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Report on a visit to assess Groundwater Potential of the Kenya Coast south of Malindi.

by

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Including Proposals for the *South Coast Groundwater Resources Project.*

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1. INTRODUCTION

This report is a summary of the findings and recommendations arising from a study of groundwater resources potential on the Kenya Coast carried out between September and November 1980. My visit to Kenya was arranged between the Institute of Geological Sciences (IGS) Wallingford, and the Mines and Geology Department of the Kenya Ministry of Natural Resources. The Mines and Geology Department are currently re-mapping the geology of the Kilifi and Mombasa 1 : 250,000 sheet areas on the coast, with British Technical Cooperation sponsored by the British Overseas Development Administration (ODA).

On my arrival in Kenya it was agreed that I would have to operate jointly with the Geological Survey and the Groundwater Division of the Ministry of Water Development (MOWD) who keep all drilling and groundwater records and who provided two counterparts, a geologist and a groundwater inspector, for the duration of the study.

Approximately one month was spent at the MOWD office in Nairobi and the rest of the time was spent at the Coast Province Water Branch in Mombasa and carrying out field visits.

2. ACKNOWLEDGEMENTS

I would like to record my appreciation of the assistance provided by Mr J Wachira, Chief Geologist, Mines and Geological Department; Dr R Cannon, Team Leader, Kenya Coast Mapping Project, and his team; Mr D M Kirori, Director, Water Resources Department, Ministry of Water Development; Mr K P Bhalla, Chief Geologist, Ministry of Water Development; Mr O S Cege, General Manager, and Messrs. Dugdale and Tomkins of the Coast Province Water Branch, Mombasa; Mr Eliud Mwai, superintending geologist, MOWD; Mr P M Mwai and Mr E G Githiora who were willing counterparts in all aspects of the work, Messrs. Majanga and Muthami, geologists MOWD and CPWB, Mr P Winani, laterly chief economic geologist, Mines and Geology Department. Canadians, Gedde, Burgener and Hanningan, Mines and Geology Department, the staff of the mineral processing laboratory Mines and Geology Department, Messrs. Salamonson and Melhuis of Planning Section, Coast Province, MOWD; Mr B G Little, engineering adviser, Development Division ODA and Mr C Widgery and Mrs H J Lucy of the Aid Section of the British High Commission in Nairobi.

3. AREA STUDIED

Initially whilst my terms of reference were rather general, it had been intended that I should concentrate on the re-mapped Karroo rock outcrop of the 1 : 250,000 Kilifi Sheet (12,000 km^2). subsequently the younger rocks close to the coast were included because they were found to have much greater groundwater potential. The study therefore placed emphasis on the post-Karroo sediments which were studied in the area between the Galana (Sabaki) River and the Ramisi River (Figure 1). The total area studied was about 10,000 km^2. The area close to the Tanzania border and north of Sabaki, including the Tana River basin and the Lamu area was not studied. Much of the groundwater information in the younger rocks comes from extensive drilling in the Tiwi area south of Mombasa and this area was looked at in greater detail.

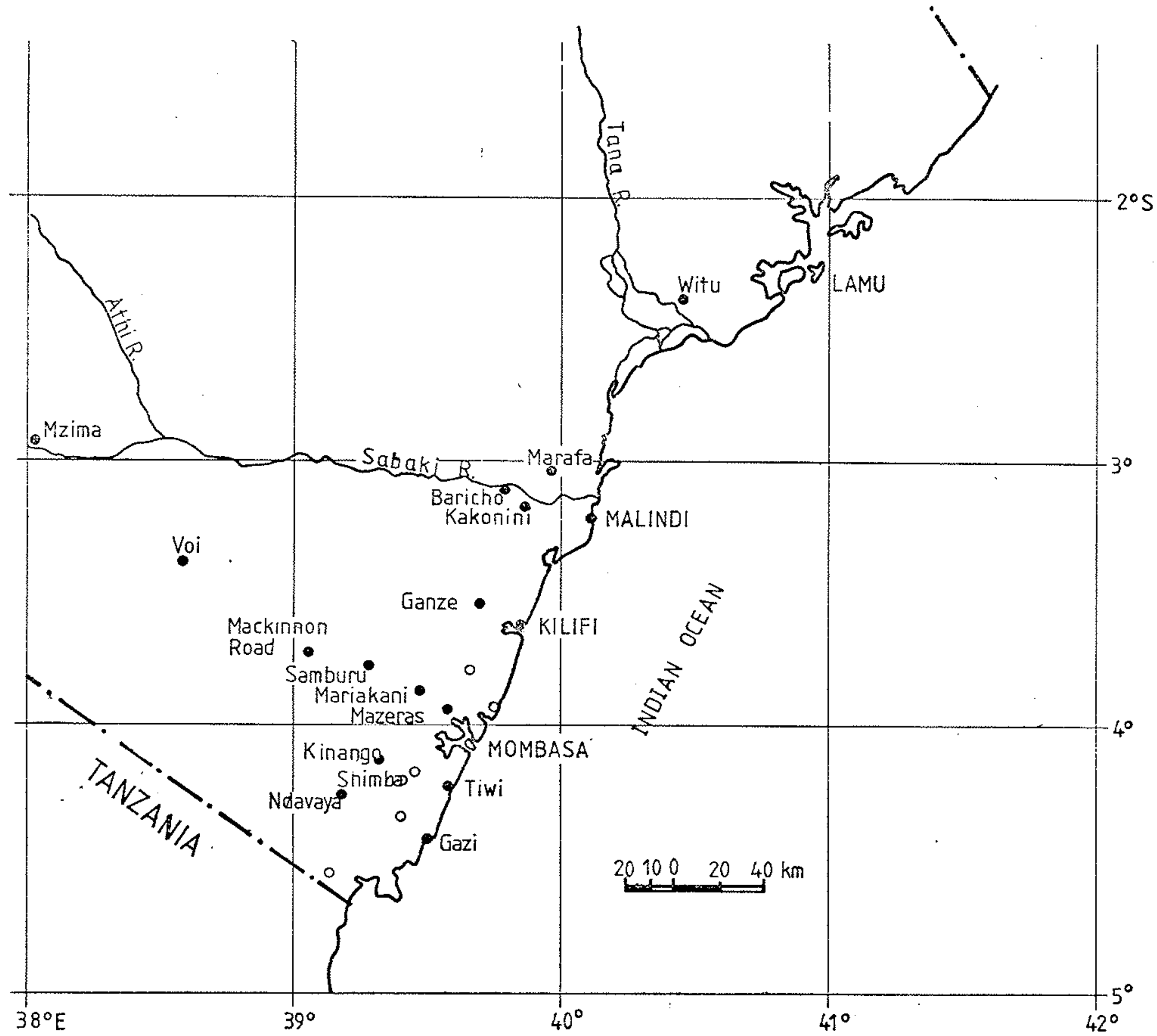

FIGURE 1 Map showing the Kenya Coast south of Malindi.

3.1 Climate.

The climate of Mombasa is warm and humid with a mean maximum temperature of 30°C and a mean minimum of 23°C. January, February and March are the warmest months but mean maximum temperatures do not exceed 33°C. Maximum humidity (0300 hrs measurement) averages 93% for the year and minimum humidity (1200 hrs) averages 69% with the highest overall humidity recorded in April, May and June which are the months of highest rainfall.

Mean annual rainfall recorded at Mombasa Town Meteorological Station (15 year period) is 1211 mm,* 53% of which falls in April, May and June (long rains) and about 15% in October and November (short rains, Figure 2). Rainfall decreases inland in zones parallel to the coast which coincide generally with physiographic regions. Maximum rainfall (1200 mm/yr) is recorded on the *Coastal Plain*, about 1000 mm is recorded at Mazeras on the *Foot Plateau* and 600 mm is recorded at Samburu on the *Nyika Platform* (locations are shown in Figure 1).

3.2 Physiographic Regions.

Coastal Kenya is conveniently divided into physiographic regions which have some basis in geological units. Three distinct physiographic units can be recognised from the Coast, extending inland. A flat *Coastal Plain* with an elevation of about 30 m above mean sea level extends from the coastline some 4 km inland. It comprises the Pleistocene reef complex and associated lagoonal sediments and windblown sands. Its western margin forms the eastern boundary of the *Foot Plateau* a zone of higher elevation 60-135 m above mean sea level and comprising Magarini Formation and further inland Jurassic shales. Further inland beyond the Mazeras/Middle Jurassic boundary fault extends the *Nyika Platform* an undulating surface formed by the Karroo and the basement rocks at about 180-300 m above mean sea level. On the south coast (i.e. south of Mombasa) a fourth unit, a *Coastal Range* formed by the Shimba Hills (from 150-420 m) is present between the *Foot Plateau* and the *Inland Platform*. The variation in rainfall within these regions is given in Table 1, and the monthly distribution of rainfall is shown in Figure 2.

4. PREVIOUS WORK

Four reports relating to groundwater resources in the study area were available. These included:

(i) The Underground Water Resources of Kenya Colony by Sikes, 1934.

(ii) Report of the Malindi-Ganda Groundwater Investigation by Bestow, 1958, Hydraulics Branch, Ministry of Works.

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* Climatological data from *Climatological Statistics for East Africa* issued by the East African Meteorological Department, Nairobi 1975.

PHYSIOGRAPHIC REGION	RAINFALL STATION	MEAN ANNUAL RAINFALL (mm)	YEARS OF RECORD
The Coastal Plain	Vanga	1120	31
	Gazi	1375	31
	Tiwi	1290	20
	Mombasa (Town Observatory)	1175	76
	Kilifi	941	44
	Malindi	1043	80
	Gede	1044	36
The Foot Plateau	Kakoneni	798	40
	Marafa	858	41
	Baricho	735	15
	Jilori	884	24
	Magarini	958	16
The Coastal Range	Kwale	1079	
	Shimba Development Scheme	1270	
	Mazeras	952	14
The Nyika Platform	Samburu	598	
	Bamba	625	30
	Mariakani	865	30
	Kinango	823	
	Ndavaya	759	
	Mackinnon Road	714	43
	Shakama	596	19

TABLE 1. Mean Annual Rainfall, selected stations, Kenya Coast.
(locations are shown in Figure 1).

