0.58	102
Mkuakuani (OW92)	Na^+	?	-	-	NO_3^-	?	-	-
	Ca^{2+}	140	7.0	59.8	HCO_3^-	441.6	7.24	80.3
	Mg^{2+}	56.0	4.7	40.1	Cl^-	61.0	1.72	19.1
	Mn^{2+}	0.1	0.0036	0.030	SO_4^{2-}	2.50	0.052	0.58
	Fe^{2+}	0.2	0.0071	0.061	F^-	0.20	0.011	0.12
	Zn^{2+}	*						
	Total		11.71	99.9			9.02	100.1
ltambwe-Muhaka OW81)	Na^+	?	-	-	NO_3^-	?	-	-
	Ca^{2+}	55.0	2.75	87.9	HCO_3^-	12.2	0.20	34.5
	Mg^{2+}	3.9	0.33	10.5	Cl^-	13.0	0.37	63.8
	Mn^{2-}	0.8	0.029	0.9	SO_{42}^-	0.38	0.0079	1.4
	Fe^{2+}	0.5	0.018	0.05	F^-	0.04	0.0021	0.36
	Zn^{2+}	*	-	-				
	Total		3.13	99.3			0.58	100.06
ibarani DW75)	Na^+	?		-	NO_3^-	?	-	-
	Ca^{2+}	138.0	6.9	72.4	HCO_3^-	385.2	6.3	97.0
	Mg^{2+}	30.0	2.5	26.2	Cl^-	5.7	0.16	2.5
	Mn^{2+}	0.1	0.036	0.38	SO_4^{2-}	1.12	0.023	0.35
	Fe^{2+}	2.5	0.089	0.93	F^-	0.20	0.011	0.17
	Zn^{2+}	*						
	Total		9.53	99.9			6.494	100.02

Table 17 (cont'd)

Name of Well	Concentration (units shown)							
	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
Kibarani (OW69)	Na^+	?	-	-	NO_3^-	*	-	-
	Ca^{2+}	112.0	5.6	60.2	HCO_3^-	307.2	5.04	62.4
	Mg^{2+}	44.0	3.67	39.5	Cl^-	99.0	2.79	34.5
	Mn^{2+}	0.30	0.011	0.12	SO_4^{2}	11.3	0.24	2.9
	Fe^{2+}	0.30	0.011	0.12	F^-	0.20	0.011	0.14
	Zn^{2+}	*	-					
	Total		9.3	99.9			8.08	99.9
Kibarani (OW73)	Na^+	?	-	-	NO_3^-	?	-	-
	Ca^{2+}	127.0	6.35	89.2	HCO_3^-	348.6	5.7	89.6
	Mg^{2+}	9.0	0.75	10.5	Cl^-	22.0	0.62	9.7
	Mn^{2+}	0.1	0.0036	0.05	SO_4^{2-}	1.75	0.036	0.57
	Fe^{2+}	0.6	0.021	0.29	F^-	0.17	0.0089	0.14
	Zn^{2+}	*	-	-				
	Total		7.12	100.04			6.36	100.01
ongwe OW87)	Na^+	?	-	-	NO_3^-	?	-	-
	Ca^{2+}	118.0	5.9	55.8	HCO_3^-	441.6	7.24	88.5
	Mg^{2+}	56.0	4.67	44.1	Cl^-	32.0	0.90	11.0
	Mn^{2+}	0.1	0.0036	0.034	SO_4^{2-}	1.25	0.026	0.32
	Fe^{2+}	0.1	0.00357	0.0034	F^-	0.20	0.011	0.13
	Zn^{2+}	*	-					
	Total		10.58	99.9			8.18	99.9
ibarani orehole	Na^+	?	-	-	NO_3^-	?	-	-
	Ca^{2+}	110	5.5	52.4	HCO_3^-	19.2	0.0031	0.42
	Mg^{2+}	60	5	47.6	Cl^-	23.0	0.65	88.5
	Mn^{2+}	0.1	0.0036	0.034	SO_4^{2-}	3.35	0.070	9.5
	Fe^{2+}	0.1	0.00357	0.034	F^-	0.2	0.0105	1.4
	Zn^{2+}	*						
	Total		10.5	100			0.734	99.8

Table 17 (cont'd)

Name of Well	Concentration (units shown)							
	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
Chalo (OW42)	Na^+	?	-	-	NO_3^-	?	-	-
	Ca^{2+}	380	19	80.7	HCO_3^-	448.6	7.35	68.0
	Mg^{2+}	-	-	-	Cl^-	0.39	0.011	0.10
	Mn^{2+}	124	4.5	19.1	SO_4^2	165.0	3.44	31.8
	Fe^{2+}	0.1	0.035	0.15	F^-	-	-	-
	Zn^{2+}	*	-					
	Total		23.54	99.9			10.80	99.9
Mwalibemba (OW71)	Na^+	?	-	-	NO_3^-	?	-	-
	Ca^{2+}	118.0	5.9	68.1	HCO_3^-	273.0	4.48	68.5
	Mg^{2+}	33.0	2.75	31.7	Cl^-	66.0	1.86	28.4
	Mn^{2+}	0.1	0.0036	0.04	SO_4^{2-}	9.25	0.19	2.9
	Fe^{2+}	0.6	0.021	0.24	F^-	0.2	0.0105	0.16
	Zn^{2+}	*						
	Total		8.67	100.08			6.54	99.9
unga-lunga /H 2	Na^+	?	-	-	NO_3^-	?	-	-
	Ca^{2+}	186	9.3	33.1	HCO_3^-	429.1	7.03	69.7
	Mg^{2+}	225	18.75	66.7	Cl^-	-	-	-
	Mn^{2+}	1.0	0.036	0.13	SO_4^{2-}	144.0	3.0	29.8
	Fe^{2+}	0.5	0.018	0.064	F^-	0.42	0.053	0.53
	Zn^{2+}	*						
	Total		28.10	99.9			10.08	100.3
agulu OW93)	Na^+	?	-	-	NO_3^-	?	-	-
	Ca^{2+}	100	5	60.5	HCO_3^-	326.7	5.36	89.04
	Mg^{2+}	3.9	3.25	39.3	Cl^-	22.0	0.62	10.3
	Mn^{2+}	0.1	0.0036	0.04	SO_4^{2-}	1.5	0.03	0.50
	Fe^{2+}	0.4	0.0143	0.18	F^-	0.2	0.0105	0.17
	Zn^{2+}	*						
	Total		8.27	100.02			6.02	100.01

Table 17 (cont'd)

Name of Well	Concentration (units shown)							
	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
Mwanaguo (OW2)	Na^{+}	?	-	-	NO_3^{-}	?	-	-
	Ca^{2+}	1.3	0.065	31.3	HCO_3^{-}	21.94	0.36	35.8
	Mg^{2+}	0.9	0.0075	36.1	Cl^{-}	19.0	0.54	53.7
	Mn^{2+}	0.3	0.011	5.3	SO_4^{2}	5.0	0.104	10.3
	Fe^{2+}	1.6	0.057	27.4	F^{-}	0.04	0.0021	0.21
	Zn^{2+}	*	-					
	Total		0.208	100.1			1.006	100.01
Shamu (OW)	Na^{+}	?	-	-	NO_3^{-}	?	-	-
	Ca^{2+}	1.7	0.085	39.3	HCO_3^{-}	4.87	0.079	6.7
	Mg^{2+}	1.1	0.092	42.5	Cl^{-}	39.0	1.09	91.8
	Mn^{2+}	0.1	0.0036	1.7	SO_4^{2-}	0.8	0.016	1.3
	Fe^{2+}	1.0	0.0367	16.5	F^{-}	0.04	0.0022	0.19
	Zn^{2+}	*	-	-				
	Total		0.216	100.00			1.187	99.9
Isambweni (I)	Na^{+}	51	2.22	33.5	NO_3^{-}	0.06	0.00096	0.019
	Ca^{2+}	50.4	2.52	38.1	HCO_3^{-}	192.0	3.15	64.5
	Mg^{2+}	22.6	1.88	28.4	Cl^{-}	60.0	1.69	34.6
	Mn^{2+}	Nil	-	-	SO_4^{2-}	Nil	-	-
	Fe^{2+}	Nil	-	-	F^{-}	0.65	0.034	0.69
	Zn^{2+}	0.06	0.0018	0.027				
	Total		6.62	100.03			4.88	99.8
omani (OW3)	Na^{+}	19.0	0.83	16.5	NO_3^{-}	0.51	0.0082	0.26
	Ca^{2+}	84.0	4.2	83.5	HCO_3^{-}	130	2.13	66.7
	Mg^{2+}	Nil	-	-	Cl^{-}	34.0	0.96	30.0
	Mn^{2+}	Nil	-	-	SO_4^{2-}	3.0	0.063	1.97
	Fe^{2+}	Nil	-	-	F^{-}	0.65	0.034	1.06
	Zn^{2+}	0.07	0.0021	0.042				
	Total		5.03	100.04			3.20	99.99

Table 17 (cont'd)

Name of Well	Concentration (units shown)							
	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
Bomani (OW4)	Na^+	26	1.13	17.23	NO_3^-	0.02	0.00032	0.0078
	Ca^{2+}	94.0	4.7	71.65	HCO_3^-	130.0	2.131	51.70
	Mg^{2+}	8.6	0.72	10.98	Cl^-	48.0	1.352	32.80
	Mn^{2+}	Nil	-	-	SO_4^{2}	29.0	0.604	14.65
	Fe^{2+}	Nil	-	-	F^-	0.65	0.0342	0.83
	Zn^{2+}	0.2	0.0061	0.093				
	Total		6.56	99.9			4.123	99.9
Ngaja Village (OW5)	Na^+	49.0	2.13	25.0	NO_3^-	0.007	0.000112	0.0018
	Ca^{2+}	113.0	5.65	66.47	HCO_3^-	160.0	2.62	42.74
	Mg^{2+}	8.6	0.72	8.47	Cl^-	104.0	2.93	47.79
	Mn^{2+}	-	-	-	SO_4^{2-}	27.0	0.56	9.14
	Fe^{2+}	-	-	-	F^-	0.4	0.021	0.34
	Zn^{2+}	0.14	0.0043	0.05				
	Total		8.50	99.99			6.13	100.01
ilalani (OW6)	Na^+	24	1.04	18.84	NO_3^-	0.3	0.0048	0.157
	Ca^{2+}	88	4.4	79.71	HCO_3^-	130.0	2.131	67.82
	Mg^{2+}	0.96	0.08	1.45	Cl^-	34.0	0.971	30.90
	Mn^{2+}	-	-	-	SO_4^{2-}	-	-	-
	Fe^{2+}	-	-	-	F^-	0.65	0.034	1.08
	Zn^{2+}	0.14	0.0043	0.078				
	Total		5.52	100.07			3.142	99.95
unge (OW8)	Na^+	20	0.869	17.91	NO_3^-	Nil	-	
	Ca^{2+}	62	3.1	63.91	HCO_3^-	116	1.90	69.60
	Mg^{2+}	10.56	0.88	18.14	Cl^-	28	0.79	28.93
	Mn^{2+}	-	-	-	SO_4^{2-}	Nil	-	-
	Fe^{2+}	-	-	-	F^-	0.7	0.037	1.36
	Zn^{2+}	0.1	0.0031	0.064				
	Total		4.85	100.02			2.73	99.8

Table 17 (cont'd)

Name of Well	Concentration (units shown)							
	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
Munge (OW9)	Na^{+}	24	1.04	16.84	NO_3^-	0.12	0.0019	0.063
	Ca^{2+}	85	4.25	68.83	HCO_3^-	148.0	2.43	81.03
	Mg^{2+}	10.56	0.88	14.25	Cl^-	32.0	0.53	17.67
	Mn^{2+}	-	-	-	SO_4^{2}	-	-	-
	Fe^{2+}	-	-	-	F^-	0.7	0.037	1.23
	Zn^{2+}	0.14	0.0043	0.069				
	Total		6.17	99.9			2.99	99.9
Munge (OW)	Na^{+}	114.0	4.96	60.2	NO_3^-	0.2	0.0032	0.052
	Ca^{2+}	36.8	1.84	22.3	HCO_3^-	168.0	2.75	44.57
	Mg^{2+}	17.3	1.44	17.5	Cl^-	100.0	2.82	45.71
	Mn^{2+}	-	-	-	SO_4^{2-}	28.0	0.58	9.4
	Fe^{2+}	-	-	-	F^-	0.3	0.016	0.26
	Zn^{2+}	0.1	0.0031	0.037				
	Total		8.24	100.0			6.17	99.7
Idzovvni (OW11)	Na^{+}	19	0.82	24.9	NO_3^-	0.12	0.00192	0.06
	Ca^{2+}	43	2.15	65.3	HCO_3^-	138	2.26	71.1
	Mg^{2+}	3.8	0.32	9.7	Cl^-	32	0.90	28.3
	Mn^{2+}	-	-	-	SO_4^{2-}	-	-	-
	Fe^{2+}	-	-	-	F^-	0.3	0.015	0.47
	Zn^{2+}	0.08	0.024	0.73				
	Total		3.29	99.9			3.18	99.9
ingwende (OW12)	Na^{+}	18	0.78	15.03	NO_3^-	0.05	0.0008	0.027
	Ca^{2+}	85	4.25	81.8	HCO_3^-	128	2.098	73.4
	Mg^{2+}	1.9	0.158	3.04	Cl^-	26	0.73	25.5
	Mn^{2+}	-	-	-	SO_4^{2-}	-	-	-
	Fe^{2+}	-	-	-	F^-	0.6	0.032	1.1
	Zn^{2+}	0.08	0.0024	0.046				
	Total		5.19	99.9			2.86	100.0

Table 17 (cont'd)

Name of Well	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
	Concentration (units shown)							
Msambweni (OW13)	Na^+	22.0	0.96	44.4	NO_3^-	0.5	0.008	0.34
	Ca^{2+}	24.0	1.2	55.6	HCO_3^-	50.0	0.82	34.9
	Mg^{2+}	-	-	-	Cl^-	28.0	0.79	33.6
	Mn^{2+}	-	-	-	SO_4^2	33.0	0.69	29.4
	Fe^{2+}	-	-	-	F^-	0.85	0.045	1.9
	Zn^{2+}	0.02	0.00016	0.007				
	Total		2.16	100.0			2.35	100.01
Milalani (OW15)	Na^+	18.0	0.78	24.3	NO_3^-	0.02	0.00032	0.011
	Ca^{2+}	39.0	1.95	60.7	HCO_3^-	136.0	2.23	82.9
	Mg^{2+}	5.8	0.48	14.9	Cl^-	16.0	0.45	16.7
	Mn^{2+}	-	-	-	SO_4^{2-}	-	-	-
	Fe^{2+}	-	-	-	F^-	0.2	0.011	0.41
	Zn^{2+}	0.11	0.0033	0.010				
	Total		3.21	100.00			2.69	100.0
abatani (OW16)	Na^+	16.0	0.69	11.4	NO_3^-	0.1	0.0016	0.054
	Ca^{2+}	94.0	4.7	77.9	HCO_3^-	156.0	2.56	86.5
	Mg^{2+}	7.68	0.64	10.6	Cl^-	22.0	0.37	12.5
	Mn^{2+}	-	-	-	SO_{42}^-	-	-	-
	Fe^{2+}	-	-	-	F^-	0.65	0.034	1.1
	Zn^{2+}	0.1	0.0031	.051				
	Total		6.03	99.9			2.96	100.2
ingwende OW17)	Na^+	25.0	1.08	25.0	NO_3^-	0.03	0.00048	0.009
	Ca^{2+}	58.4	2.92	67.6	HCO_3^-	150.0	2.46	46.5
	Mg^{2+}	3.8	0.32	7.4	Cl^-	40.0	2.82	53.3
	Mn^{2+}	-	-	-	SO_4^{2-}	-	-	-
	Fe^{2+}	-	-	-	F^-	0.3	0.0158	0.29
	Zn^{2+}	0.07	0.0021	0.049				
	Total		4.32	100.0			5.29	100.1

Table 17 (cont'd)

Name of Well	Concentration (units shown)							
	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
Kingwende (OW18)	Na^+	18.0	0.78	21.8	NO_3^-	0.3	0.0048	0.17
	Ca^{2+}	48.0	2.4	67.0	HCO_3^-	140.0	2.29	79.8
	Mg^{2+}	4.8	0.4	11.2	Cl^-	20.0	0.56	19.5
	Mn^{2+}	-	-	-	SO_4^{2}	-	-	-
	Fe^{2+}	-	-	-	F^-	0.35	0.018	0.63
	Zn^{2+}	0.07	0.0021	0.058				
	Total		3.58	100.1			2.87	99.1
Kingwende (OW20)	Na^+	28	1.22	14.6	NO_3^-	0.15	0.0024	0.068
	Ca^{2+}	83	4.15	49.8	HCO_3^-	140.0	2.29	64.9
	Mg^{2+}	35.5	2.96	35.5	Cl^-	42.0	1.18	33.4
	Mn^{2+}	-	-	-	SO_4^{2-}	1.0	0.021	0.59
	Fe^{2+}	-	-	-	F^-	0.75	0.039	1.1
	Zn^{2+}	0.02	0.00061	0.007				
	Total		8.33	99.6			3.53	100.1
unge (OW21)	Na^+	51.0	2.22	37.9	NO_3^-	0.1	0.0016	0.032
	Ca^{2+}	47.0	2.35	40.2	HCO_3^-	150.0	2.46	48.5
	Mg^{2+}	15.4	1.28	21.9	Cl^-	92.0	2.59	51.1
	Mn^{2+}	-	-	-	SO_4^{2-}	-	-	-
	Fe^{2+}	-	-	-	F^-	0.3	0.015	0.29
	Zn^{2+}	0.1	0.0031	0.053				
	Total		5.85	100.1			5.07	99.9
unge (OW23)	Na^+	91.0	3.96	38.3	NO_3^-	-	-	-
	Ca^{2+}	99.0	4.95	47.9	HCO_3^-	180.0	2.95	41.2
	Mg^{2+}	17.2	1.43	13.8	Cl^-	148.0	4.17	58.2
	Mn^{2+}	-	-	-	SO_4^{2-}	-	-	-
	Fe^{2+}	-	-	-	F^-	0.75	0.039	0.5
	Zn^{2+}	0.13	0.0039	0.038				
	Total		10.34	100.0			7.16	99.9

Table 17 (cont'd)

Name of Well	Concentration (units shown)							
	Cations	mg/l	meq/l	meq %	Anions	mg/l	meq/l	meq %
Kiriogo (OW24)	Na^{+}	26.0	1.13	30.6	NO_3^-	0.28	0.0045	0.15
	Ca^{2+}	48.8	2.44	66.1	HCO_3^-	144.0	2.36	78.9
	Mg^{2+}	1.4	0.12	3.3	Cl^-	22.0	0.62	20.7
	Mn^{2+}	-	-	-	SO_4^{2}	-	-	-
	Fe^{2+}	-	-	-	F^-	0.2	0.011	0.36
	Zn^{2+}	0.08	0.024	0.65				
	Total		3.69	100.6			2.99	100.1
Shirazi (OW26)	Na^{+}	7.8	0.34	11.76	NO_3^-	0.06	0.00096	0.021
	Ca^{2+}	26.4	1.32	45.67	HCO_3^-	156.0	2.56	57.65
	Mg^{2+}	14.8	1.23	42.56	Cl^-	54.0	1.52	34.23
	Mn^{2+}	-	-	-	SO_4^{2-}	16.0	0.33	7.43
	Fe^{2+}	-	-	-	F^-	0.6	0.032	0.72
	Zn^{2+}	0.05	0.0015	0.052				
	Total		2.89	100.0			4.44	100.1

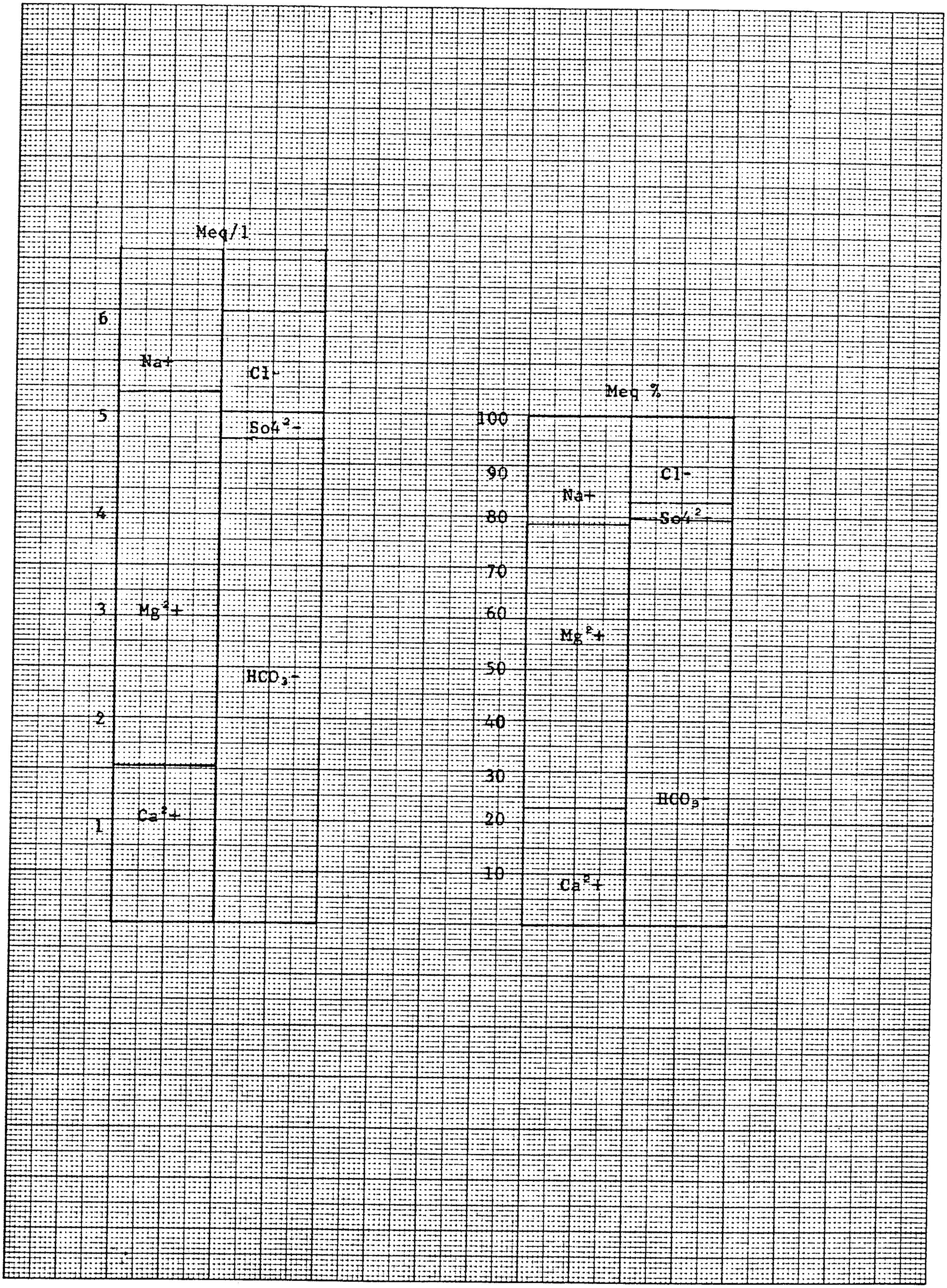

FIGURE 19: CHEMICAL PRESENTATION ON A BAR GRAPH (DATA FOR MILALANI III WELL)

Organization (WHO) standards for drinking water and plotting the individual ions relative to these bounds, it is possible to identify those boreholes with good water, moderately good water and those boreholes with water unfit for consumption. The plots showing this information for each well and each contaminant examined are shown in Figures 20-28.

For those wells which had concentrations of particular ions above the limit of general acceptability, a ratio indicating the number of deviations from the limit of general acceptability was developed. This ratio was defined as the height (deviations) above the line of general acceptability divided by the distance (deviations) between the line of general acceptability and the line of maximum allowable limit. Any element having a ratio greater than one was considered to be excessive. Tables 18 and 19 show wells with ions having concentrations above the limit of general acceptibility.

None of the wells showed excessive contents of chloride, sulphate or fluoride. All were below the limit of general acceptability. Five of the boreholes showed pH values which are indicative of acidity (below 6.5).

8.4 Multivariate Diagrams

In order to be able to show chemical analyses from many water samples, multivariate diagrams can also be used. Different symbols are used to represent data from different aquifers (wells). One type of multivariate diagram commonly used to present data on chemical analyses is the trilinear diagram. It shows the combinations of ions (cations and anions) in milliequivalent percentages. In trilinear diagrams,