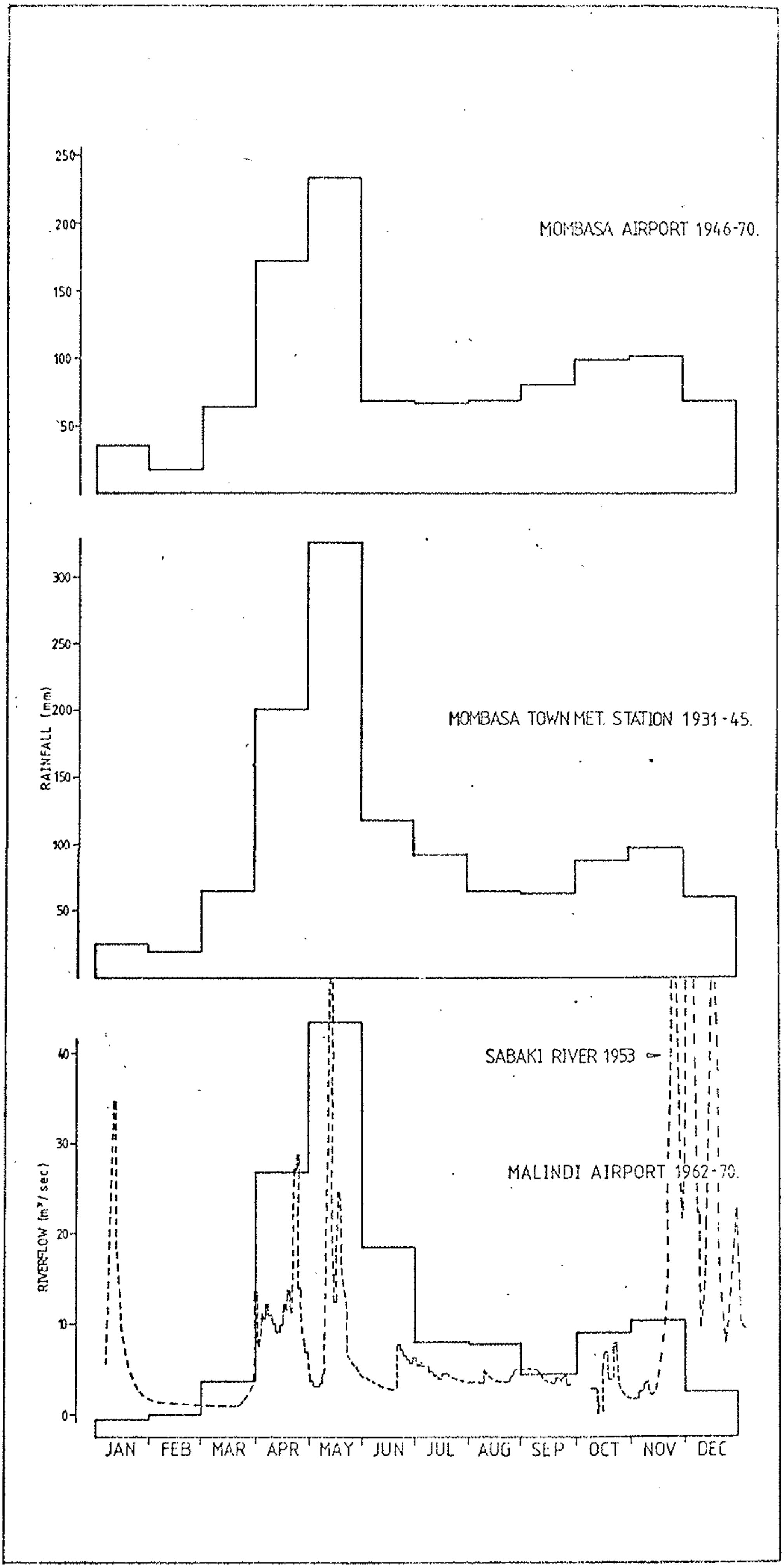

FIGURE 2 Monthly mean rainfall, selected stations, Kenya Coast.

(iii) The Hinterland of Kwale District and its Water Resources, a review by G A Classen MBE, 1974.

(iv) MOWD Malindi Pipeline. Report on Preliminary Hydrogeological Investigation, January 1980. Wellfield Consulting Services (Pty) Ltd.

In addition there are many geological reports relating to the Cainozoic rocks (Eocene-Holocene) of the coast, including Maufe (1908), Gregory (1921), Krenkel (1924), Parsons (1928), McKinnon Wood (1930), Busk and de Verteuil (1938), Busk (1939), Miller (1952), Caswell (1953, 1956), Thompson (1956), Williams (1962) and more recently reports by Cannon for the Mines and Geology Department.

Several of these reports contain some mention of groundwater and the Geological Report Series section on water-supply usually emphasises the better yields and better quality supplies obtained from the Mazeras Sandstone than from the older Karroo units, and the poor quality and poor yields of the Jurassic rocks, and the 'very variable' supplies from Cainozoic rocks which are of better quality than those from the older Karroo rocks.

A lot of information has been obtained from drilling records kept by the MOWD, some of which are included in Appendix 1. Progress Reports of the Australian-aided (ADAB) Magarini Lands Settlement Project, just north of the Sabaki River also give groundwater information of some relevance to the coastal sediments.

There is sufficient information from drilling and geophysical studies in some areas, e.g. Tiwi area (Figure 1) for the hydrogeology of the coastal strip to be well understood.

5. MINISTRY OF WATER DEVELOPMENT

5.1 Organisation of Groundwater Studies.

The Ministry of Water Development (MOWD) was established in November 1974 as the Government agency responsible for water supplies. Prior to that responsibility for water supplies, drilling, etc. came at different times under the Ministry of Works, the Ministry of Natural Resources and the Ministry of Agriculture.

The MOWD is presently the only Government agency with technical expertise in water affairs and in recent years its activities have increased dramatically as a result of the high priority given to water supplies and the intention to provide a clean water supply to each household by the year 2000.

The MOWD has 2 main Departments. The Engineering Department which attends to civil engineering aspects of water supply including design and planning, and the Water Resources Department which attends to study of the natural processes of the hydrological cycle.

The Water Resources Department has 3 divisions: Surface Water Division, Pollution Control Division and Groundwater Division.

Groundwater Division was only formed in 1979-80, by the joining of drilling section and geology section. Both sections are administered by the chief geologist.

5.2 Geology Section.

There are 10 graduate geologists in Geology Section and much of their routine work is to make recommendations for the siting of boreholes. This is done using previous drilling records from adjacent areas and by surface geophysical measurements at potential drilling sites, usually electrical resistivity measurements. There are 10 groundwater inspectors to assist in this work. They are technical assistants, normally school leavers who have attended the MOWD Training School for three years. Geology Section is expected to locate and recommend suitable sites for drilling based on their studies.

The equipment presently used for the resistivity measurements is AC-equipment (ABEM Terrameters) and the interpretation procedure adopted is not standard practice. (Type curves are not used and the method reduces all measurements to a 2-layer model regardless of the real number of layers involved). Several of the interpretations may therefore be suspect, and there is no trained geophysicist attached to Geology Section to advise on appropriate field procedures or interpretation methods.

5.3 Electrical Resistivity Measurements.

Electrical resistivity measurement to locate groundwater is the most widely used and probably the most over-rated method in hydrogeophysics. In electrical sounding four electrodes are placed in the ground and electrical current, usually DC, is introduced into the earth via two other electrodes A and B and the potential difference developed is measured between the two inner electrodes M and N. In the Schlumberger array the two outer current electrodes are moves successively further apart (at logarithmic intervals) causing a deeper penetration of current flow and progressively greater depth of investigation. This depth of investigation depends upon the electrode separation and the geo-electrical layering present and in practice it usually varies between AB/4 and AB/12, so that the depth of investigation of typical measurements AB = 120 m is 10-30 m.

For interpretation the apparent resistivity value at each current electrode separation is calculated and plotted on vertical axis against half the current electrode separation (AB/2) on log-log paper of standard size to give a sounding curve. The curve is then compared with standard curves published for combinations of layer thicknesses and resistivities. If the curve can be matched to one of the published curves the geo-electric section can be calculated. In practice there is rarely a unique solution and the field curve may match several similar type curves representing different combinations of layer thickness and resistivity so that several interpretations are possible.

The resistivity of a particular rock varies widely depending upon the mineral constituents present, the amount of water present, the salinity of this water and its distribution. Dense dry rocks have very high resistivities and saturated rock has lower resistivity than unsaturated rock. Resistivity is also related to porosity; high porosity saturated rocks have lower resistivities than lower porosity rocks because of the high proportion of fluid, but the presence of clay minerals can have a similar effect so that interpretation of the resistivity values in terms of rock type or saturation is never unambiguous. For these reasons considerable experience and skill is required to interpret sounding curves correctly. This equivalence of solutions is a major limitation of the method which can sometimes be resolved when other data, such as drilling results or downhole resistivity measurements, from logging, are available, but this is often not appreciated in routine application, nor generally available.

A further limitation is suppression. Suppression occurs when layers with resistivities intermediate between adjacent beds are present. Unless these layers have a thickness of at least 10% (i.e. the thickness is at least 1/10 the depth of burial) they have little effect upon the field curve obtained.

Some field curves do not match the published curves completely and in such cases partial curve matching to 2 or 3-layer curves with auxilliary diagrams may be necessary. The interpretation can also be checked by computing the theoretical curves of a range of geo-electric sections to compare with the field curve obtained.

Thus in summary the resistivity method is open to several interpretations and supporting information is often needed to identify lithology or water saturation. The method should not therefore be relied upon to give unequivocal information of subsurface conditions at a drilling site. Much information of value will be obtained if the resistivity interpretation of the drilling sites is compared with the results of subsequent drilling or downhole logging so that the general validity of the method can be assessed.

The determination of the depth to the water table, which can be expected to appear as a conductive layer on a sounding curve, is often impossible especially where the water table is overlain and underlain by several layers of different resistivities.

Much of the resistivity work in Kenya is likely to have restricted depth of penetration due to limitation of the equipment and deep water levels so that saturated rock is probably not reached in many soundings. Calculation of the geo-electric section using the Schlumberger type curves, and comparison with depth-to-water maps and measurements will give an indication where this is so.

5.4 Drilling Section.

There are five geologists attached to drilling section and their activities include preparation of borehole designs and documents tendering for borehole construction. They supervise drilling and pump testing and prepare completion records on drilling carried out. There are 11 drilling inspectors and in the last 12 months 112 boreholes have been drilled (66% by Private Drilling Contractor) so that a high proportion has been unsupervised. Drilling records cannot therefore be fully checked or completely understood so that some information may be incorrect.

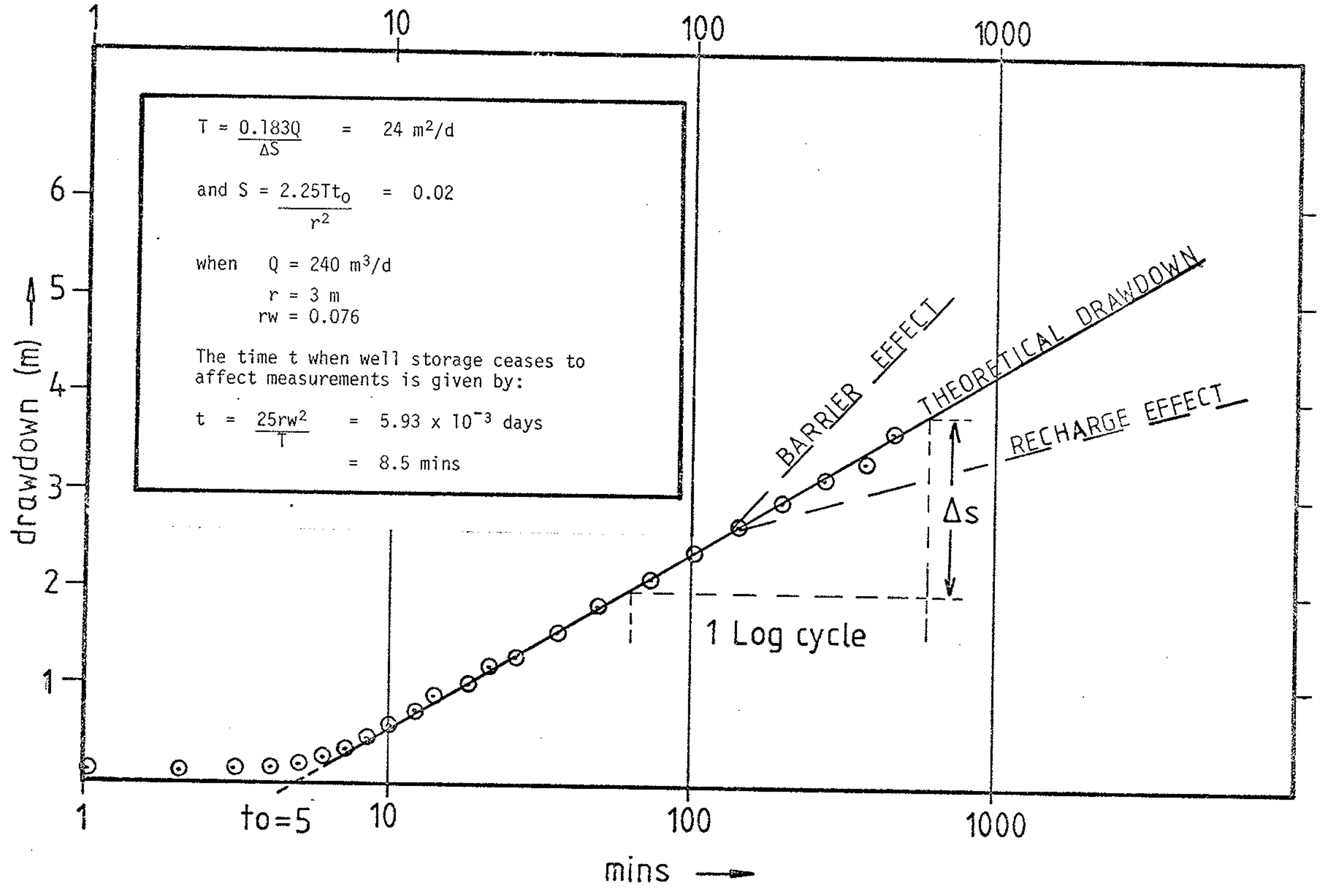

FIGURE 3 Time-drawdown plot, pumping test measurements.