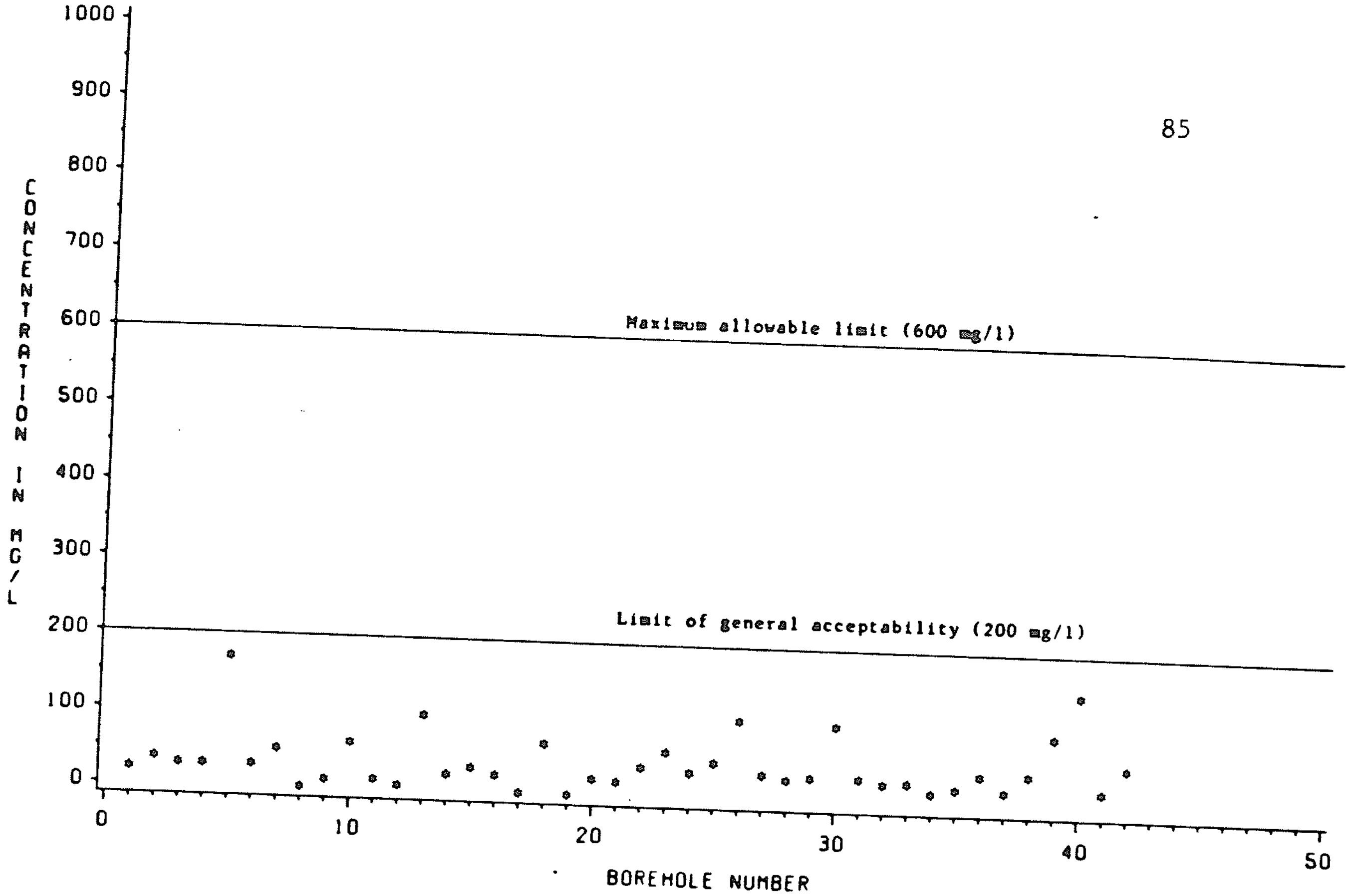

FIGURE 20 :CHLORIDE CONCENTRATION IN BOREHOLES

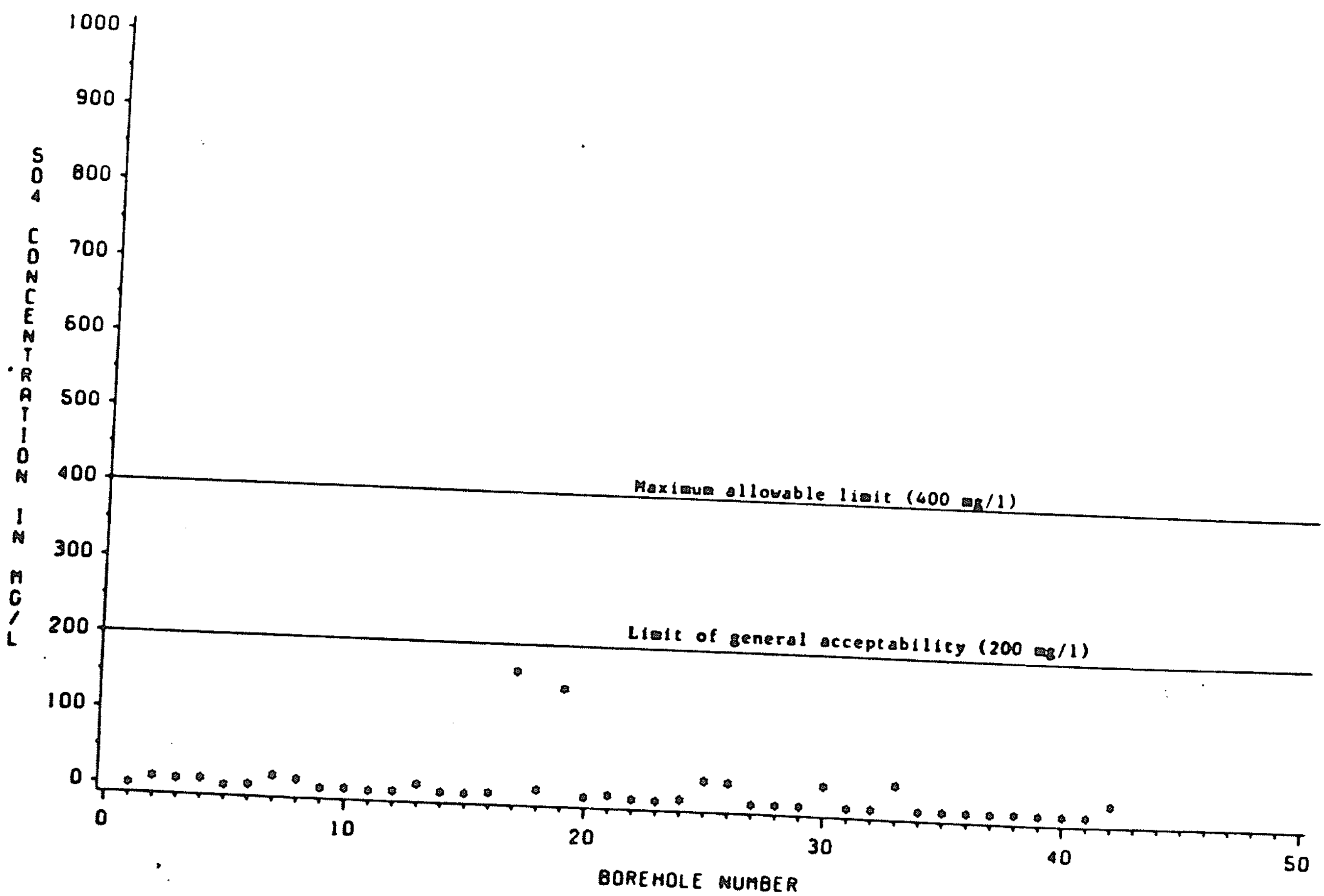

FIGURE 21 :SULPHATE CONCENTRATION IN BOREHOLES

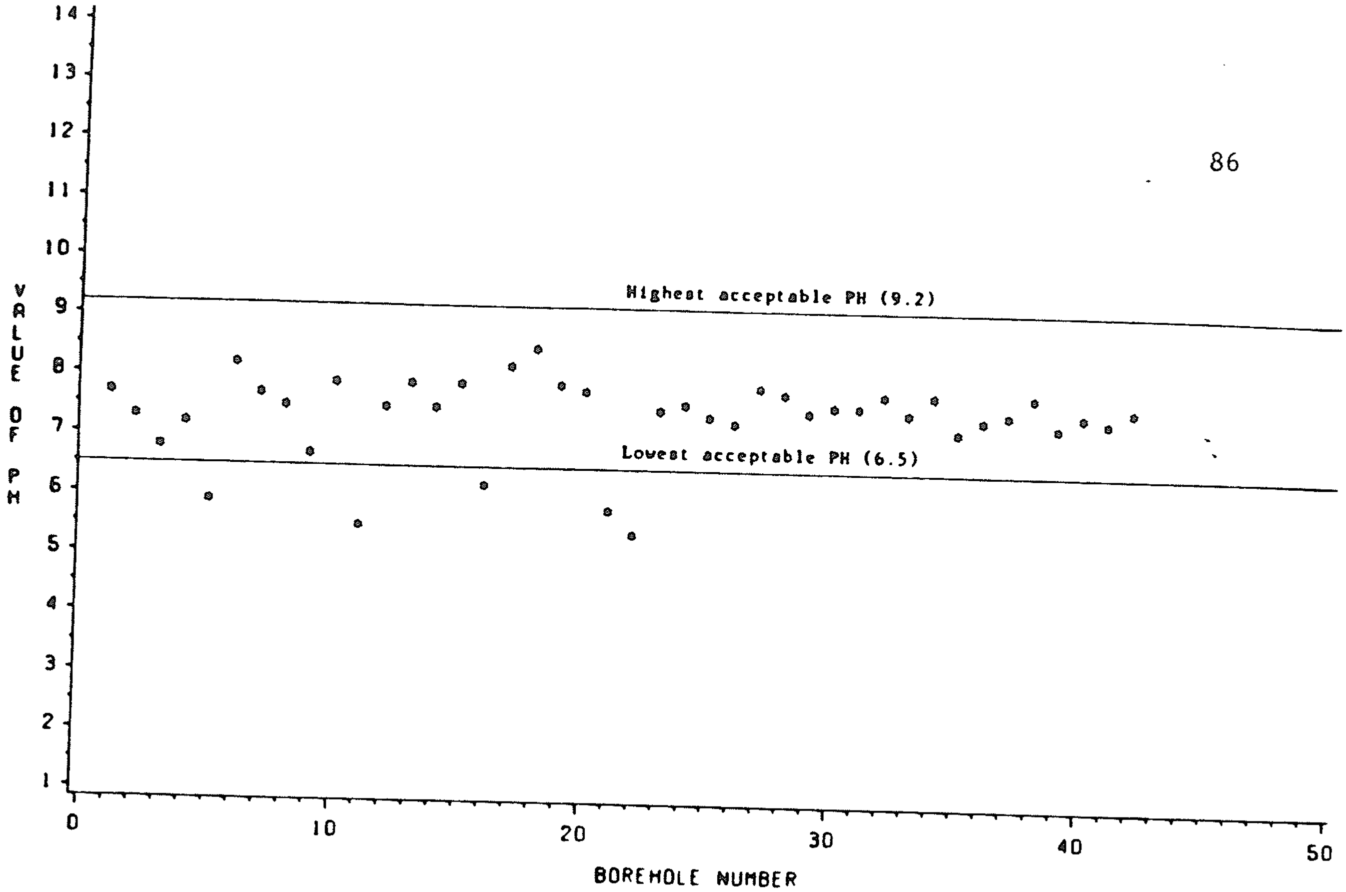

FIGURE 22 :PH VALUES IN THE BOREHOLES

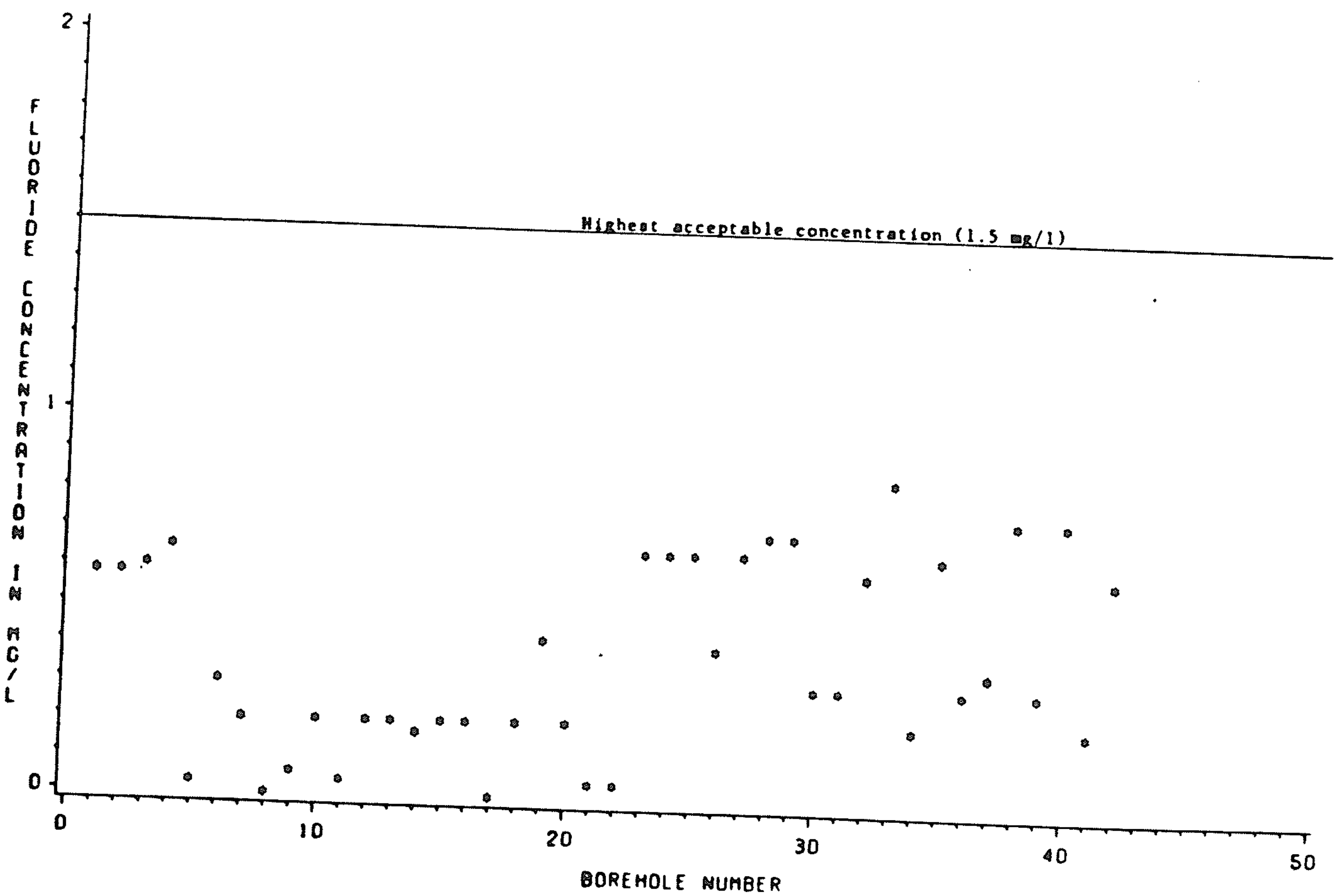

FIGURE 23 :FLUORIDE CONCENTRATION IN BOREHOLES

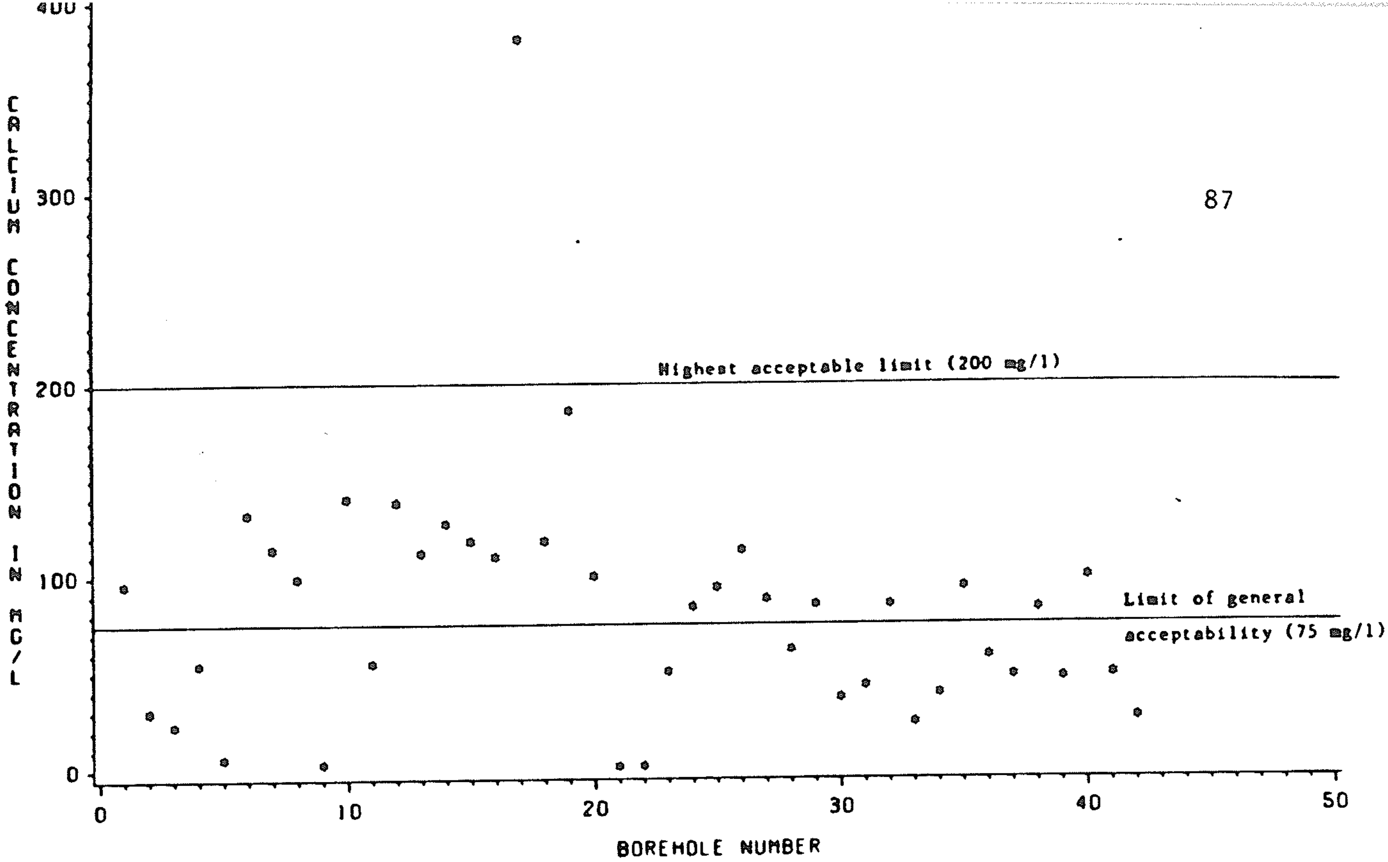

FIGURE 24:CONCENTRATION OF CALCIUM IN THE BOREHOLES

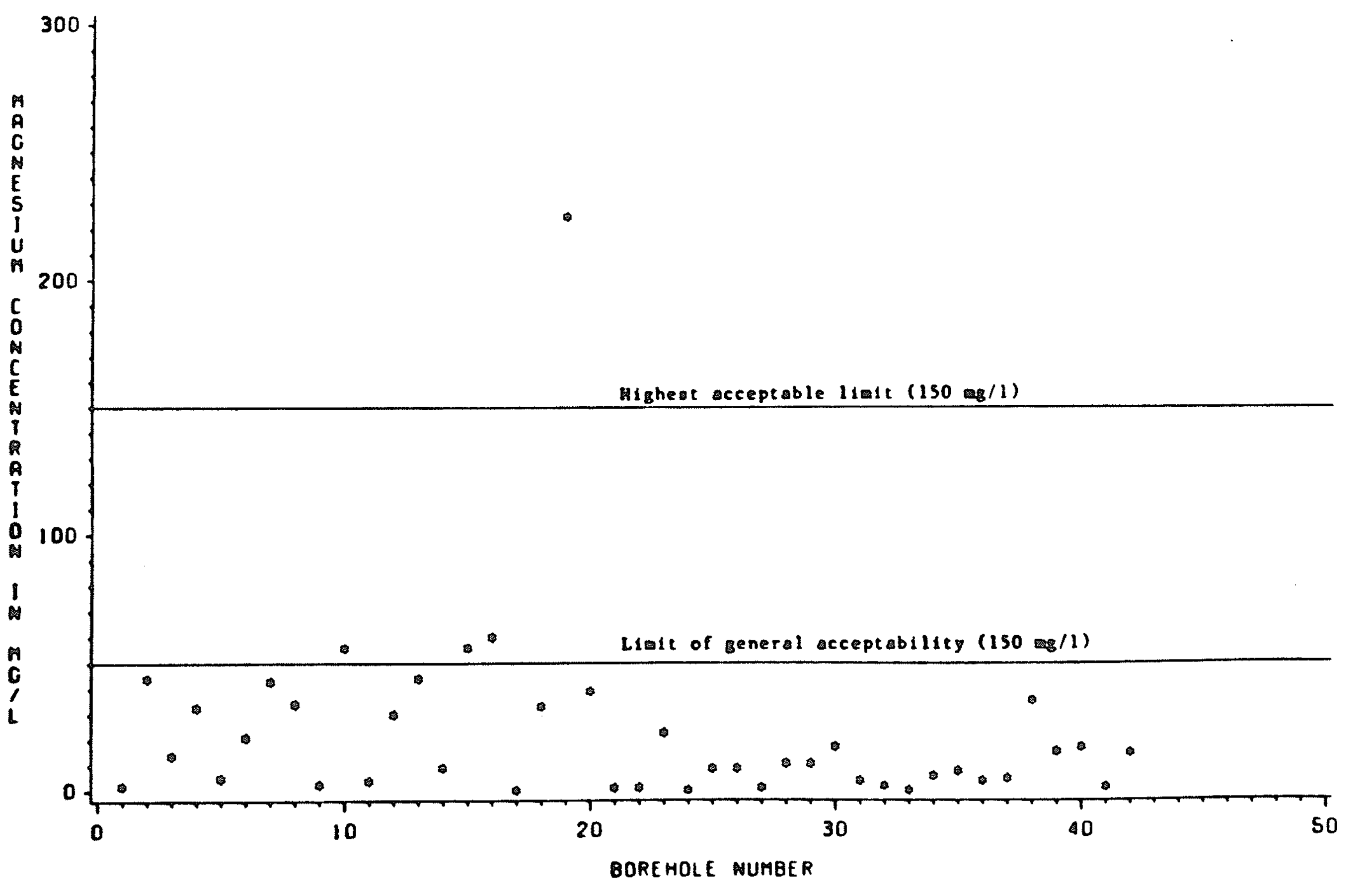

FIGURE 25 :CONCENTRATION OF MAGNESIUM IN THE BOREHOLES

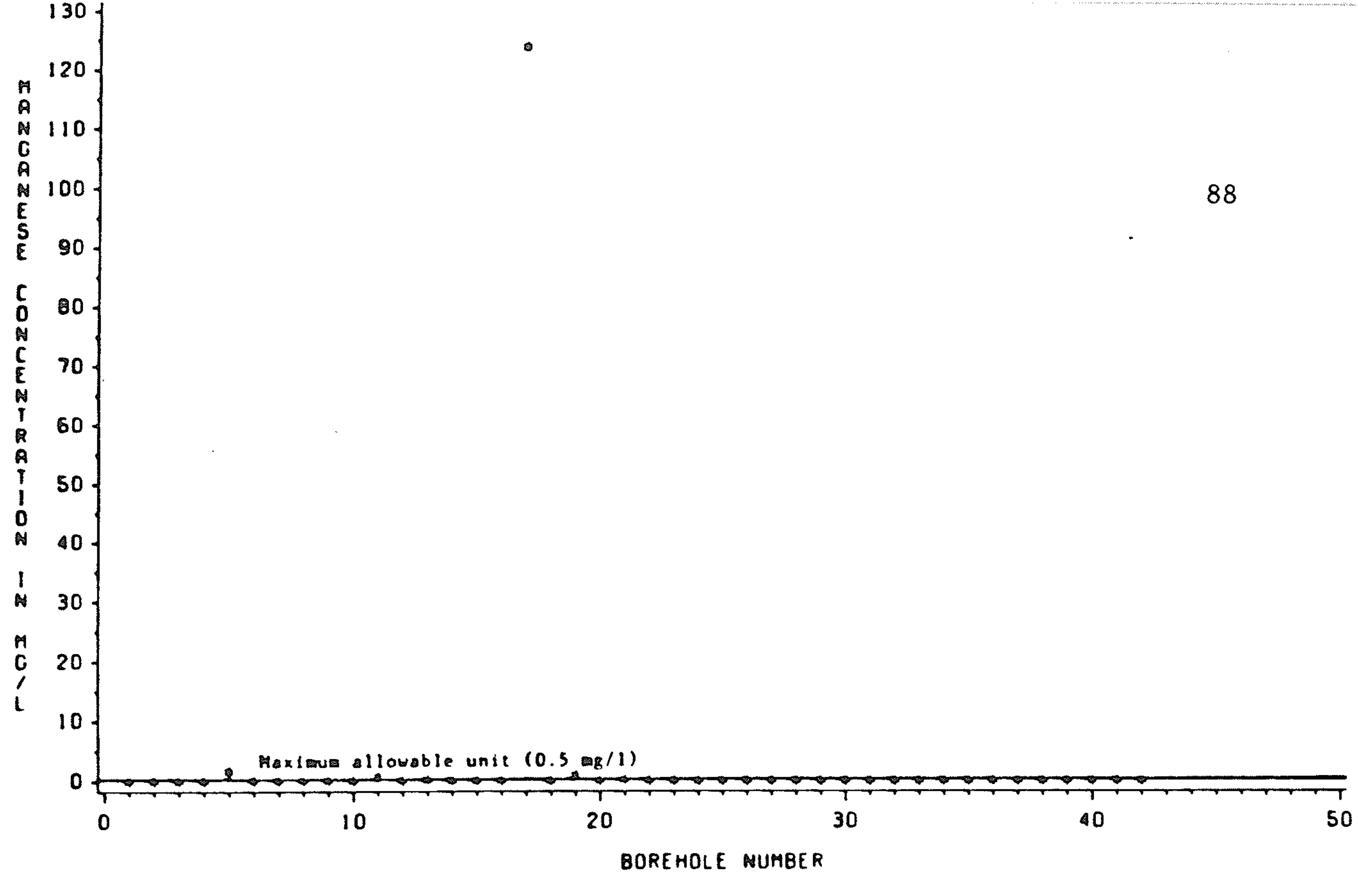

FIGURE 26 :CONCENTRATION OF MANGANESE IN THE BOREHOLES

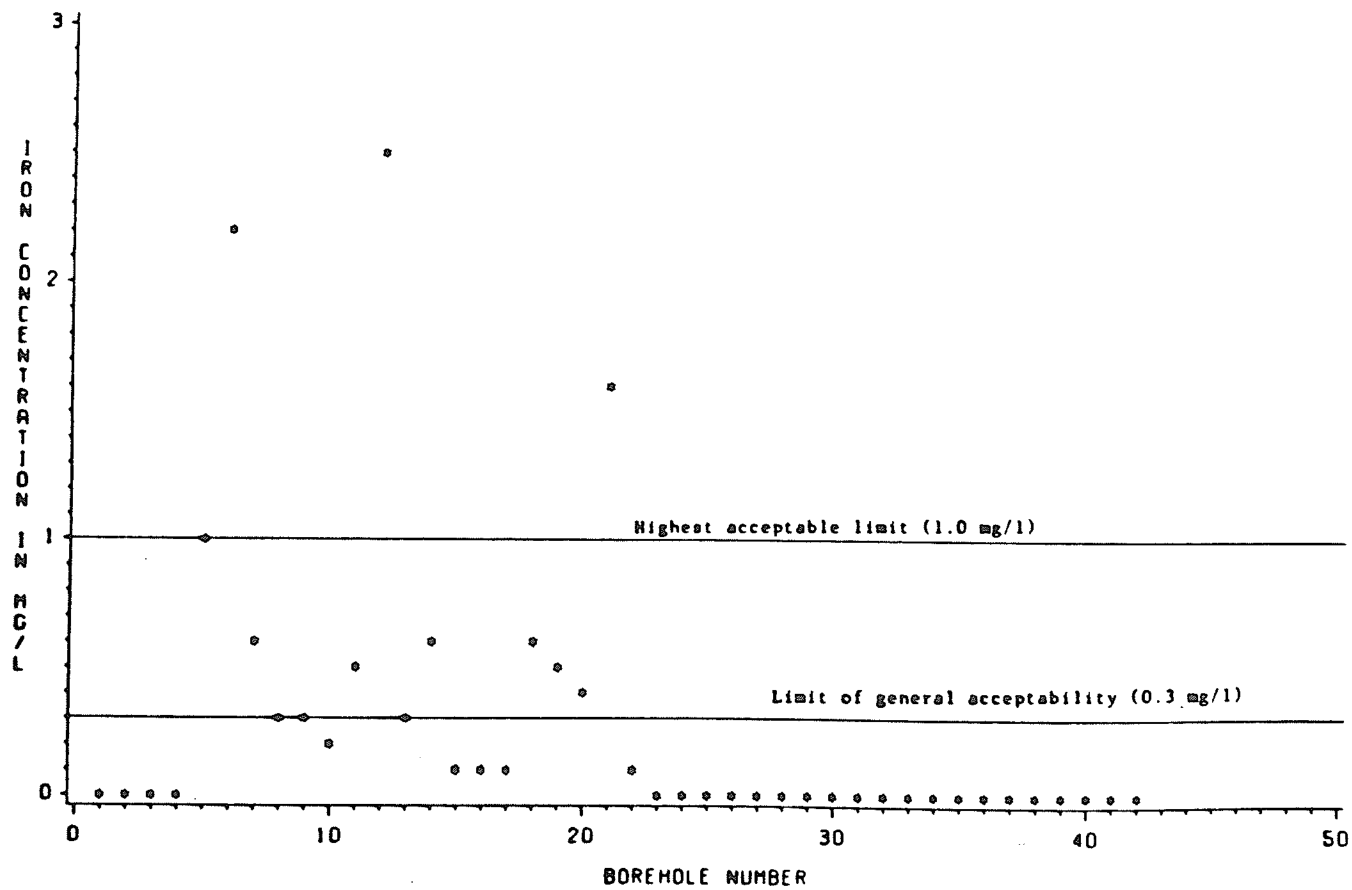

FIGURE 27:CONCENTRATION OF IRON IN THE BOREHOLE

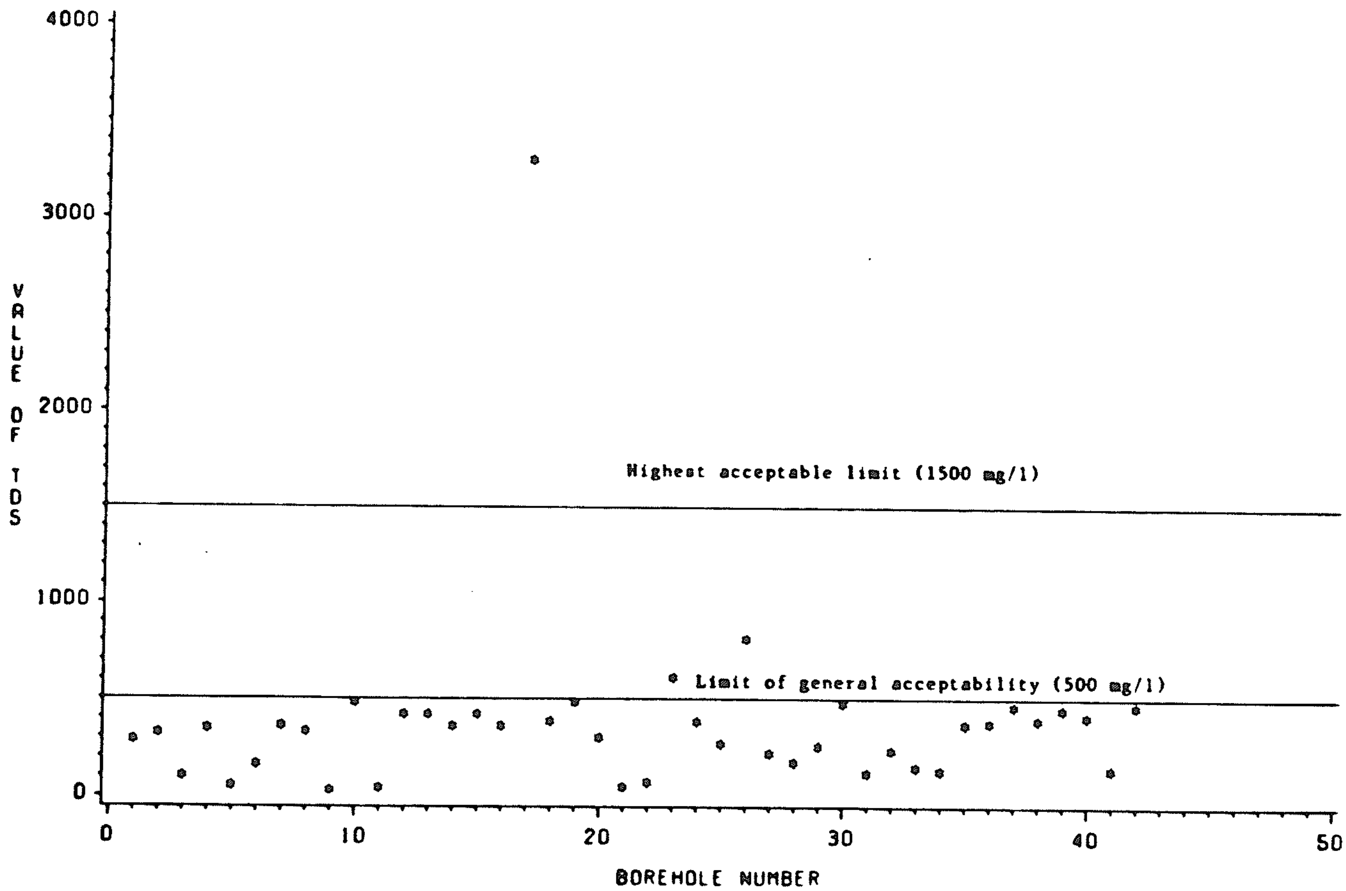

FIGURE 28 : TOTAL DISSOLVED SOLIDS IN THE BOREHOLES

Table 18. Wells with above limits of general acceptability.

Element	Name of Well	No. of Deviations (mg/l)	Width of Band	Deviation / Width of Band	Comments
Iron	Mbuani	35	35	1.0	Reasonably good water
	Kibarani (OW76)	95	35	2.7	Excessive
	Mwangoloko	15	35	0.43	Reasonably good quality
	Muhaka	10	35	0.29	"
	Kibarani (OW75)	110	35	3.14	Excessive
	Kibarani (OW73)	15	35	0.43	Reasonably good quality
	Mwalibembo	15	35	0.43	"
	Lungalunga	10	35	0.29	"
	Magutu	5	35	0.14	"
	Mwamaguo	65	35	1.85	Excessive
	Shamu	35	35	1.0	Reasonably good water
Magnesium	Mkuakuani	28	50	0.56	Reasonably good water