5.5 Pump Testing.

Drilling section maintain 2 pump testing units. These are modified percussion rigs, equipped with generator and equipment for lowering 4 or 6 inch electric submersible pumps. The pump testing crew perform yield tests on recent drillings usually for 24 hours (drawdown) and 8 hours recovery. Discharge rate is measured by flowmeter and water levels are measured by electric sounder. Electrical conductivity and temperature is also measured and water samples are collected for analyses. The crew are well experienced and take good measurements.

Test analysis on the other hand is virtually non-existent. The test performed serves as a well yield test and the pumping rate at the end of the test is usually considered to be the well yield (if the water level has not reached pump suction). Test measurements are not plotted (log time versus drawdown) to see if water levels are approaching equilibrium or still falling after 24 hours (Figure 3).

The majority of the yield tests are carried out by Private Contractors who are required to complete standard pump test forms taking regular measurements of water level and discharge rate for 24 hours pumping and 8 hours recovery. Many of the returns show that these measurements are not made accurately if at all or are just impossible. Discharge rate is often incorrectly measured, fluctuates widely or is reported in incorrect units. There are several examples of incorrect or inadequate measurements which given no analysis has led to installation of production pumps in boreholes only to find that the borehole has no useful capacity.

If the measurements that are collected are plotted such inadequacies will be apparent. A simple log time versus drawdown plot or residual drawdown plot as shown in Figure 3 would be sufficient. Analysis by the Jacob drawdown or Theis recovery method (Kruseman and de Ridder, 1970) shown in Figure 3, is straightforward and the shape of the time-drawdown graph will indicate the presence of boundaries or other aquifer heterogeneity. The frequency of measurements during pump testing should be such that the points fit conveniently on a logarithmic scale. A suggested frequency of observation is given below:

1 - 10 minutes	-	every minute
10 - 20 minutes	-	every 2 minutes
20 - 60 minutes	-	every 5 minutes
60 - 120 minutes	-	every 10 minutes
120 +	-	10 readings per log cycle

A test duration of 24 hours may be sufficient in some cases but in some aquifers, especially unconfined aquifers, it may be inadequate to obtain precise values of T and S.

A simple test where the borehole is pumped at different rates for short periods as in a step test could be used to obtain well efficiency. If the step test results are presented as Q-s curves, as in Figure 4, they may indicate that specific capacity is not a constant but can change with pumping rate.

The results of yield tests should therefore take this into account. A guide to step-drawdown testing and methods of analysis is given by Clark (1977).

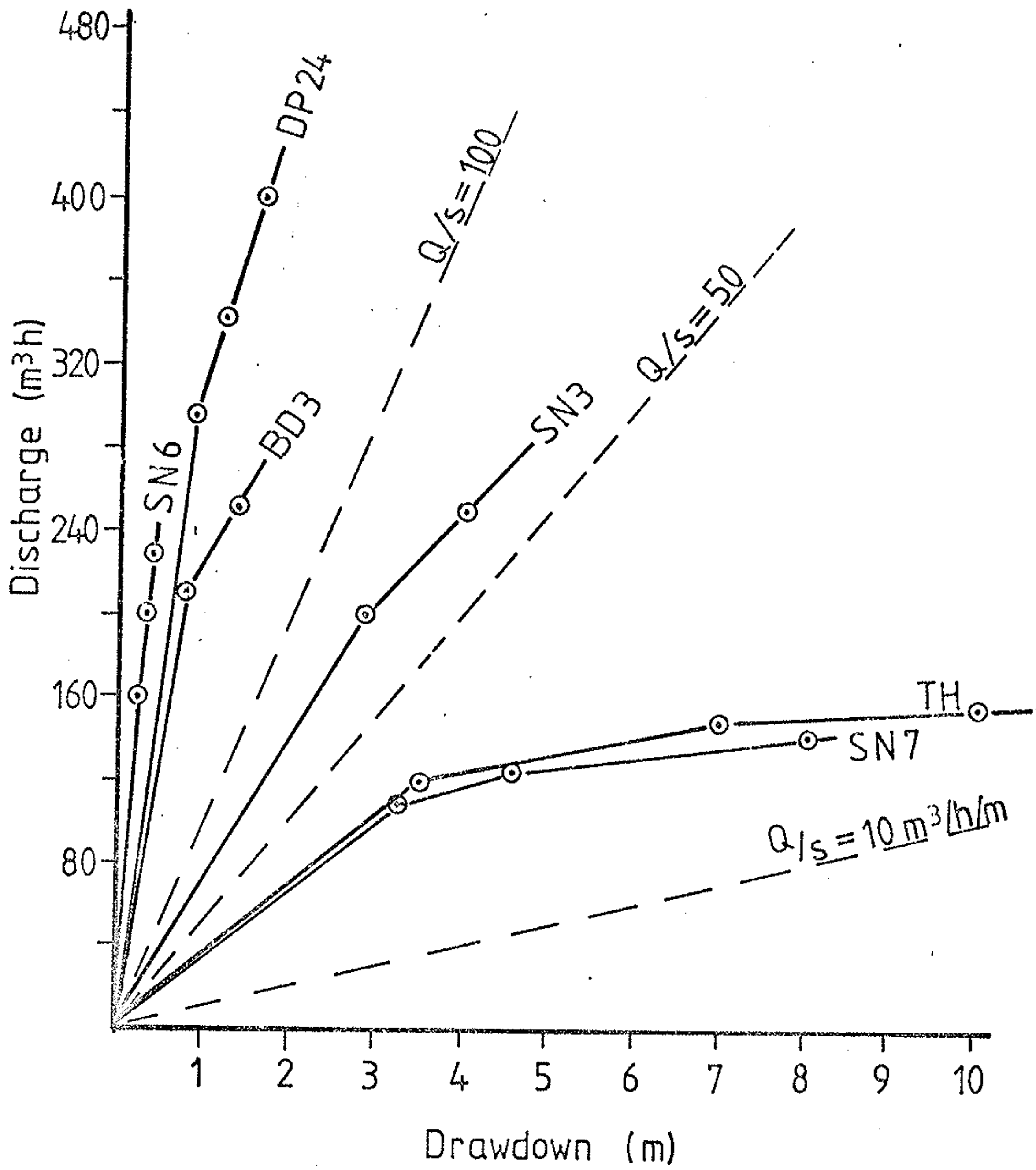

FIGURE 4 Q-s Curves from step drawdown tests.

It is recommended that recovery measurements should be continued for at least the duration of the pumping period and preferably longer if analysis of the recovery is to be carried out. Water level recorders can be used for convenience to record the recovery after removal of the pump.

Results of pumping tests in the Karroo and Cainozoic rocks of the Coast for which measurements are available are given in a later section.

5.6 Borehole Logging.

Geophysical borehole logging is carried out to obtain measurements from a drilled borehole which may be interpreted in terms of lithology, water content, water salinity and rock type. In favourable circumstances the results allow a correlation of the drilled sections between drillings so that the knowledge of the sub-surface rock units can be projected to other areas without drilling which can be an economic benefit.

As a routine natural gamma and electrical resistivity measurements are made to identify the formations present but there are other methods which produce useful information relating to borehole construction and the position of water inflow into the borehole.

The MOWD have the following geophysical logging equipment:

(i) WIDCO 1200 (American) with point resistance (PR), spontaneous potential (SP) and natural gamma.

(ii) HYDROLOGGER (British) with PR, SP, gamma, short and long normal resistivity and caliper (CAL).

The HYDROLOGGER is a British-made logging system manufactured by Wuidart Engineering. It was sent to Kenya in March 1978 where it remained unused because nobody knew how to use it, there being no trained geophysicist in the Groundwater Section. Similarly the WIDCO instrument was not used because nobody knew how to operate it, although it had been used by the Australian hydrogeologist of the Magarini Project.

I arranged for the HYDROLOGGER to be installed in a LandRover and to demonstrate its use. In the event most of the logging functions failed to work satisfactorily and it fell apart when transported to boreholes on the coast so that the Kenyans were left with an impression of poor workmanship, bad design and a feeling that the equipment was unfieldworthy*.

At present the MOWD have no experience in borehole logging yet there is a very strong requirement for it. Most of the MOWD drilling is carried out by Private Drilling Contractor and borehole logging is required as a check on construction as well as providing the additional information to guide well design and permit a correlation between the drilled sections.

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* A separate report detailing the use of the HYDROLOGGER in the field and the condition of the equipment is included in Appendix 2.

None of the boreholes on the Coast have been logged and with exception of boreholes drilled by the ADAB Magarini Project it is almost true to say that none of the boreholes in Kenya, of which there are several thousand, have been geophysically logged. This information is required if the Water Resources Department are to move from well site studies to more fundamental hydrogeological studies and groundwater resources assessment. An advisory visit by a well logging expert would therefore be useful.

5.7 General Comments.

The analysis of the resistivity measurements can be greatly improved if standard interpretation techniques are adopted and the services of a surface geophysicist are available to advise on appropriate geophysical methods and methods of analysis to use.

There is a need for a thorough assessment of drilling records to ensure that their details are correct. There is also a more general requirement for a systematic appraisal/assessment of the drilling results in terms of hydrogeology so that Groundwater Regions can be defined and the hydrogeology better understood. Several African countries produce hydrogeological maps where such data is summarised.

Pumping tests conducted by drilling contractors should be supervised to ensure that information given is reliable. Preferably tests should be run by the MOWD pump test unit.

The quality of the yield test measurements should be checked by plotting the data and this should be carried out by the geologists and simple analysis to obtain transmissivity should be carried out as a routine. By plotting the data it will be apparent if tests need to be conducted for periods longer than 24 hours to obtain a yield and given a transmissivity it will be possible to calculate drawdown for any period or rate of pumping which can be required for production purposes and design.

There is within the Geology Section too much emphasis and reliance placed on the resistivity method as a means of locating suitable drilling sites. More attention should be directed towards analysis of pump test and drilling results and the review of existing data for particular areas which will be necessary if the hydrogeological activities are to move from wellsite studies to groundwater resource studies.

At present the Groundwater Section has neither the manpower nor the technical expertise to carry out groundwater resources studies. The MOWD plan to establish a Resources Research Section soon to carry out more fundamental hydrogeological studies, whose activities ought to go some way towards this objective but the staff of this new Section will be drawn from the other Sections where there is only an introductory knowledge of hydrogeology. There is therefore a need for a hydrogeological adviser to give advice on modern hydrogeological techniques and, say, to head-up and organise the activities of the proposed Resources Research Section.

To some extent these requirements will be met by the groundwater resources projects soon to commence with Dutch co-operation* which would appear to involve the majority of the Geology Section over the next three years, and which have significant training components, but further discussion with the MOWD about their general requirements might be desirable.

6. GEOLOGY

A simplified geological map of the study area is given in Figure 5 and Figure 6. The area north of Mombasa (Kilifi sheet 1 : 250,000) has recently been re-mapped at 1 : 50,000 scale by the Mines and Geology Department with British technical cooperation using a new stratigraphic nomenclature, and Figure 5 is a simplified map based on this work. The re-mapping of the south coast geology has only just started and the south coast geological map (Figure 6) is therefore based on the recent Austromineral study (1980) which uses a slightly different stratigraphic classification.

Figure 5 and 6 show the outcrop of the Karroo and younger rocks has a north-north-easterly strike generally parallel to the coastline and a simple seaward dip so that the younger rocks are closer to the coast. In detail the geology is quite complex with extensive faulting of the Karroo rocks and a wide variety of deposits close to the coast, several of which have been reworked by coastal processes at different times.

6.1 Karroo Rocks.

The Karroo rocks (Caroniferous-Jurassic) in Kenya occur within fault-bounded sedimentary troughs which are part of a much larger depositional basin 600-700 km wide and extending NNE-NE from northern Kenya some 1600 km to Lake Malawi. The orientation of this basin is roughly parallel to the main structural trend of the underlying basement which is the Mozambique Belt metamorphic complex. The Karroo outcrop in Kenya is about 20,000 km^2 and the rocks comprise sandstones, arkoses, grits, shales and siltstones with a complex history.

The earliest Karroo rocks in Kenya are Taru Formation arkoses - high energy feldspar-rich sediments which are river derived from the basement (the lower layers have incorporated gneiss and pegmatite fragments) and it appears that they are the products of erosion and rapid deposition from fault scarps.

Three Taru Formation members are recognised. The Middle Taru was examined at Samburu where it consists of sandstones, arkoses, conglomeratic lenses and grits with shales and siltstones. Intergranular permeability was extremely low and groundwater storage would be restricted to bedding planes, jointing and the interfaces between layers of different lithologies. A shale separates the Middle and Upper Taru. The Upper Taru is also arkositic and conglomeratic which suggests re-activation of the basement. There is a gradation from the Taru Formation to the overlying Maji ya Chumvi Formation.

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* Ndeiya-Karai Project
Elgeyo-Marakwet and West Pokot Project.

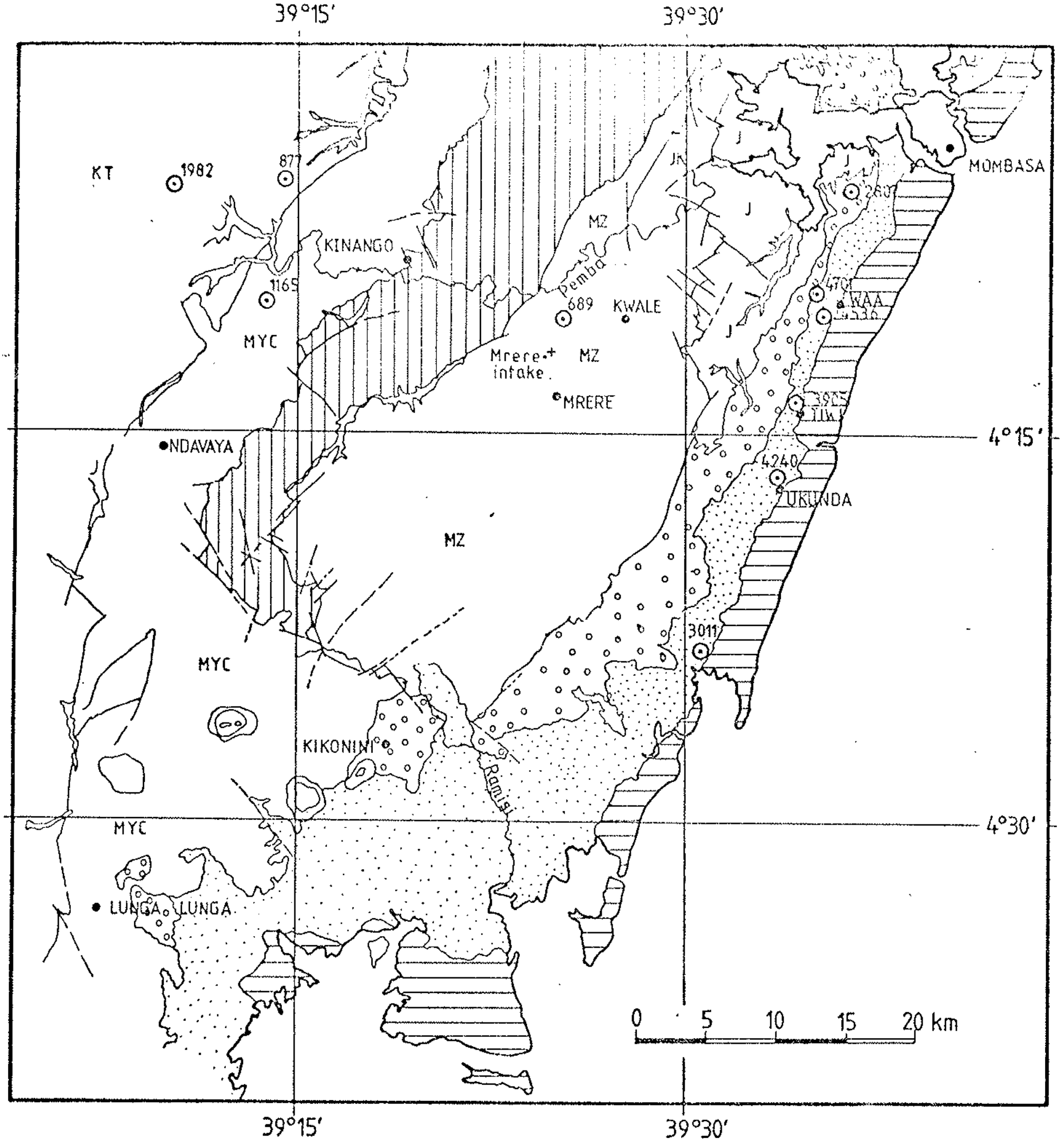

FIGURE 6 Geological map of study area, south of Mombasa.

The Maji ya Chumvi Formation (MyC) is predominantly shale and siltstone with subordinate sandstones which become more important upwards. Three members are recognised in which there is a general coarsening of grain-size upwards. The lithology indicates a quite low energy depositional environment and the presence of shallow water structures (mud cracks, ripple marks, worm tracks, parting lineations) suggest it is likely that these sediments represent deltaic deposition in inland lakes. Ground-water in this formation is saline (Maji ya Chumvi in Swahili = salt water), and it is interesting to note that at Mandava, in Tanzania, there are at least 2000 m of evaporites in the equivalent Karroo rocks.

An important marker bed separates the siltstones and shales of the Lower MyC and the similar siltstones and shales of the Middle MyC (probably indistinguishable otherwise) and is a horizon containing ironstone concretions containing fossil fish*. The fish appears to be of marine type thus indicating a marine incursion which was probably triggered by faulting, but it could perhaps be one that could tolerate saline conditions in a closed basin without access to the sea.

A distinctive hard blue-grey sandstone (referred to as siliceous sandstone by Miller (1952) is present in the Middle MyC which, whilst having no groundwater potential whatsoever, might be recognised in some drilling descriptions.

The Upper Maji ya Chumvi Formation is sandstone, usually flaggy and containing abundant shallow water features (rippling, parting lineations etc.) which again indicate continued deltaic conditions.

After deposition of the Upper MyC flaggy sandstones an important change occurred because the rest of the Karroo sequence consists of current-bedded sandstones and cyclic sedimentation (siltstone/shale/sandstone) patterns. A major period of uplift and faulting is likely to have initiated this sedimentation because the sediments are coarser and contain more abundant feldspar and mica.

The Mariakani Sandstone Formation overlying the MyC consists of medium-grained arkoses and massive gritty sandstones and is distinguished in Figure 6 and 7 by the vertical ornament. Three members are recognised. The Lower Mariakani is a distinctive mottled green and red cross-bedded sandstone, the only Karroo rock which displays mottling. The Middle Mariakani and Upper Mariakani are buff sandstones with cyclotherm units of siltstone/shale/sandstone at their bases. The Upper Mariakani characteristically forms high land and can be recognised by its rounded weathering at outcrop. There is a general coarsening in grainsize upwards throughout the Formation and continued deltaic deposition is indicated.

The overlying Mazeras Sandstones are white or pale sandstones weathering to orange or buff and they are more coarse grained and arkositic than the Mariakani Sandstones. Significantly they contain a higher proportion of feldspar and garnet and quartz pebbles and a period of faulting is therefore likely to have initiated the Mazeras sedimentation (in Upper Triassic times). Palaeocurrent data reveal a drainage to the north

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* *Australosomus* of Lower Triassic age.

east. At the base of the Middle Mazeras is a distinct shale/siltstone horizon containing silicified logs.

6.2 Jurassic Rocks.

In Middle Jurassic times a marine transgression overstepped the Karroo rocks and brought littoral and marine limestones and shales onto the continental and deltaic Mazeras Sandstone thus marking an important change in depositional environment.

In many places the Mazeras Sandstone/Middle Jurassic junction is faulted, but at low lying elevations the Middle Jurassic rocks are unconformable on the Mazeras Sandstone. The general absence of Jurassic rocks on the Mazeras outcrop however, except at low lying elevations, has suggested that the Middle Jurassic sea must have lapped against cliffs of Mazeras Sandstone probably close to where the Mazeras fault scarp is today. Later faulting along the cliff line (itself probably a fault line) dropped down the Middle Jurassic rocks so that the junction is now seen to be faulted.*

An important limestone, the Kambe Limestone (fossil content confirms the Middle Jurassic age) with interbedded shales, represents the base of the Middle Jurassic and the lowest layers of the Kambe Limestone contain fragments of Mazeras Sandstone confirming the sequence and overstep. The Kambe Limestone is not continuous so that the overlying Mtomku Formation (Upper Jurassic shales, sandstones and thin limestones) may rest directly on the Mazeras Sandstone.

The Jurassic shales on the downthrow side of the fault form the 'Foot Plateau' between the Mazeras escarpment and the 'Coastal Plain'. It is a gently sloping region with a distinct dendritic drainage pattern of incised and interlocking valleys; a feature characteristic of Jurassic shale country.

6.3 Cainozoic Rocks.

Overlying and seaward of the Jurassic shales are the younger Cainozoic sediments (Miocene-Holocene). They comprise unconsolidated and semi-consolidated sands, gravels, clays and occasional sandstones and shales derived from the pre-existing rocks further inland. They form a mantle on the Jurassic rocks and become thicker towards the coast where a Pleistocene reef complex is developed forming a conspicuous feature immediately behind the present shoreline. They include sediments of Miocene, Pliocene, Pleistocene and Recent age.

In detail the geology of these sediments is very complex because they have been reworked and redeposited several times, especially during Pleistocene times when there were repeated fluctuations in sea level. As a result fluviatile, deltaic, lagoonal and eolian types of deposition can be recognised and specialist information can be required to identify their ages. Because of the diversity there is incomplete agreement by geologists on their precise identification and nomenclature.