	Bonqwe	28	50	0.56	"
	Kibarani	32	50	0.64	"
	Lungalunga	88	50	1.76	Excessive
TDS	Chalo	106	40	2.65	Excessive very saline
	Msambweni (I)	0.4	40	0.010	Moderately saline
	Ngaja	0.7	40	0.0175	"

Table 19. Wells with concentration of calcium above the limit of general acceptability.

Name of Well	No. of Deviations	Width of Band	Deviation / Width of Band	Comments
Milalani II	8	50	0.16	Within limits
Kibarani (OW746)	22	50	0.44	"
Mwangoloko	25	50	0.38	"
Kibarani (OW66)	19	50	0.38	"
Mkuakuani (OW92)	25	50	0.50	"
Kibarani (OW75)	24	50	0.48	"
Kibarani (OW69)	14	50	0.28	"
Kibarani (OW73)	20	50	0.40	"
Bonqwe (OW87)	16	50	0.32	"
Kibarani (B/H)	13	50	0.26	"
Chalo	115	50	2.30	Excessive
Mwalibembo	16	50	0.32	Within limits
Lungalunga	47	50	0.94	"
Magutu	10	50	0.2	"
OW (3)	3	50	0.06	"
Bomani	7	50	0.14	"
Ngaja	15	50	0.3	"
Milalani	5	50	0.1	"
Munge	4	50	0.08	"
Kingwende (OW12)	4	50	0.08	"
Mabatani	7	50	0.14	"
Kingwende (OW20)	3	50	0.06	"
Munge	9	50	0.18	"

groundwater is assumed to have three cation constituents (Na, Mg, Ca), and three anion constituents (HCO_3^-, SO_4^{2-} and Cl^-). The milliequivalent percentages of the three cation groups and the three anion groups are plotted as a single point on the triangle whose scale reads in 100 parts. Data from Table 17 is used to illustrate the presentation of chemical analysis using trilinear diagram in Figures 29 to 34. From these figures and also from Table 8, it is evident that most of the wells have bicarbonate water, the principal cations being calcium and magnesium. The high concentrations of bicarbonate and carbonate ions causes hardness. Most of these wells are drilled in coral limestones which are predominantly composed of calcium carbonate. The carbonate ion also finds its way into the groundwater from the adsorption of carbon dioxide from the atmosphere. All hardness found in the wells is temporary hardness, i.e., caused by the bicarbonates of calcium and magnesium. The sulphate ion, which is responsible for permanent hardness is hardness is present but only in very small amounts (less than 20 meq %) in all wells but one, Msambweni (OW13) which has 29 meq % of sulphate ion. However in the interpretation of the chemical analysis, the meq % can be misleading especially when the total meq/l of cations and anions is less than 5 (Hem, 1970).

In this case, the actual concentration of the ions in mg/l should be used and compared to the limit of general acceptability as stipulated by the World Health Organization (WHO). For the case of Msambweni (OW13), it shows that the meg % of the sulphate ion is 29%, while the actual concentration of the sulphate ion is 33.0 mg/l, a figure well below the limit of general acceptability of 50 mg/l. Table 21 shows those wells which are considered to have hard water.