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* This faulting is well documented in Tanzania where vertical displacement of 3-6 km is recorded which clearly indicates a period of major faulting.

The sediments comprising the Cainozoic wedge include the Baratumu and Marafa Formations - a confusing sequence of clays, sandy clays, clayey sands and gravels; Magarini Formation - medium to coarse quartz sands and bright red windblown sands, and a Pleistocene reef complex comprising reef limestone and a quartz sand facies which has significant groundwater potential.

6.3.1 The Baratumu Formation.

The oldest Cainozoic rocks are the Baratumu Formation which is thought to be of Miocene age. The Formation was examined at Baratumu north of Shauri Moyo near Kilifi and at Kipevu on Mombasa island. The Baratumu sediments are generally light-coloured yellow sandy marls, clays, conglomerates, thin limestones and sands that formed in a shallow water beach environment and deposited in a lensing fashion on the Jurassic surface.

6.3.2 The Marafa Formation.*

Thompson (1956) proposed the name Marafa Beds for a thick series of clays, sands, gravels, pebble beds and conglomerates of fluviatile or deltaic origin which occur at Marafa near the Sabaki River.

The Marafa sediments in the Malindi area are fine white to creamy white clays, fine sands and non-calcareous sandy clays. They appear to be derived from the Baratumu Formation and the older rocks and are probably Pliocene-Pleistocene in age. Their fine-grained nature with an implied shallow gradient in a coastal situation suggests a shallow lagoon environment so that the formation of evaporite minerals such as gypsum might be expected within the sediments. Roads constructed on Marafa sediments are sticky during the wet season because of the high proportion of clay.

The Marafa Formation is not recognised by the same lithology south of Malindi. It may be that the sediments are different further south, possibly sandier because of an increased drainage gradient, or they may be absent. In fact Thompson (1956) correlated his Marafa Beds around the Sabaki River with coarse-grained fluviatile quartz sands (probably Lower Magarini Formation) in the Mombasa area.

The Marafa Formation appears to occupy local pockets in the Baratumu Formation and it is not easy to differentiate it from the Baratumu Formation by lithology on drilling logs.

6.3.3 The Magarini Formation.

The Magarini Formation is a much easier Formation to recognise. The name Magarini Sands was proposed by Gregory (1896) to describe the deposits forming brilliant red sandhills behind the Kenya Coast. (He believed then to be Triassic on account of their position and colour but they are probably of Pliocene age).

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* The existing stratigraphic nomenclature of the coastal geology has recently been revised by Cannon and the terms given in this report are the terminology used by Cannon.

The Magarini Formation, like the other Cainozoic sediments, is derived from the pre-existing rocks. Two Members are recognised. The Lower Magarini is especially coarse-grained, comprising mainly unconsolidated buff or creamy white medium to coarse quartz sands, boulder gravels, silty clays and pebbles of feldspar, Mazeras Sandstone pebbles, rounded fragments of silicified wood (from the Middle Mazeras) and rounded pebbles of Basement rocks. These features indicate faulting must have initiated their deposition (as river gravels at the foot of fault scarps) and renewed movement along the Mazeras/Jurassic fault is most likely. The Lower Magarini is said to contain heavy minerals (e.g. zircon, tourmaline and garnet) and garnet is certainly abundant in the Pleistocene derivatives of the Magarini Formation.

The Upper Magarini is a bright red well sorted dune sand deposited by wind as coastal dunes and present at elevations exceeding 210 m (asl) in the Arabuko-Sokoke Forest where they vary in thickness from 91-122 m. Their red colour is due to a coating of iron oxide. Rivers crossing the Upper Magarini Formation contain only white sands in the channel because the iron-oxide coating has been removed by abrasion.

The outcrop of Magarini Formation is extensive (Figure 5 and 6). It partly conceals the Jurassic outcrop on the Foot Plateau and in the Kilifi area it covers the Mazeras/Jurassic boundary fault. Seawards the Magarini Formation merges into Pleistocene reef complex sands (Kilindini Sands) or becomes obscured beneath younger wind-blown Pleistocene sands both of which are in part or wholly derived from the Magarini Formation.

6.3.4 Pleistocene Sediments.

The complicated history of sea level fluctuation during Pleistocene times promoted the reworking of the sediments close to the coast and gave rise to the development of a fringing reef offshore and patch reef formation in the lagoon. In the lagoon which formed behind the coral reef the sediments from the mainland were mixed with coral debris to comprise a mixture of sediments which have been penetrated by fairly extensive drilling on the Coastal Plain behind the raised coral reef.

It was believed by Caswell (1956) that the Pleistocene reef developed on a Jurassic platform at about -60 m OD, and as sea level rose reef growth from this base kept pace. Conspicuous terracing of the reef at about +35 m OD which forms an extensive flat landsurface on the Coastal Plain indicates the general rise in sea level that occurred. The reef complex may therefore be expected to be about 100 m thick.

A subsequent fall in sea level to about -50 m OD (as indicated by submarine terrace levels) promoted the reworking of the coastal sediments and probably gave rise to the deposition of coarse quartz grains in the lagoon immediately seaward of the Shimba Hills. (Elsewhere where the Coastal Range is not developed the coastal sediments are not as coarse grained.) During this low sea level the coastal rivers cut channels in the lagoon and the reef and these can be expected to have hydrogeological significance. The channels now drowned by a later rise in sea level are represented by the numerous creeks along the coast (Port Reitz and Tudor Creek, surrounding Mombasa Island, Mtwapa Creek, Kilifi Creek, Mida Creek, etc). The later rise in sea level is recorded by terracing of the reef at about +7 m OD and a later fall is recorded by cliff formation on the seaward edge at about -7 m OD prior to the latest rise to present sea level.

6.3.4.1 The Pleistocene Reef.

The raised Pleistocene coral reef which is developed along the length of the coast (Figure 5 and 6) has a narrow outcrop extending to a maximum 4 km but more usually less than 1 km wide. Further inland it passes into sandy lagoonal deposits - a sandy facies of the reef complex, or it becomes obscured by wind-blown sands. The reef itself consists of a tough white to yellowish white limestone that is relatively compact and dense compared to other Pleistocene reefs. No reef structure is immediately obvious and much of it comprises shell debris rather than coral growth.

6.3.4.2 The Sandy Facies of the Pleistocene Reef.

The sediments found immediately inland of the reef structure are referred to as the sandy facies of the reef complex. They comprise coarse quartz sands, fine (windblown) sands, clays and limestone debris which have been shifted by current and wave action in the lagoon. They were referred to as Kilindini Sand by Caswell (1956). The sandy facies sediments are generally unconsolidated or semi-consolidated and they represent excellent aquifer material. Their outcrop extends inland for up to 10 km, but is normally much less (see Figure 5 and 6).

7. EXISTING WATER SUPPLIES

The main rivers in the area studied are the Sabaki draining into the sea near Malindi, the Rare and Ndzovuni draining into Kilifi Creek, the Mwachi and Pemba draining into Port Reitz near Mombasa and the Ramisi and the Umba near the Tanzanian border (Figure 5 and 6). Intakes have been constructed on the Sabaki River at Baricho and the Pemba River at Mrere (Figure 5 and 6) which have significant baseflow components. Riverflow records were not available for the other streams although they are unlikely to represent significant water sources. The Rare River and Ramisi Rivers are known to be saline for part of their length.

Lake Jilore lies adjacent to the Sabaki River about 16 km from Malindi and is likely to be fed by the Sabaki River and from groundwater.

The area studied is presently served by several water supply schemes and many people obtain water at source, from streams, wells and natural rock catchments. The MOWD is responsible for large scale public supplies and at present 19 supply schemes are in operation under the MOWD in the coastal area.

The majority of the population is located on the Coastal Plain and along the main Mombasa-Nairobi Highway. Outside of the main areas small villages on the Coastal Plain obtain water from dugwells and until recently the South Coast water was derived from a dugwell at Likoni. On the Karroo outcrop small villages may use borehole water, stream water or occasionally only rainwater. Several programmes of exploration drilling in the Karroo rocks to provide water supplies to the villages have taken place but the majority of the boreholes are now disused although a few, constructed in the 1950's are still in working condition (e.g. 1024 Rima ra Pera, 1106 Kwa Dem, 1035 Tsangatsina), although the water quality is poor but probably unchanged.

Several borehole supplies in the Karroo rock areas have been replaced by better quality water by pipeline branching from the Mzima Springs Pipeline which was installed in 1956. The Mazeras-Jaribuni pipeline delivers Mzima water to Ribe, Kaloleni, Dzitsoni, Kilifi and Jaribuni north of Mombasa.

The Sabaki Pipeline Scheme which is expected to supply water to Mombasa in early 1981 includes a river intake at Baricho and a modern water treatment plant to remove the heavy silt concentration of the river during periods of flood flow. The catchment area of the river is very large (39,000 km^2) yet the dry season flow can fall to 1-3 m^3/sec. The Sabaki River flow originates from the Athi and Tsavo rivers upstream. The Athi discharge features rapid recessions after rainfall peaks and has clearly little groundwater component to sustain dry season flow. The Tsavo river flow however contains a continuous large baseflow component from the Mzima Springs and the Upper Tsavo river so that the low flows are observed when the Athi river is low or dry, usually in February or March.

The Sabaki Pipeline is also intended to supply water to areas of the North Coast including the Tezo-Roka settlements, Mnarani, Takaungu, Mtwapa and Vipingo by 1990.

The Sabaki Pipeline is not intended to serve the area south of Mombasa so that water supply for the South Coast will have to come from elsewhere. At present there are three major supply sources in the South Coast area. These are spring sources at Mrere in the Shimba Hills, a river intake on the Pemba river nearby and direct abstraction of groundwater from boreholes in the coastal sediments at Tiwi and Waa.

The Mrere supply was the first water supply system for Mombasa. Installed in about 1916 it comprised two spring intakes on the western side of the Shimba Hills and was designed to obtain 2500 m^3/d of spring water (which is obtained from the Mazeras Sandstone). It has subsequently been extended to 13500 m^3/d and also delivers a small quantity of water to Kwale and Kinango (240 m^3/d), and supplies a reservoir at Kaya Bombo from which water is distributed to various parts of the coastal zone south of Mombasa.

Several boreholes were constructed between the Mrere springs and the Pemba River in the 1940's to investigate the spring source. They penetrated lower levels of the Mazeras Sandstone and probably the Mariakani Formation. Well yields were variable and specific capacities calculated from measurements made during 'cleaning' operations in 1972 and 1973 range from 5.15 m^3/h/m (C317, 243) to 19.2 m^3/h/m (C689). Water quality ranged from 'good' to 'moderately saline' (TDS 4494 mg/l) but was generally slightly saline.* The borehole water was blended

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* See for example a salinity classification given in Hem, J D (1970).

	TDS (mg/l)
Slightly saline	1000-3000
Moderately saline	3000-10000
Very saline	10000-35000
Briny	> 35000

with the spring supply (EC ∿ 500 micromhos) but was discontinued due to its poor quality and the introduction of the Pemba River supply of better quality.

No report appears to be available which discussed the groundwater circulation of the Mrere springs and the area was not studied in detail during the present investigation.

Direct abstraction of groundwater from boreholes takes place at Tiwi where two boreholes are currently producing 4000 m^3/d of good quality water which is supplied by pipeline to kiosks in areas on the Coastal Plain. Until recently the population of Tiwi, Ngombeni, Waa and Diani obtained the same water at source by direct abstraction from dugwells. Further details of the Tiwi boreholes are given in section 8.5.

Malindi obtains its water from the Sabaki River by an old river intake and from the Ganda Wellfield a little distance inland. The Ganda wellfield also supplies a small quantity of water to Gede and Watamu on the coast. Further details of groundwater abstraction in the Ganda area are included in section 8.8.