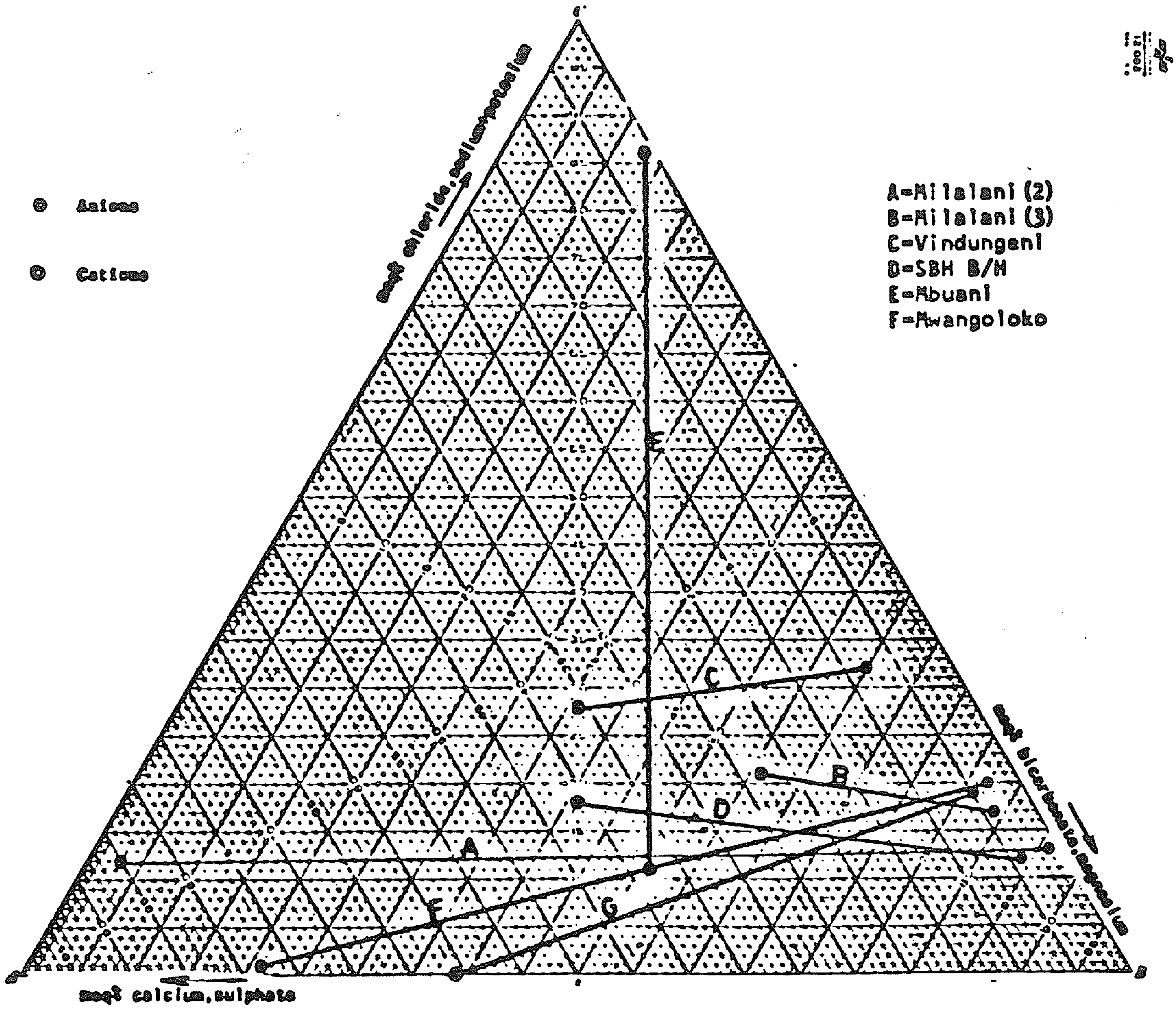

Figure 29: Trilinear diagram 1

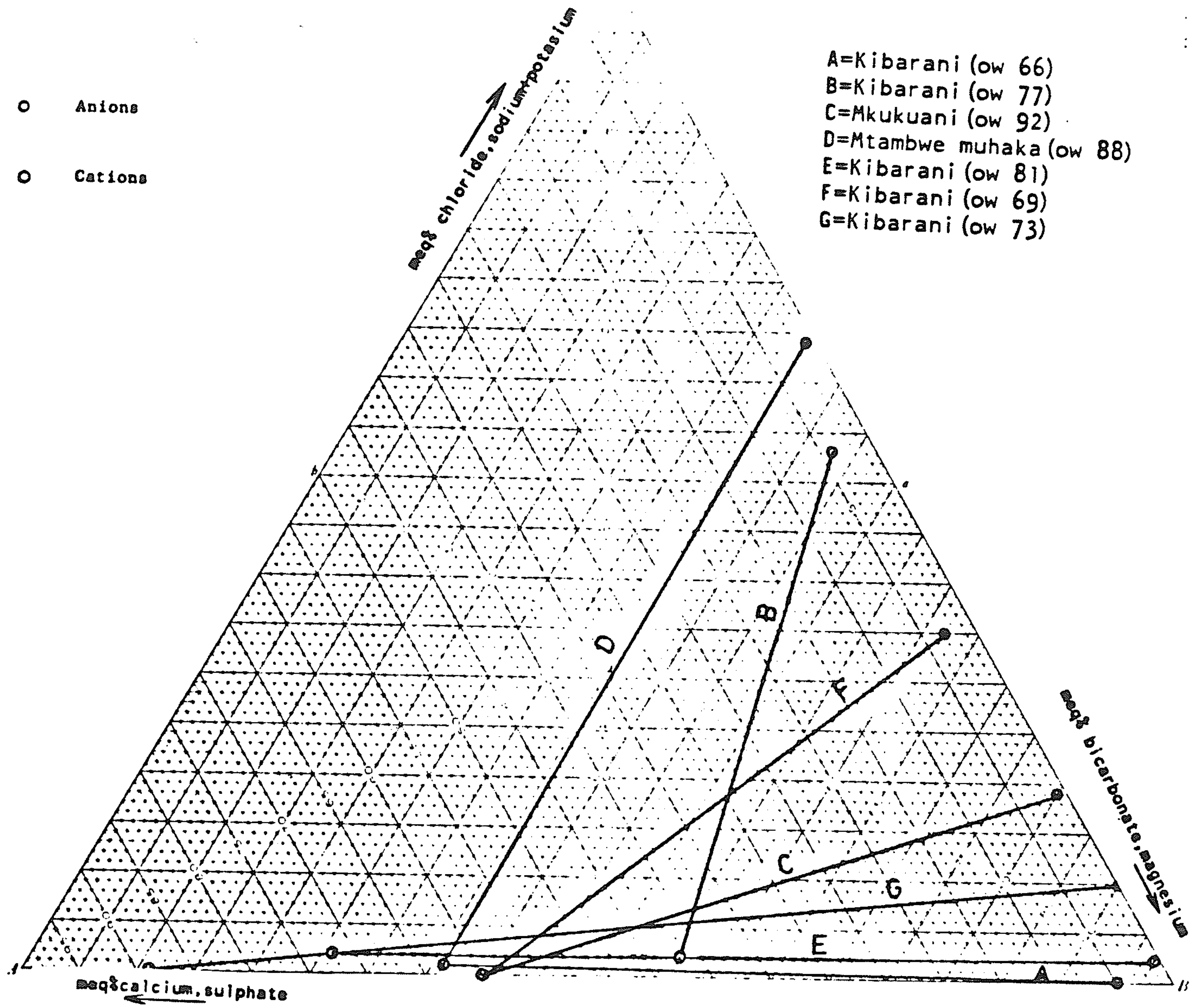

Figure 30: Trilinear diagram 2

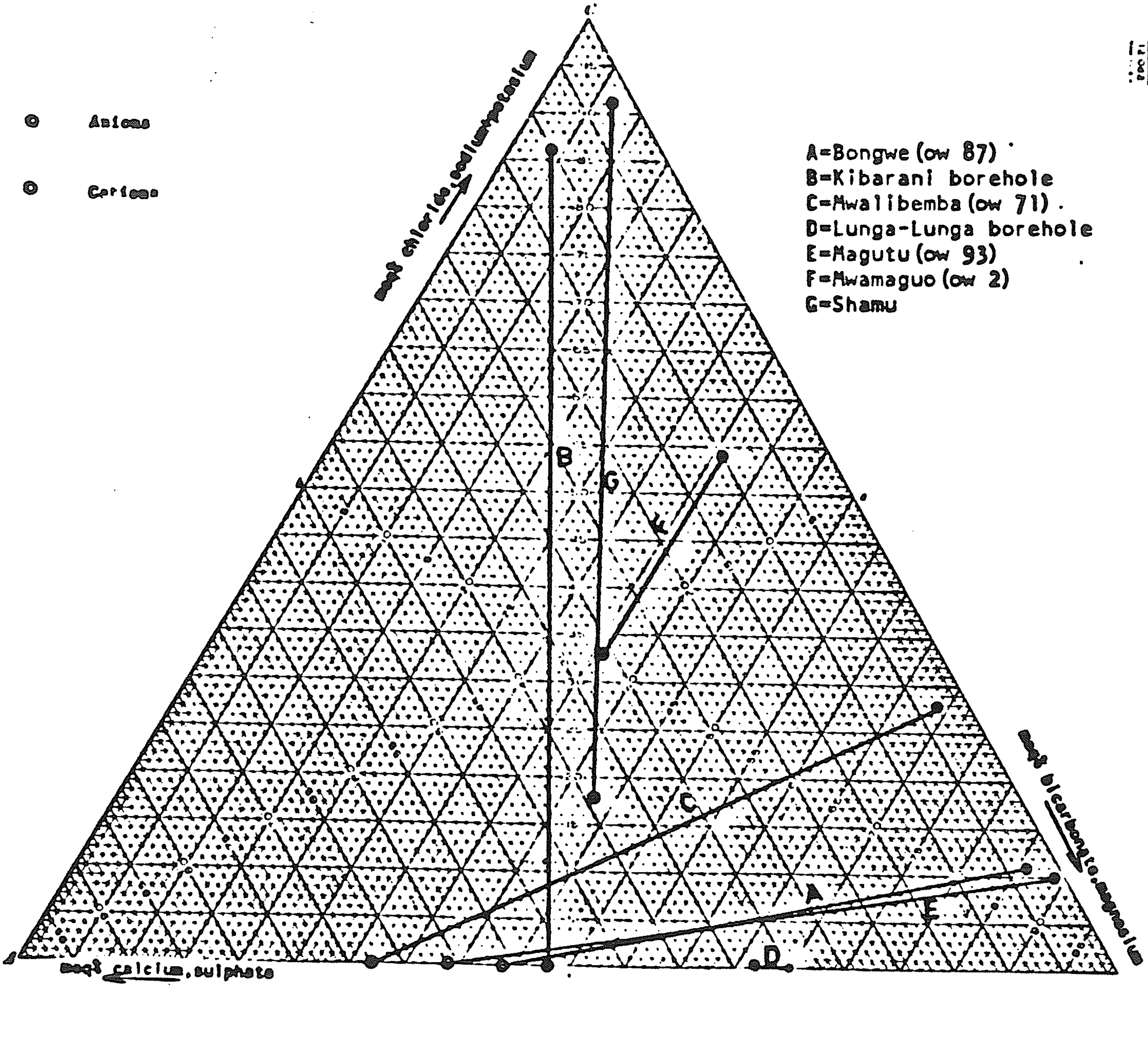

Figure 31: Trilinear diagram 3

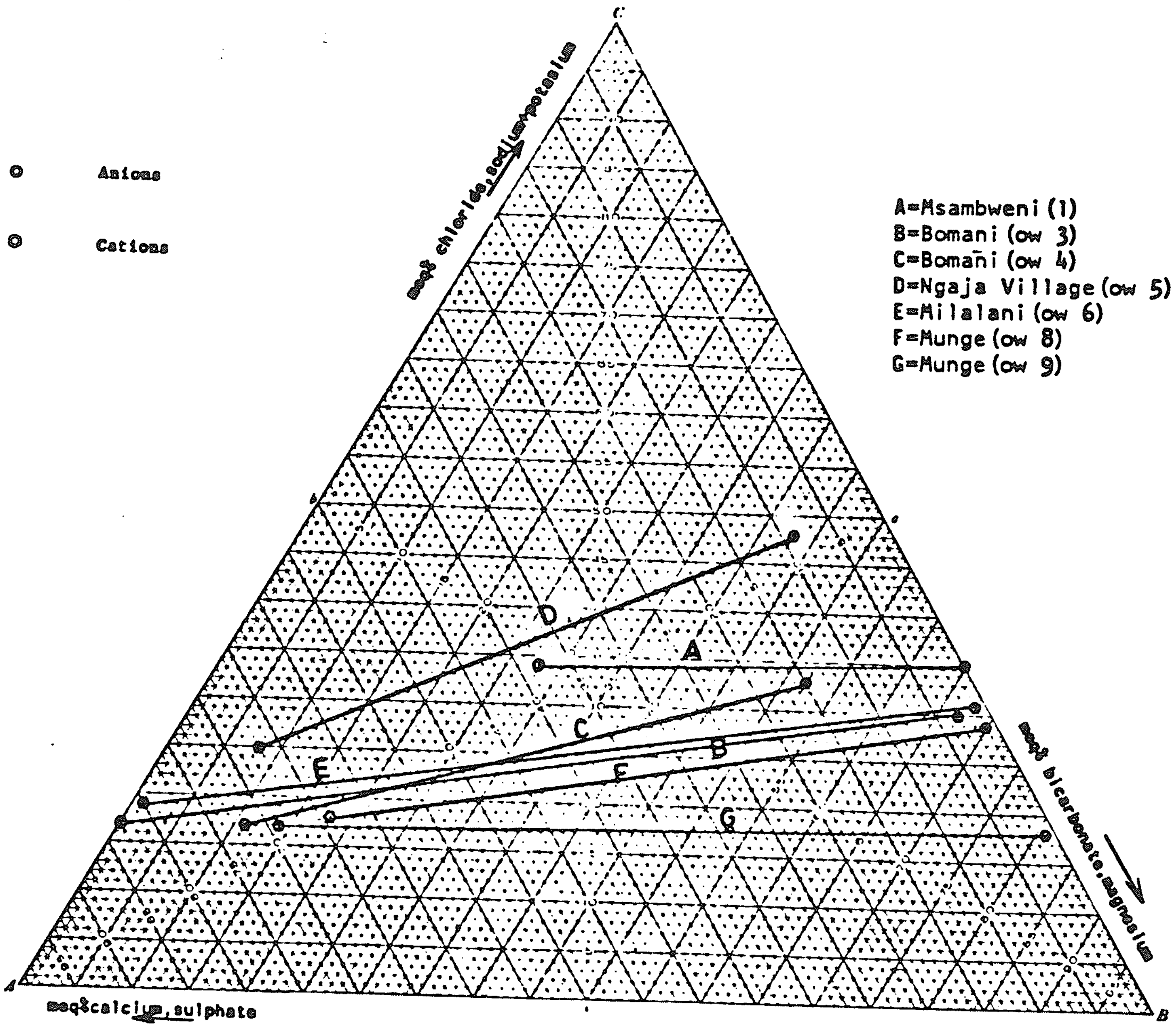

Figure 32: Trilinear diagram 4

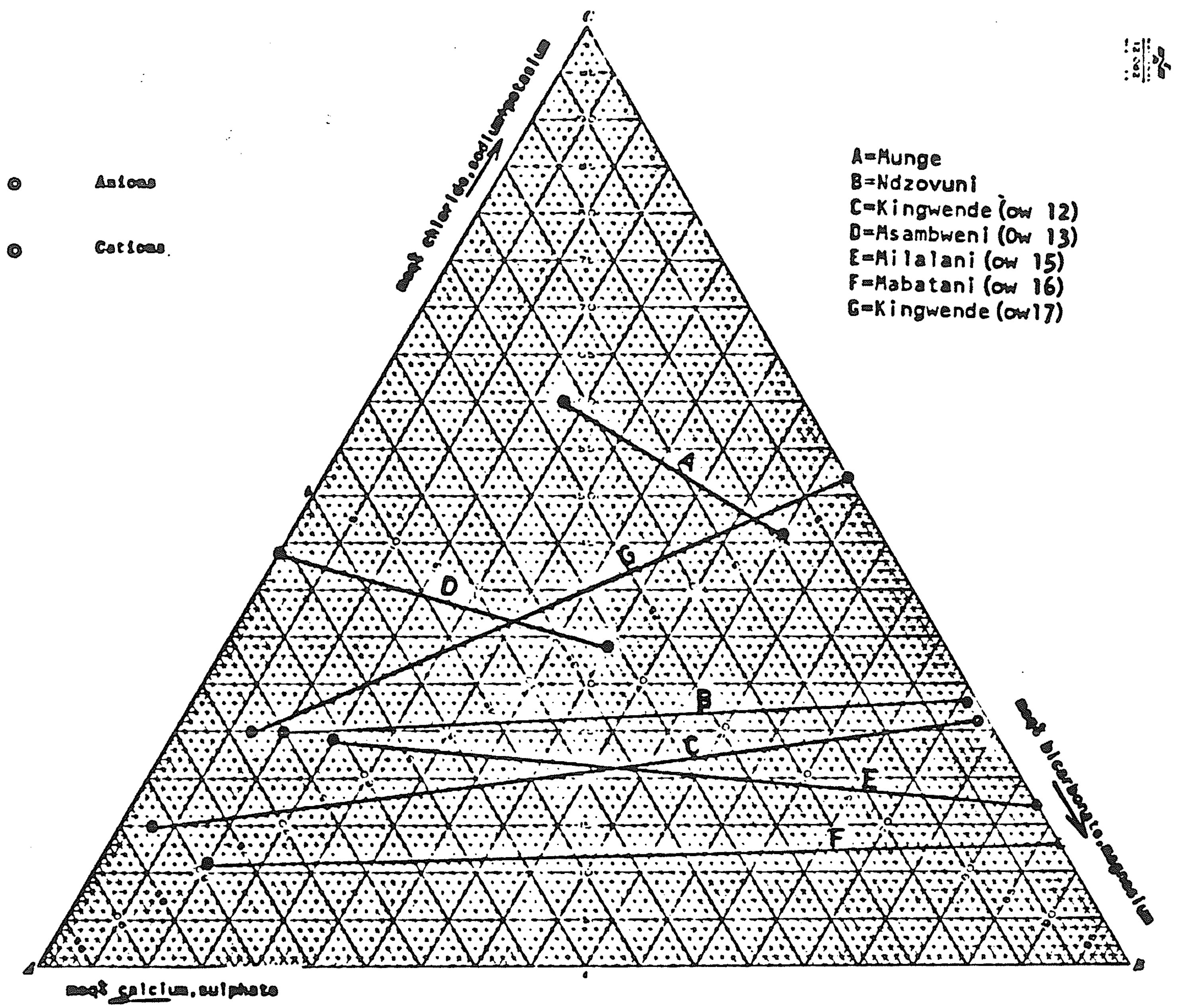

Figure 33: Trilinear diagram 5

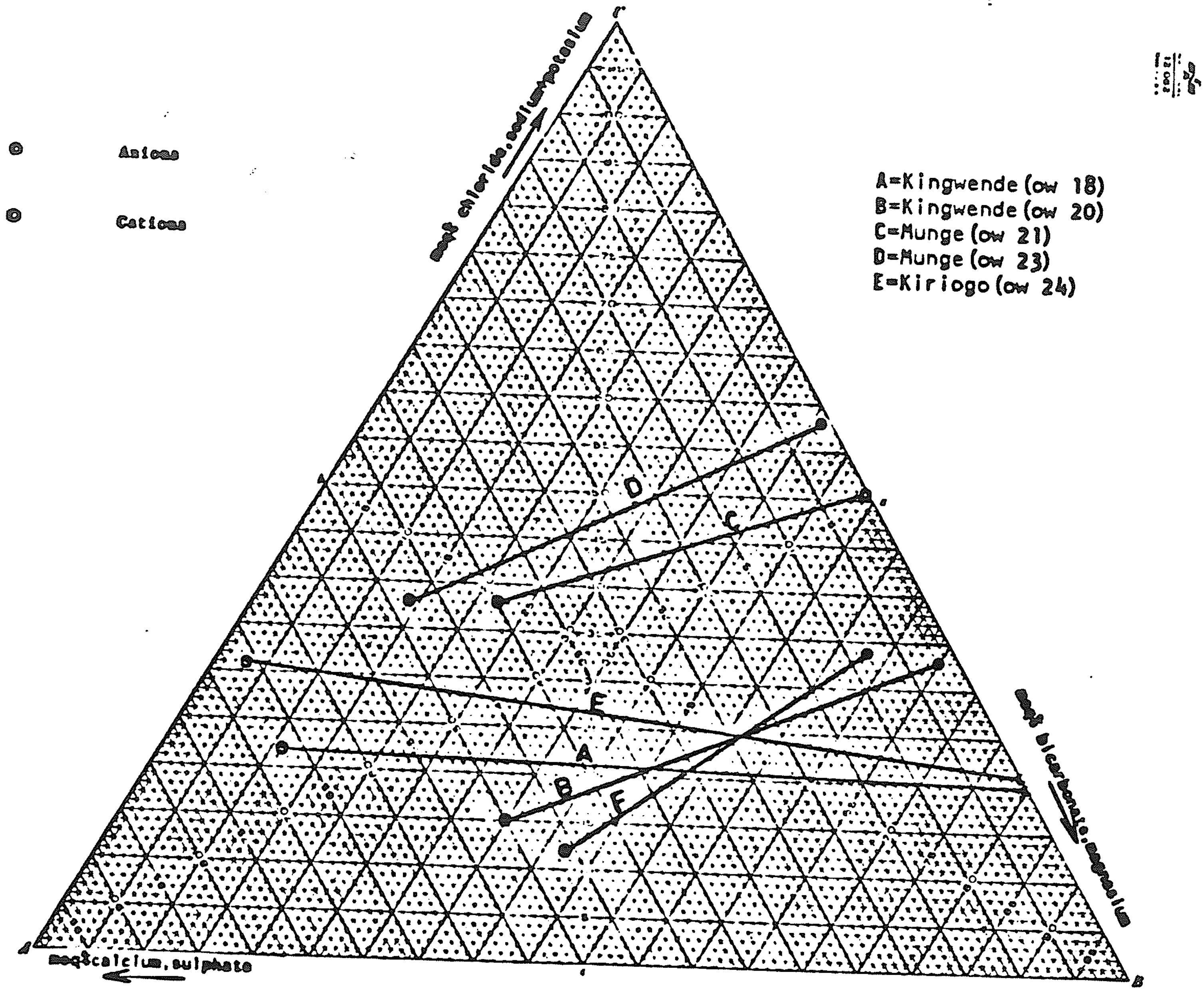

Figure 34: Trilinear diagam 6

Table 21. Wells with hard water.

Name of Well		Concentration (mg/l) Calcium	Magnesium	Bicarbonate
1. Kibarani	(OW76)	132.0	21.0	187.2
2. Mkuakuani	(OW92)	140.0	56.0	441.6
3. Kibarani	(OW75)	138.0	30.0	385.2
4. Kibarani	(OW69)	112.0	44.0	307.2
5. Bongwe	(OW87)	118.0	56.0	441.6
6. Chalo	(OW42)	448.5	-	380.0
7. Mwalibemba	(OW71)	118.0	33.0	273.0
8. Lungalunga borehole		100.0	39.0	326.0

The hardness can be attributed to the high concentrations of calcium ion and the bicarbonate ion especially in the coral and coral brecia which are predominantly composed of limestone ($CaCO_3$) and dolomite ($MgCO_3$). The relative proportions of these ions depends on the source of the sediments. In the south coast the sediments usually come from the erosion of the igneous intrusions which form isolated hills within the Digo Settlement areas and which contains more calcium and magnesium minerals. Jombo and Mrina Hills are covered by a thick layer of distinctive red-brown soil caused by the weathering of the manganese and iron ores (Baker, 1953). The effects of these ions is to make the water objectionable by imparting some colouration on it. Three wells, Kibarani (OW75), Kibarani (OW76) and Mwamaguo were found to have objectionally high quantities of iron while none of the wells had concentrations of manganese, high enough to affect the potability. Water from these wells is, however, likely to stain laundry and is therefore undesirable in this respect.

9. WELL DESIGN

Once the well (borehole) has been drilled it has to be constructed in such a manner as to guarantee a flow of water which is free of particles from the aquifer and the overlying soils. Construction consists of three parts:

1. The screen section, through which the water from the aquifer flows into the well (intake portion).

2. The casing section (blind pipe) which serves as a permanent wall of the borehole and prevents the borehole walls from caving in. It also serves as a housing for the pumping equipment and as a vertical conduit for water flowing upwards from the aquifer to the pump intake.

3. Cement plate on the surface to prevent contaminants from entering the well. The cement plate should slope outwards slightly to prevent water from collecting beside the casing and percolating into the well.

Before the casing is inserted, the drill samples (taken after every two metres or at any time when the change of formation is apparent) are carefully examined by a hydrogeologist who, with the help of other information such as water struck level, water rest level and the driller's log, determines what length of blank casing and screen should be installed. If the formation is firm enough to stand on its own (rarely so in the South Coast Project) the borehole can be left open, i.e. uncased.

The objectives of a good well design is to ensure the following:

1. The highest yield with minimum drawdown consistent with aquifer capability.

2. Good quality water with proper protection from contamination.

3. Water should remain sand free.

4. A well that has long life (> 25 years).

5. Reasonable short-term and long-term costs.

There are two types of screened production wells: natural pack and artificial pack. In a natural pack production well materials surrounding the production well are developed 'in place' while in the artificial pack production well, materials having a coarser uniform grain size than the natural formation are artificially placed around the production well. In the natural pack case development removes the finer material from the aquifer so that only coarser material surrounds the screen, i.e. materials around the production well are made more uniform in grain size and the sand and gravel are graded in such a way that fine deposits from the aquifer cannot clog the natural pack. Design and development of wells with 'artificial' pack material is described in sections 9.2 and 9.3.

9.1 Well Depth

This is usually determined from the lithological log of the area and confirmed by the electrical resistivity and drilling time logs. The well is usually drilled down to the bottom of the aquifer so that the full aquifer thickness is available permitting greater well yield.

9.2 Well Screen

Well screen design determines the length of the screen, its location, percentage of open area, size and shape of the slots and the selection of the screen material. The length of the well screen is chosen in relation to the aquifer thickness, available drawdown and stratification of the aquifer. In homogeneous artesian aquifer about 70 to 80% should be screened, and the screen should be positioned to be equal distance from the top and bottom of the aquifer.

In water table aquifers it is best to screen the bottom portion of the aquifer as the upper part is necessarily dewatered in forming a hydraulic gradient for flow into the well. Selection of screen length is a compromise between two factors--a higher specific capacity can be obtained by using as long a screen as possible, while greater drawdown results from using as short a screen as possible.

Theory and experience have shown that screening the bottom 1/3 of the aquifer provides the optimum design. (Driscol, F.G. 1986). The size of the slots in the screen depends upon the gradation and size of the formation material so that there will be movement of fines into the slots and all the fines around the screen are washed out to increase permeability. In the case of naturally developed wells the slot size is taken as 40 to 70% of the size of the formation material. Artificial gravel pack is required when the aquifer material is homogeneous with a uniformity coefficient of less than 3 and effective grain size less than 0.25 mm. The pack aquifer ratio, i.e. the ratio of 30 to 50% size of the gravel pack material to the 30 to 50% size of the formation material, should be kept at 4:1 if the formation is fine and uniform and 6:1 if the formation is coarse and non-uniform. The gravel pack material should have a uniformity coefficient of less than 2.5. The gravel pack material should be clean, rounded, smooth and uniform consisting mostly of siliceous material with the maximum grain size of the pack material being less than 10 mm. Appendix 15 (top) shows the seiving of artificial gravel pack.

The diameter of the screen is determined so that the entrance velocities (expected yield/total area of openings in the length of the screen chosen) will not exceed 3 to 6 cm/sec to prevent incrustation and corrosion and to minimize friction losses.

9.3 Well Development

Well development requires reversals of flow through the screen openings so as to wash out the fines and rearrange the formation particles in a naturally developed well and form a graded filter with rings of increasing porosity and permeability towards the well in an artificially gravel packed well, so that ultimately the well will yield sand-free water. Reversals of flow around the screen overcomes the tendency for several small particles to bridge between large particles. Methods of well development include:

(i) Mechanical surging by use of a solid or valve type surge plunger. The plunger is operated up and down in the casing like a piston in a cylinder producing the required alternate reversals of flow.

(ii) By use of compressed air. This involves a combination of surging and pumping by using sudden releases of large volumes of air.

(iii) High velocity jetting of water. A high velocity jet of water is directed horizontally through the screen openings.

(iv) Overpumping and back washing. When the well is pumped at a higher rate than the optimum rate recommended excess drawdown is created, i.e. higher gradients are created, and this washes out the fine particles.

Of the four well development methods, compressed air and overpumping are the ones commonly used in Kenya. If the method of drilling is by rotary rig both compressed air and overpumping can be used but if the method of drilling the percusion rig only overpumping or mechanical surging can be used.

10. SUMMARY

Groundwater development in the south coast region of Kenya is considered adequate for rural communities. However, due to the low yields (average of 3 m^3/hr), groundwater alone cannot be sufficient for municipal uses and other sources need to be considered. The yields from the wells are variable but generally low. This is mainly due to the poorly sorted nature of the sands and partly due to the filling of most of the intergranular spaces by secondary minerals. The wells seldom exceed 40 m in depth, but the nature of the strata is such that there is little or nothing to be gained in terms of quantity or quality of the water by drilling deeper.

Most of the wells in the area have yields varying from $1m^3$ per hour to $3m^3$ per hour with an average of $2.8m^3$ per hour. Eight of the wells around Msambweni and Gazi have relatively higher yields (average of $9m^3$ per hour). Both to the north and south of Msambweni and Gazi area the average yield of the well is about $3m^3$ per hour. The Msambweni and Gazi wells may be tapping a much more expansive and thicker aquifer than the wells to the north and south of this region but the real extent and thickness of the aquifer can only be determined by electrical profiling and sounding respectively.

Apart from the wells yielding hard water, the water is generally potable. Those wells drilled in the sandstone formation are slightly mineralised but the water is still potable. The concentration of the mineral salts in the wells drilled in the sandstone formation is due to the fact that the sandstone series were deposited under conditions of semi-aridity which led to evaporation of the water with the consequent precipitation of mineral salts, mainly carbonate, chlorides and sulphates. These salts were disseminated throughout the succession with varying degrees of concentration and being partially soluble, they were readily re-dissolved by groundwater and hence the water derived from these beds is most likely to be saline.