The bulk of the Mombasa water supply requirement is obtained from Mzima Springs in the Tsavo West National Park, some 220 km from Mombasa. The Mzima Springs supply was completed in 1956 and a pipeline 220 km in length delivers 36000 m^3/d to Mazeras reservoirs from where it is distributed to a service reservoir at Changamwe and then to the distribution main serving Mombasa and and areas further north.

The Mzima Springs form part of an area of groundwater discharge within Tsavo National Park. The spring water is groundwater which discharges at the base of a basalt lava flow where it is in contact with calcareous lake sediments occupying a depression in the basement rocks. The lava flow appears to be tongue extending from Chyulu Volcano and the groundwater system of which the Mzima discharge is a part is very large. The springflow is said to be fairly constant (approximately 244250 m^3/d) throughout the year, although some significant variation has been observed from year to year.

Recent studies of the spring discharge* and analysis of the flow records[1] point to a delayed response between inferred recharge and springflow of the order of 3 years or more. A detailed site investigation of the intake area including core drilling was carried out in 1954 (Squires, 1954) and details of the geology and inferred groundwater circulation of Chyulu Volcano are given by Temperley (1960). No quantitative hydrological/hydrogeological study leading to an understanding of the water balance of the Chyulu area has yet been carried out but this was suggested in 1973 (Mansell-Moullin). In view of the dependence of the Mombasa supplies on Sabaki River flow (Sabaki Pipeline Scheme) and Mzima groundwater, both derived from the Chyulu Range, a comprehensive hydrogeological/hydrological study of the area is seen as desirable.

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* The Flow Regime of Mzima Springs, MOWD, August 1978 (not located).

[1] JICA Report, September 1980.

8. HYDROGEOLOGY

8.1 Basement Rocks.

The Basement rocks were not studied as part of the survey. They crop out in the extreme west of the area at Mackinnon Road (Figure 5) where several boreholes have been drilled (C178, 668, 2200, 2201 and 3707). Borehole 2201 proved 20 m of weathered gneiss and saline water. The water was struck at 23 m in hard, obviously fractured or jointed gneiss. Borehole 3707 proved 25 m of weathered rock but no water was found in the weathered zone.

8.2 Karroo Rocks.

Details of the history of drilling of the Karroo rocks are given in Appendix 3. These give only a general picture of the hydrogeology but it is clear that groundwater in the Karroo is almost always saline. There is virtually no groundwater in the Karroo rocks having a TDS of 1500 mg/l or less, the recommended maximum concentration for drinking water*. The water is however generally suited for stock watering.

8.2.1 Aquifer Properties.

About 100 boreholes penetrate the Karroo rocks mainly on the Mazeras and Mariakani Sandstone outcrop and the location of selected boreholes is shown in Figure 5 and 6. The drilling has largely been restricted to locations close to the main roads, particularly along the main highway from Mombasa to Nairobi which crosses the central part of the Karroo outcrop.

The drilling records indicate that the Karroo rock aquifers are typical of hard sedimentary rocks in which the productivity is generally poor. Some descriptions suggest that a 'zone of weathering' similar to that found in igneous and metamorphic regions, containing water-bearing layers, may be present, and other descriptions indicate the presence of primary aquifers. The boreholes can normally be constructed 'open hole' (without slotted casing or screen).

The water struck levels and rest water levels imply that the groundwater is very often confined and water level rises of 10-20 metres are not uncommon. The difference between water struck level and static level could however also be explained by low productivity. During drilling poorly productive rocks aquifers are often not apparent until the borehole has penetrated a significant thickness. Unconfined aquifers (water level at atmospheric pressure) and perched aquifers are also present.

Examination of the geological descriptions indicate that water is commonly found at the junction between layers (shale/sandstone) within shale sequences and less commonly within the sandstone sections. Intergranular permeability within much of the Taru, Maji ya Chumvi and Mariakani Formations as judged by examination of the rock

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* The maximum permissible TDS for drinking water is 1500 mg/l (about 2250 micromhos conductivity) which is just met by water from borehole 997 and 3661 penetrating Mazeras Sandstone.

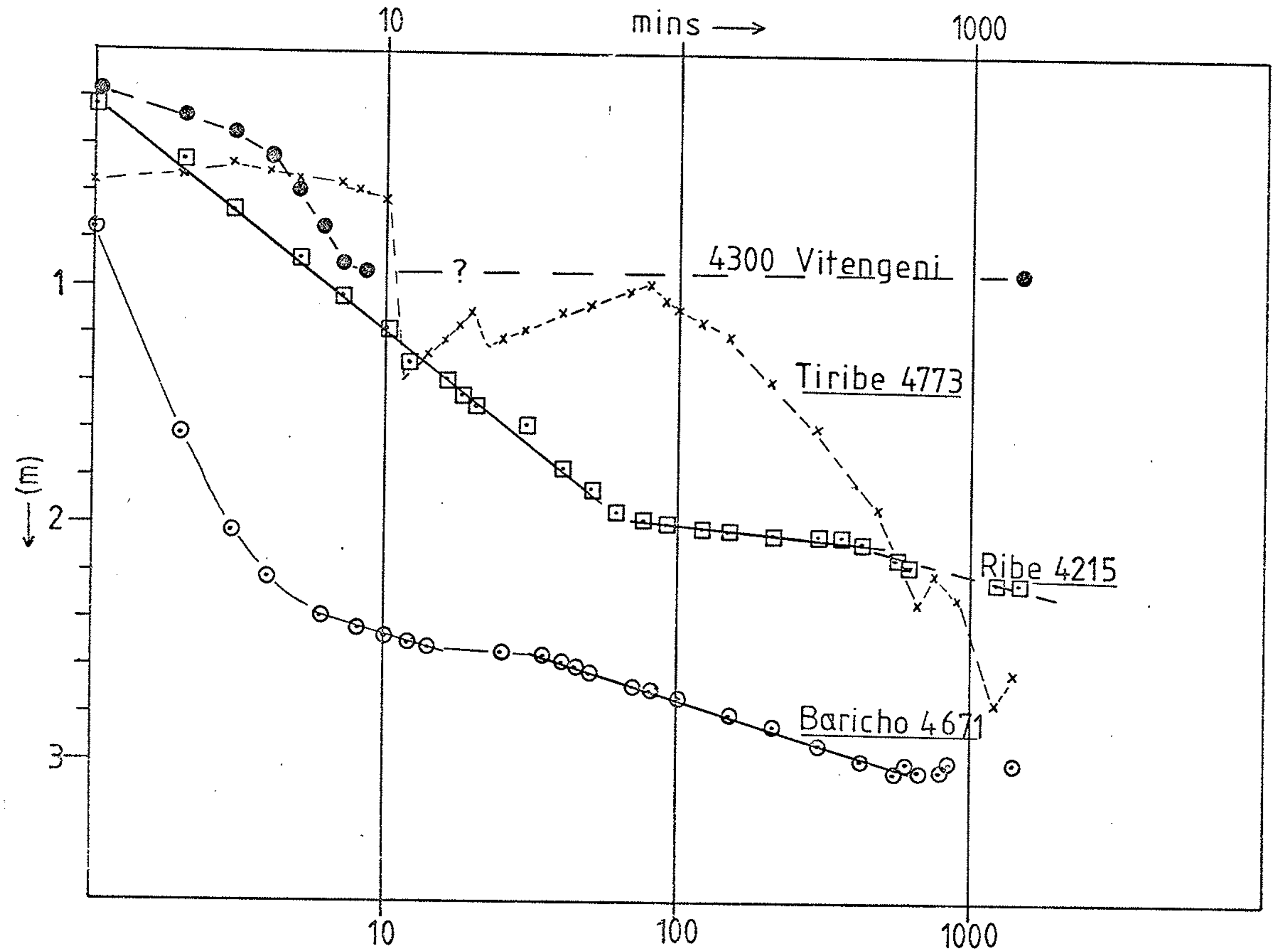

FIGURE 7 Time-drawdown, Karroo rock pumping tests.

at outcrop, is very low or minimal and it can be expected that groundwater circulation in these Formations must be dominated by the presence of joints, fractures and bedding plane features rather than pore space. Large areas of the Taru Formation form 'rock pavements' or have only a thin soil cover which ponds surface water for long periods after rain and there can be little infiltration. The intersection of joints in some areas has given rise to the development of circular sinks known locally as 'ngurungas' which are described in Classen (1974), and which also pond the surface water for significant periods.

Specific capacities of boreholes in the Taru Formation are very low (0.018-0.138 $m^3/h/m$) - about the equivalent of the output of a domestic tap for a metre of drawdown. The specific capacity of boreholes in the younger Karroo rocks is also low but generally improves progressively in the direction of higher rainfall. Specific capacity in the Maji ya Chumvi Formation (borehole 4443) is 3.58 $m^3/h/m$; in Lower and Middle Mariakani Formation (borehole 1035) is 4.9 $m^3/h/m$; and in Mazeras Sandstone (borehole 2501) is 6.45 $m^3/h/m$. However a wide range in productivity can be expected in all Formations and some boreholes in the Mazeras Sandstone have very low specific capacity (e.g. 4422 which is only 0.19 $m^3/h/m$). A wide variation in well yield is typical of rocks where production is obtained from joints, fissures and discontinuity surfaces rather than pore space.

8.2.1.1 Pumping Tests in Karroo Rocks.

Most of the pumping tests on the early drillings refer to yield tests carried out by the driller on completion of the well and a pumping water level or drawdown is not often given so that specific capacity cannot be calculated. The figures for specific capacity quoted above are from tests where a pumping water level is available, but they are not generally specific capacities at equilibrium, nor after the same duration of pumping, both of which affect the value obtained.

Time-drawdown plots from the few tests for which measurements are available are shown in Figure 7. These show that the Baricho borehole appears to approach equilibrium after 700 minutes although the test should have continued beyond a day to confirm this. The Ribe borehole approached equilibrium after 120 minutes at the initial pumping rate but later drawdown increased due to an increase in discharge rate. Fluctuations in discharge rate during the first 100 minutes are also apparent in the Tiribe test data (Mazeras Sandstone aquifer) but the increasing drawdown after 100 minutes, is at a reduced pumping rate signifying that the cone of depression has entered a zone of lower permeability and no equilibrium was approached during the test period.

These measurements and those from other tests show that more attention should be given to the accurate measurement of water level and pumping rate during routine tests, particularly those performed by the drilling contractor. The pumping rate should be kept constant and should not be allowed to vary by more than 10% otherwise the tests can be difficult to interpret. Water level measurement should be made by electric sounder using graduated tape in metric units. It should then be possible to measure water levels to the nearest millimetre which helps to improve the accuracy of the measurement. Slight variation in pumping rate will not affect analysis of the recovery. It is important however that the recovery measurements are made for at least the duration of pumping, and preferably longer.

8.2.2 Aquifer Recharge.

The rainfall measurements recorded at the various stations throughout the region (Figure 1 and Table 1) show that the Karroo outcrop between Mackinnon Road and Mariakani receives about 750 mm/year which increases towards the coast and rainfall is highest over the Mazeras Sandstone ($\sim$ 1000 mm/year).

High run-off must occur in March, April and May but there is little data available to indicate which streams on the Karroo outcrop are perennial or which have a high baseflow component. Mean annual potential evapotranspiration exceeds rainfall throughout the area. Potential evapotranspiration ratios* for stations on the coast receiving higher rainfall are 3.52 (Mombasa Airport) and 3.03 (Malindi Airport) so that they can be expected to be higher inland over Karroo outcrop where the amount of rainfall decreases by up to 50%. Pan evaporation measurements at Mombasa Airport is 2234 mm (1958-70 Class A pan mean) and at Voi is 2058 mm (1958-70 mean) so that a high proportion of the rainfall will be lost to evaporation.