There has been no case of salt water intrusion from the sea into the wells though some wells are drilled quite close to the sea. This is because the wells are very shallow and the method of drawing water is by means of handpumps, which does not create a drawdown large enough for the cone of depression to intercept the sea water level. However, the possibility of sea water intrusion should not be ruled out and especially in deeper wells and in those wells where electrical submersible pumps are installed. In such cases, a continuous trial test should be done to determine how long it takes for the cone of depression to intercept the salty water level. Based on this information a length of pumping time should be recommended after which pumping must be stopped to allow the water level to recover to the original water rest level before pumping can be started again.

For a project like this to succeed proper maintenance is essential. The Ministry of Water technicians in Kenya are well trained for the maintenance of hand pumps. The local people (women groups) have also been taught the importance of keeping the well surroundings clean and to report any cases of breakdown to the nearest Ministry of Water Development's Office. Spare parts for the hand pumps are readily available in Kenya. Initially spare parts used to be a problem as most of the hand pumps were imported, but with local modifications of these pumps, spare parts are now available. It is expected that with the realization by the local people of the importance of keeping their village well properly maintained, shallow wells will remain the only cheap method of supplying clean water to the rural communities in Kenya.

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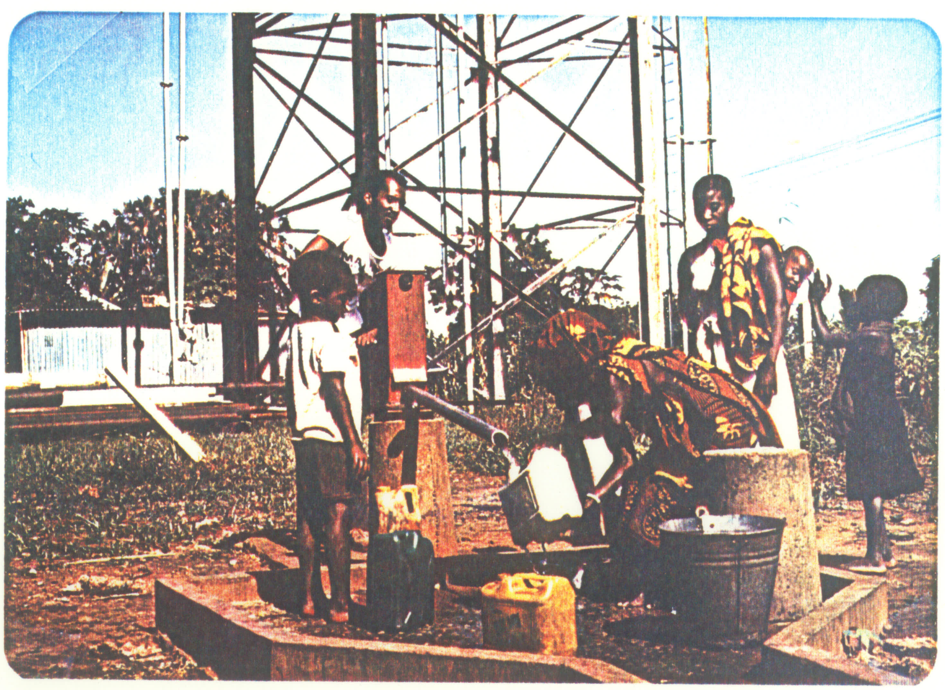
Appendix 1 : Drawing water from a well using a hand pump



Appendix 2. Names (Locality of Wells Shown in Fig. 1B.)

Number of Wells	Name of Well (Locality)
1	Milanani II
2	Milalani III
3	Mwabungo
4	Kinondo
5	Mbuani
6	Gandini
7	Gazi
8	Vingujini
9	Ngaja
10	Kidzumbani
11	Muhaka
12	Mafisini
13	Vindungeni
20	Magutu
22	Shamu
23	Msambweni
25	Mwachande
26	Kilole
27	Mabokoni
36	Kingwendel1
37	Kingwendel2
38	Kingwendel3
39	Munge1
40	Munge2
41	Mwabungo
42	Shirazi

Appendix 4. South-Coast Hand Pump--Project Shallow Boreholes Summary of the Construction Data.

Well No.	Borehole Number	Name of Borehole & Locality	Total Depth	Water Struck	Water Rest Level	Yield (LPM)
1	C-5371	Kigwende/Kinango	24	16, 19	13	37
2	C-5372	Milalani Primary School	24	16	8	36.6
3	C-5373	Marigiza N. Nbodzi	20	13	6.10	55
4	C-5419	Kikunguni	23	10, 22	7.5	55
5	C-5420	Milalani No. 2	23	12	7.74	36.6
6	C-5421	Vidugeni	23.5	9, 12	4.20	36.6
7	C-5422	Milalani No. 3	28	6, 19	12	44
8	C-5374	Mwangundu No. 1	29	15	13.3	44
9	C-5507	Kidziru	20	11, 15	9.3	27.5
10	C-5508	Kidzumbani	19	12, 25	7.95	20
11	C-5509	Mafisani Forest Edge	26	18, 22	14.66	20
12	C-5510	Kivingoni	31	19, 25	12.70	55
13	C-5511	Barabarani	19	8, 16	2.45	22
14	C-5512	Nganja	22	13, 22	11.23	55
15	C-5513	Muhaka Mtambwe	43	6, 27	23.70	55
16	C-5514	Muhaka Primary School	40	10, 28	24.5	35
17	C-5515	Kingwende Primary School	31	18, 22	15.4	110
18	C-5516	Muhaka Misangatifu	38	30	23.5	30
19	C-5550	Muhaka Zengwa	34	27, 34	25.30	Abandoned
20	C-5551	Msambweni Camp	25	18	13.36	330
21	C-5552	Mwagundu No. 2	25	18	15	220
22	C-5553	Mabatani	27	22	15	44
23	C-5554	Milalani No. 4	28	9, 24	15	132
24	C-5555	Vingujini Primary School	25	10, 23	10	110
25	C-5556	Mwachande No. 1	21	15, 21	8.70	26
26	C-5557	Mwachande Pr. School No. 2	18	14	8.87	25
27	C-5558	Mafisini Pr. School No. 1	27	20, 25	13.8	8
28	C-5763	Mafisini, Kibanoi	15	6, 15	3	Little Water
29	C-5764	Mafisini Mtituni No. 1	28	18, 22	13	5
30	C-5765	Kigombero No. 1	53	48, 52	45	20
31	C-5766	Kigombero No. 2	47	40	30.9	50
32	C-5767	Kidzumbani No. 2	25	6-8, 15-18	4.0	28
33	C-5768	Kigombero No. 3	37	28	24.5	12
34	C-5769	Gazi No. 1	14.6	12-14	9.43	130
35	C-5770	Gazi No. 2	17	12-14	9.38	104.3
36	C-5771	Gazi No. 3	12	9-10	9.22	100
37	C-5772	Kivuleni	34	27	17.8	10
38	C-5559	Mafisini Mtituni No. 2	33	14, 22, 31	11.20	6
39	C-5903	Kidzuru No. 3	28	18, 22	12.4	40
40	C-5904	Ganja La Simba (Kibarani)	30	25	23.3	60

Appendix 4 (cont'd)

Well No.	Borehole Number	Name of Borehole & Locality	Total Depth	Water Struck	Water Rest Level	Yield (LPM)
41	C-5905	Mwabungo (Kiuzini)	30	23	.6	18
42	C-5906	Mwabungo (Mwembeni)	28	25	22.1	60
43	C-5907	Ganja La Simba (Gandini)	25	22	21.3	60
44	C-5908	Mwabungo (Mwamura No. 1)	32	26	20.85	73
45	C-5909	Ganja La Simba (Kibarani No. 2)	32	30	28	60
46	C-5910	Mwabungo (Mwamura No. 2)	34	26	21.4	60
47	C-5911	Muhaka Zengwa No. 2	34	27	23	15
48	C-5912	Ganja La Simba (Gandini 2)	33	25	25	60
49	C-6039	Mwabungo (Jadini)	34	24	21.1	50
50	C-6040	Kilole (Mahendo No. 1)	48	32, 42	29.8	25
51	C-6041	Kilole (Mahendo No. 2)	46	34	29	18
52	C-6042	Mwabungo (Kiuzini No. 2)	32	29	22	60
53	C-6043	Mwamanga Pr. School No. 1	30	25	18.2	50
54	C-6044	Mwabungo (Kiuzini No. 3)	32	24	19	16
55	C-6045	Mwamanga Mwololo No. 2	32	23, 27	18.5	48
56	C-6046	Mwamanga Kibaoni No. 3	31	20	14	20
57	C-6047	Mwamanga Kienyere Farm	42	32, 40	29.5	60
58	C-6048	Shamu Primary School	30	19	14.2	9
59	C-6075	Mwamanga No. 4	33	26	18	65
60	C-6076	Shamu Jambo No. 1	34	22, 30	16.2	50
61	C-6077	Shamu Jambo No. 2	32	16, 26	11.4	66
62	C-6078	Mbuani Shamu	32	22	13	Little Water
63	C-6079	Ukunda-Magutu	36	28	23.5	54
64	C-6278	Mabokoni Primary School	29	11, 24	9.0	54
65	C-6279	Mabokoni	27	11, 21	6.22	22.1
66	C-6280	Mabokoni Ndaluni	31	19, 29	13.2	12
67	C-6281	Mbuani Primary School	31	9, 24	16	50
68	C-6282	Muhaka-Kigaleni	31	17, 24	8.5	20
69	C-6283	Mbuani-Petuko	45	15, 40, 44	29	50
70	C-6284	Mbuani-Kirore	33	20, 38	13	12
71	C-6285	Mbuani-Dugumura	36	28-30	18	18
72	C-6286	Mbuani-Hills Park	40	34	23	48
73	C-6297	Tsimba	102	-	-	Dry
74	C-6339	Diani Settlement Scheme No. 1	26	25	23	66
75	C-6340	Makongeni-Kinondo	10	5	4.5	60
76	C-6341	Mwambungo-Biga	10.5	7, 9	5.90	66
77	C-6342	Kinondo No. 1	16	12	11.60	94
78	C-6343	Kinondo No. 2	16.2	11, 15	14.2	60
79	C-6344	Msambweni Hospital No. 1	15	11	5.75	5

Appendix 4 (cont'd)

Well No.	Borehole Number	Name of Borehole & Locality	Total Depth	Water Struck	Water Rest Level	Yield (LPM)
80	C-6345	Kinondo No. 3	7	5	3.8	66
81	C-6358	Tiwi No. 4	66.70	31, 54	30	88
82	C-6490	Mazola No. 1	10	7	2	Not Tested
83	C-6497	Mazola No. 2	82	30, 70	19.2	88
84	C-6499	Kwale	140	56-58 74-128	14.7	16
85	C-6488	Kinango	49	6	5.21	48
86	C-6489	Rima	42	6	2.65	24
87	C-6500	Bush No. 2	10			
88	C-6505	Mwakijembe	32	26, 45, 74	23.60	
89	C-6589	Msambweni Hospital No. 2	22	17	10.22	60
90	C-6590	Makongeni No. 2	16	11	5.35	40
91	C-6591	Golden Beach Diani	21	10, 14	8.35	67
92	C-6592	Diani Settlement No. 2	27	24	21.40	75
93	C-6593	Ukunda Settlement No. 1	25	17	13.90	50
94	C-6594	Diani Settlement No. 3	18	15	13.50	60
95	C-6595	Barabarani No. 2	14.4	12	2.60	15
96	C-6596	Msambweni Police Station	29	23	15.35	50
97	C-6597	Bomani	25	17, 20	10.50	10
98	C-6598	Kanana Parish	24	15, 20	7.60	5
99	C-6666	Mwachande No. 2	70		20	53
100	C-6667	Tswaka-Kidimu	18	10-11	8.12	50
101	C-6668	Mlachake-Majoreni	13.2	8	4.9	8
102	C-6669	Kivuleni-Mwachande	18	14	7.30	9
103	C-6670	Kibarani-Kikoneni Town	57			
104	C-6671	Kikoneni Hospital	57	18, 34	13.25	73
105	C-6672	Mwazangumbe-Majoreni	22.80	13, 17	9.53	10
106	C-6673					
107	C-6674					
108	C-6675					
109	C-6715	Kivuleni Waza	28	26	11.20	18
110	C-6716	Zakalanguni-Majoreni	26	18	14.23	30
111	C-6717	Kivuleni Waza No. 2	52.5	37, 50	26	5
112	C-6718	Magawani-Majoreni	27	19, 27	14.25	60
113	C-6719	Mrima Primary School No. 1	27	20, 26	9	8
114	C-6720	Mrima Ndooni No. 2	32	19, 26	12.34	40
115	C-6721	Kivuleni No. 1	40	17, 24	8	53
116	C-6722	Mombasa Showground No. 1	23	16, 23	12	70
117	C-6723	Mrima Market No. 3	40	26, 30	17.20	41
118	C-6724	Kivuleni No. 2	52	25, 32	18.02	20
119	C-6725	Mombasa Showground No. 2	18	14	10.20	60

Appendix 4 (cont'd)

Well No.	Borehole Number	Name of Borehole & Locality	Total Depth	Water Struck	Water Rest Level	Yield (LPM)
120	C-6726	Mrima-Bumbuni	18	17	5.40	20
121	C-6727	Mombasa Showground No. 3	18	17	12.75	80
122	C-6728	Mrima Marenge No. 1	27	18, 24	8.33	43
123	C-6729	Mrima Marenge No. 2	Drilling not completed at time of data collection			
124	C-6730	Mrima Ndooni No. 2	"	"	"	"
125	C-6731	Kombani-Waa Location	"	"	"	"
126	C-6732	Mafisii Dispensary	"	"	"	"
127	C-6733	Mrima Marenje No. 3	"	"	"	"

Appendix 5: Sieving for artificial gravel pack (top) and installation Of pump in Tiwi borehole c4570