The potential for groundwater recharge must therefore be faily low and in the absence of baseflow measurements and other measurements, the quantity is largely unknown. There are no records of borehole water level fluctuations either to demonstrate if seasonal changes in groundwater storage occur, or to indicate their magnitude. There are however significant springs at Mrere, from the Mazeras Sandstone in the high rainfall area of the Shimba Hills, which will give an indication of the recharge, and there may be other springs.

It is reported by Classen (op.cit) that several coastal rivers are saline, especially in the dry season. This is unusual, and it is important to determine whether it is due to saline baseflow from saline groundwater or due to saline salts in the near surface layers concentrated by evaporation. Water quality of some streams (e.g. Kigutu, Ramisi) is said to improve downstream which might suggest that groundwater in the older Karroo rocks is responsible but a proper investigation is required.

8.2.3 Water Quality.

A summary of the chemical analyses of Karroo rock groundwaters is given in Table 2 and Table 3 where it is apparent that the poor quality water places a major constraint on development although well yields are not large so that only local development could be considered.

Table 3 shows that only rarely has the groundwater a TDS of 1500 mg/l or less, the recommended maximum concentration for drinking water, and those occurrences are boreholes located close to the eastern edge of the outcrop where rainfall is highest (Figure 5). The TDS content is however generally less than 7000 mg/l so that the water can be considered

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* Potential evapotranspiration ratio = $\dfrac{\text{mean annual potential evapotranspiration}}{\text{mean annual precipitation}}$

Borehole	Locality	Formation Penetrated	TDS (mg/l)
C966	Kinango	MYCu	2237
C794	Mtaa	MYCu	4921
C856	Ndvaya	MYCl	1680
C934	Kinangoni	MYCl	5000
C1107	Kitvu	MYCl	1685
C1165	Sapo	MYCu	1665
C1104	Tsangatsina	MKm+l	6270
C236	Mariakani	MKm+l	2830
C997	Mangea	MZm	1307
C930	Bamba	MZm	4300
C4215	Ribe	MZm, KL	2634
C3661	Changombe	MZm	920
P91	Bamba	MKm+l	7562
C689	Mrere	MZl+Mk	2440
C243	Mrere	MZl+Mk	4162

Table 3. Summary of Groundwater Quality in selected Karroo Rock Boreholes.

suitable for stock watering*.

The origin of the saline water in the Karroo rocks is believed to be due to disseminated soluble evaporite minerals within the sediments which have not been removed by groundwater circulation. No evaporite mineral beds are known in the Karroo of Kenya but the environment in which the Karroo rocks were deposited, in fault-bounded basins or rifts under shallow water conditions and arid climate, particularly during Maji ya Chumvi times is one that must have given rise to evaporite minerals within the sediments and as previously mentioned over 2000 m of evaporite beds are present in equivalent age rocks in Tanzania. Classen (op.cit) also reports that efforescence is observed on outcrops after rain in some areas.

Better quality water is found at the edge of the Mazeras Sandstone outcrop and in the Shimba Hills where the possible effects of lateral transfer of saline groundwater from the lower units are diminished and where modern recharge and groundwater circulation is likely to be greatest.

8.2.4 Groundwater Exploration.

Study of the drilling records shows that depth to water in the Karroo is within the range 5-50 m and water struck levels are generally within 6-150 m from the surface. The deepest borehole is a coal exploration borehole constructed in 1950 near Maji ya Chumvi station which penetrated an artesian aquifer at 45 m and an aquifer at 880 m which was reported to be only slightly saline (2305 mg/l). This borehole could not be located, but if still open (which is unlikely; there is a record that it was filled with rocks) it affords a useful stratigraphic section for geophysical borehole logging. Borehole 3661 drilled by the Mines and Geology Department close to the Mazeras escarpment in 1970, was an inclined diamond-drilled hole which has artesian flow of good quality water (1390 micromhos in October 1980) discharging from the Mazeras Sandstone confined by a wedge of Jurassic shale in an area disturbed by faulting. Groundwater prospects are certainly likely to be higher in structurally disturbed areas such as these and the Mazeras Sandstone/ Jurassic boundary fault is a useful target for exploration which has already been investigated at Ribe (borehole 4215) and Baricho (boreholes 4671, 4673 and 4675). Results of a spring and baseflow survey (including water quality measurement) may demarcate further areas for exploration close to the Mazeras fault.

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* See for example suggested limits by McKee and Wolf (1963) quoted in Hem, J D (1970).

Poultry	2860 mg/l
Pigs	4290
Horses	6435
Cattle (dairy)	7150
Cattle (beef)	10100
Sheep	12900

Geophysical methods may be useful to assist selection of drilling targets but there may be serious limitations to their application. The water-bearing horizons may be too thin or specific to produce detectable geophysical anomalies and they may be at a depth beyond the range of the instruments. Surface resistivity measurements and seismic refraction surveys may be capable of resolving the thickness of the weathered material where sufficient contrasts exist but they are unlikely to generally identify water saturation. The resistivity method might however be able to identify saline-water saturation which would be valuable information. The resistivity method may also have application for identifying vertical fracture zones which could be water-bearing. The use of depth-sounding, constant-separation-traversing and gradient arrays would be appropriate to identify such features provided the masking effect of the overburden is not too severe.

It should be possible using the drilling results available and from location of the boreholes on the geological map, to geologically classify the drilled sections. This information may indicate the continuity of water struck levels, piezometric levels and other aquifer properties. Borehole geophysics, particularly gamma logging may also be useful for correlating the drilled sections.

8.2.5 Summary and Recommendations.

1. Groundwater in the Karroo rocks in the area studied, with exception of the Shimba Hills, has almost always proved to be of poor quality and generally unsuitable for domestic purposes but is suitable for stock watering.

2. Well yields are generally low and sufficient only for small scale local supply. The well yields and water quality appear to improve higher up the sequence so that groundwater prospects are better in the youngest rocks (the Mazeras Sandstone) which are in the highest rainfall area.

3. Significant spring discharge is known from the Mazeras Sandstone at Mrere in the high rainfall area of the Shimba Hills. Spring flow measurements and measurement of baseflow and hydrograph construction in other areas may usefully indicate areas of greater potential.

4. Surface geophysics may have a limited application for groundwater exploration in the Karroo but the potential of the various methods has not been assessed. The surface resistivity method may be capable of identifying saline-saturation and if the effect can be differentiated from the presence of shale/siltstone or freshwater-saturation the technique will be useful to guide exploration drilling. The resistivity and VLF electromagnetic techniques may be capable of identifying structurally disturbed areas having greater water-bearing potential.

5. Drilling to depths currently investigated at Bamba and Vitengeni (about 300 m, see Appendix 1) is unlikely to locate potable water unless modern recharge is conducted to such depths via deep fractures or faults. Deep drilling is also more likely to encounter low permeability and it is therefore not generally recommended.

8.3 Marine Jurassic Rocks.

The Middle and Upper Jurassic limestone and shales have not been extensively drilled. The Kambe Limestone has a narrow outcrop and significant water supplies would probably only be obtained if there was transfer of water from the Mazeras Sandstone. The Ribe borehole, (4215) is the only borehole on record which penetrates the Kambe Limestone. It has a low specific capacity (0.14 $m^3/h/m$) and slightly saline water is reported (2634 mg/l). Further exploration of the Kambe Limestone outcrop is probably justified, particularly so because its outcrop is close to the Mazeras fault.

The Jurassic shales are unlikely to contain supplies of potable groundwater. There are no boreholes appearing to be sited directly on the shale outcrop but several boreholes appear to penetrate the shales at depth and these are reports that they contain no groundwater or saline water (1079 NaCl = 4038 mg/l).

Hydrogeologically the Jurassic shales are important in forming a seaward dipping impermeable base to the overlying Cainozoic sediments and in some areas contact springs are observed at the junction. On the Coastal Plain the Jurassic rocks are not exposed but they are penetrated by some boreholes.

8.4 Cainozoic Rocks.

At least 213 m of Cainozoic sediments have been penetrated by drilling on the South Coast at Ukunda (borehole 4020) and drilling at Kilifi (borehole 4382) indicates that they probably form a wedge about 235-250 m thick under the Coastal Plain.

The sediments comprising this wedge include the Baratumu Formation and the Marafa Formation, a confusing sequence of clays, sandy clays, clayey sands and gravels with little groundwater potential, the Magarini Formation, medium to coarse quartz sands and bright red fine wind blown sands, of relatively untested groundwater potential, and a Pleistocene reef complex with an associated sandy facies containing the most productive aquifer on the coast. The history of exploration drilling in the Cainozoic rocks of the Coastal Plain is summarised in Appendix 3.

8.4.1 The Baratumu and Marafa Formations.

The Baratumu and Marafa Formations are known from drilling in the area around Malindi and Ganda and from drilling results of the Magarini Project, north of Malindi.

Borehole 4382 at Kilifi penetrated about 100 m of Baratumu sediments below the Pleistocene reef complex. The log describes hard abrasive sandstones, sandy clay layers and hard brown sandy clay. Borehole 4358 close-by probably enters the same sediments at 105 m. The sequence in 4358 describes sands and sandy clays and a hard conglomerate containing quartz pebbles which is almost certainly a Baratumu beach deposit close to a Jurassic shoreline.

The only record of testing of Baratumu Formation is from borehole 4382 (15/9/77) but the test results cannot be correct. Testing during cleaning of borehole 848 in the Ganda wellfield, which penetrates Baratumu Formation at total depth, gave a specific capacity of only 0.24 $m^3/h/m$ which is low.

More recently (1978) borehole 4526 drilled at Shauri Moyo (Vipingo 198/4) penetrated 182 m of probable Baratumu Formation comprising grey limestone and clay, dark silty clays and reddish brown sandy clays. No water was struck except seepages between 108-116 m and 128-132 m. The Baratumu Formation changes lithology laterally and is thought to overlie the Jurassic shales in a lensing fashion. The well yields can therefore be expected to vary widely.

Borehole 4596 (Jilore 192/2) penetrates 200 m of white sand and light brown sand and clay which is probably Marafa Formation. Boreholes northeast of Marafa, 1041, 1042, 4321, 4322, 4344, 4401, 4428, 4458, 4595 and 4716 penetrate white or grey clays with sandy layers or sandy clays. The drilling records indicate caving difficulties and results of testing show transmissivity to be generally $< 10\ m^2/d$ so that well yields are low and dugwells rather than boreholes will be more appropriate groundwater abstraction structures in some cases.

It is possible and indeed probable that these Formations are present at depth in the Mombasa and South Coast area but it is difficult to identify them by drilling descriptions alone. Specialist information on palaeontology is required to differentiate these sediments from those of the Pleistocene but geophysical borehole logging may possibly assist the interpretation.

8.4.2 The Magarini Formation.

The Magarini Formation has a relatively wide outcrop at the edge of the Foot Plateau along the length of the coast, (Figure 5 and 6). Borehole 1159 (Sokoe 192/4), 1079, 1087, 2565, (Kilifi 198/2), 217, 4137, 1678, 1722 (Vipingo 198/4) and 2807 (Mombasa 201/1) are located on the outcrop.

Borehole 1159 penetrated 45 m of red sand and 'light red stone' overlying grey sandstone, white sandstone and sand. Blue shale was reported at 112 m which is probably Jurassic but could be Marafa or Baratumu Formation. The borehole was dry, and a similar result was obtained from boreholes 1079 and 1087.

Borehole 2565 penetrated only 7.3 m of sand overlying coral. The Magarini Formation is normally found landward of the Pleistocene reef complex so the sand referred to at this site is more likely to be a Pleistocene sand. The description of coral near the surface in this borehole is however a little surprising and it probably refers to Baratumu limestone because the ground elevation is at about 100 m (assuming the borehole is correctly located on the map) and Pleistocene coral is not generally found above 35-40 m OD. The section penetrated is therefore likely to be 7.3 m of Magarini Formation overlying 93 m+ of Baratumu Formation containing limestone bands. Water was struck in these

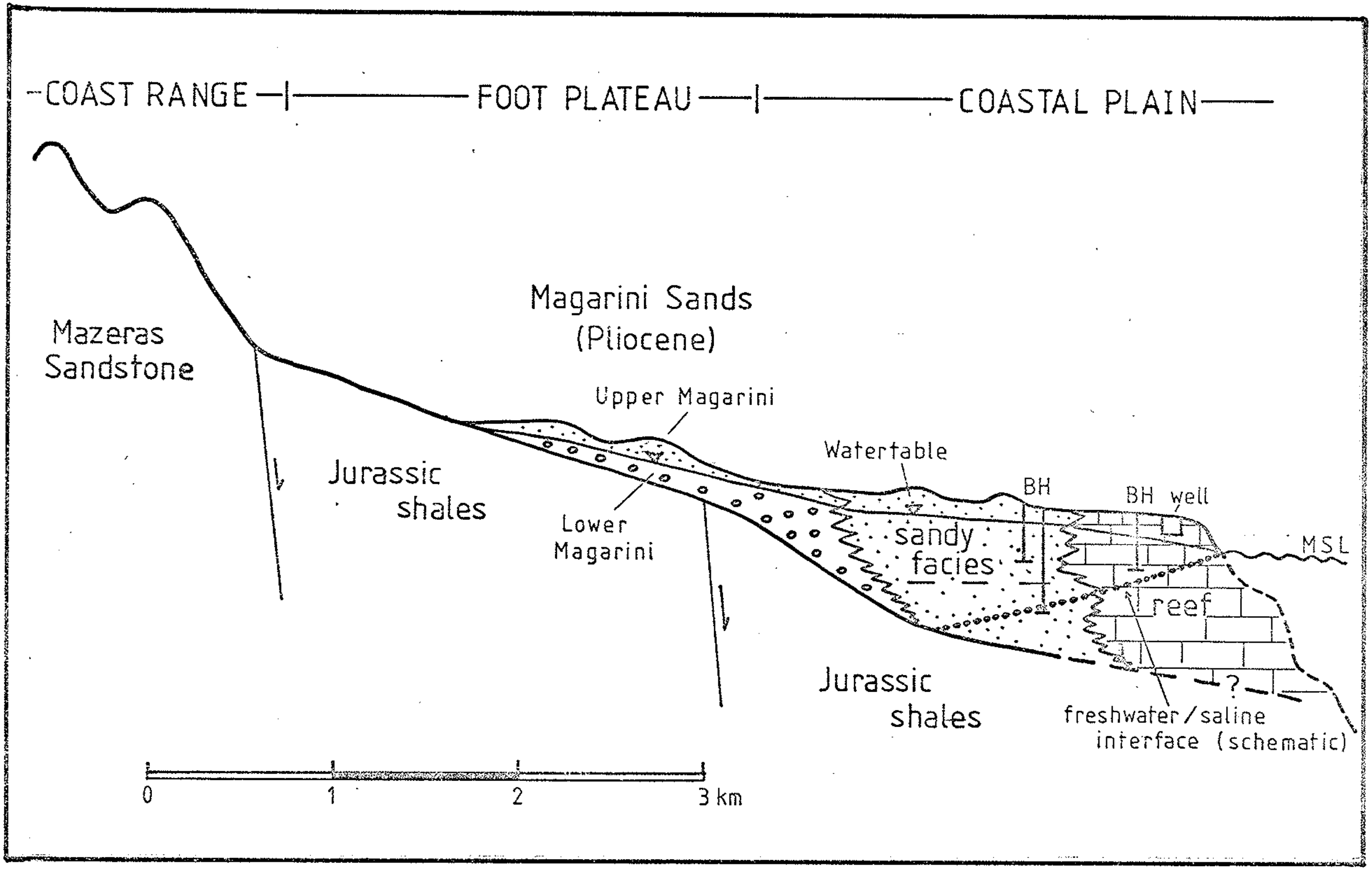

FIGURE 8 Schematic hydrogeological section of the Tiwi aquifer.

Baratumu sediments and the specific capacity was characteristically low (0.04 $m^3/h/m$ which suggests it is Baratumum limestone rather than Pleistocene limestone. The quality was reported to be good but no measurements are available.

Close to the coast in the Vipingo Estate area south of Kilifi, the distinction between Magarini Formation and Magarini sands reworked in Pleistocene times is not clear-cut. A dugwell located on the dunes behind the Vipingo Estate farm (and equipped with a windpump) penetrates such sands which are fine-grained. The well has a SWL of 28.025 m when visited on 15/10/80 and it was reported that the water level fluctuated greatly after rain which is consistent with low storage (low porosity fine grained sands) and its location in a recharge area. The yield was reported to be low but the quality was very good (380 micromhos).

The lower member of the Magarini Formation is a coarse-grained quartz sand which is unlikely to have been windblown. The Upper Magarini Formation might therefore be distinguished from the Lower Magarini by the grain size distribution. There are however no drillings where Lower Magarini Formation can be clearly recognised and differentiated from the sandy facies of the Pleistocene reef which is of similar lithology. In Figure 8 it is apparent that the sandy facies of the Pleistocene reef which represents an excellent aquifer, could be Lower Magarini Formation, but because of the close association with the Pleistocene reef, it is assigned to the Pleistocene. Specialist information is required to classify these sediments, and where they have been reworked, but it would appear that much of the Upper Magarini Formation is above the zone of saturation, and where saturated, as for example at Vipingo Estate, the productivity is low because of the restricted and uniform grain size (Figure 12).

8.4.3 The Pleistocene Sediments.

Most of the successful drilling on the Kenya Coast has been in the Pleistocene reef complex, particularly in the sandy facies of the reef complex immediately behind the reef structure. There are about 40 boreholes penetrating the Pleistocene sediments and the same general lithology of coral, loose sand and water can be recognised at each site. There are many reports of construction difficulties and the attempts to cope with the fine and flowing sand which entered the wells during construction. These boreholes were normally constructed by percussion drilling and completed using slotted casing, but flowing sand posed a difficulty to their construction so that fine sand was sometimes cased off or the borehole was backfilled to above the casing fine sand section usually with a reduction in yield. A reduction in yield was also noted during subsequent testing of some of the boreholes and the evidence points to fine sand moving to the intake portion of the well (slotted casing) and clogging the pore space of the material around the slots thus increasing the drawdown. This sand movement is also confirmed by reports of greater quantities of fine sand discharged at higher pumping rates.

Borehole 2575 at Vipingo Estate is a good example of this. It was tested during construction and the test measurements are particularly informative. It was drilled in November 1956 to a TD of 40.8 m and later backfilled to 33.8 m to prevent excess sand (with water) entering. The test results on the backfilled borehole show a specific capacity of only 0.14 $m^3/h/m$. A second test after the casing was lifted 6.7 m showed an improvement to 16.1 $m^3/h/m$ and a third test at a higher discharge rate gave a specific capacity of 11.6 $m^3/h/m$, but caused pumping of sand. These results point out the importance of using correctly designed boreholes with wellscreen and gravel packing if optimum yield is to be obtained.

More recent drilling in the Tiwi area (15 km south of Mombasa, Figure 1) adopted the use of wellscreens and gravel packing. Borehole 3905 (also known as Tiwi 1) was constructed to a depth of 50.9 m by percussion and wellscreens of 0.01 inch and 0.015 inches (0.25 mm and 0.38 mm) slot widths were placed against the sandy portions and a gravel pack was used as a formation stabliliser. The borehole has high specific capacity (11.1 $m^3/h/m$ and has been producing up to 70 m^3/h of sand-free good quality water (EC = 500 micromhos) to supply continuously since 1976. Subsequently 9 further boreholes were constructed in the Tiwi area, all penetrating good quality water and indicating considerable groundwater potential although their design proved inappropriate and only 2 can be used without pumping excessive amounts of fine sand.

Boreholes that are located close to the sea often show an increase in salinity at depth. The first recorded evidence of increasing salinity of groundwater at depth in these Cainozoic deposits close to the coast comes from borehole 2608 at Vipingo Estate, which when drilled in 1956 yielded 'good water' at 25 m and saline water at 46 m. Several boreholes penetrating the reef limestone structure report 'saline water' but there is little factual evidence to support this. Much of the information relating to the hydrogeology of the Pleistocene rocks is from results of studies in the Tiwi area south of Mombasa where high yielding boreholes (60-80 m^3/h) have been constructed. Details of these studies and the hydrogeology of the 'Tiwi aquifer' are given in the following section.

8.4 Tiwi Area Studies.

There are now 12 boreholes in the Ngombeni-Tiwi-Ukunda area, south of Mombasa, penetrating the sands of the Pleistocene reef complex. Their location is shown inFigure 9 and 10. Drilling had taken place in the coral reef at boreholes 2555 and 2558 (at Diani) in 1956 but there was no exploration of the sandy facies of the reef until 1972 when boreholes 3904, 3905 and 3906 were drilled at Ngombeni, Tiwi and Ukunda.

Borehole 3906 at Ngombeni which was drilled in December 1972/January 1973 to a TD of 76.2 m penetrated the sandy facies of the reef overlying at 27 m yellow silty clays and hard laminated shaley clay which may be Baratumu Formation. Screens were placed at 30.48-33.53 m and 51.82-54.87 m and SWL is given as 35.97 m (below top screen?) so that if the interpretation is correct the sandy facies was unsaturated at this site. Yield testing at 4.81 m^3/h drew water level down to 49.69 m (within shaley clay) to give a specific capacity of only 0.35 $m^3/h/m$ which tends to confirm that production is from the Baratumu Formation and not the reef complex sands. The casing was withdrawn and the borehole was abandoned.

Borehole 3904 was drilled at Ukunda during January and February 1973. It was drilled by percussion to 76.2 m and penetrated yellow brown sandy clay, stiff laminated yellow clay overlying fine coral sand (water bearing) at 19.81 m, which overlies stiff yellow sandy clay at 24.4 m which continued to total depth. The presence of fine coral sand (Pleistocene) within the yellow clay suggests that the yellow clay sections are probably also Pleistocene and probably reworked Baratumu sediment. The aquifer can be expected to vary in lithology according to the nature of the material reworked in Pleistocene times and the structure of the lagoon and its channels and patch reefs will therefore have an important bearing on the aquifer properties. Water was struck in borehole 3904 at 19.81 m and the quality was good (EC = 420 micromhos). During testing drawdown occurred in the coral sand and a specific capacity of 1.55 $m^3/h/m$ was obtained. (Full lithological details of the Tiwi area drillings are presented in Appendix 1 for reference).

Subsequent to the drilling of borehole 3905 at Tiwi, the further exploration drilling of the Tiwi area was by hydraulic rotary method to moderate depths (200 m). Eight boreholes were constructed (4141, 4158A, 4158B, 4470, 4570, 4240, 4536 and 4708) but their design was such that they permitted sand entry and only two boreholes (4536 and 4708) can be used. Details of their construction are given in Appendix 1 and is shown in Figure 11.

8.5.1 The Design of Boreholes in Unconsolidated Sediments.

The design and construction of boreholes in unconsolidated aquifers is subject of much borehole technology. Wellscreens of appropriate slot width have to be placed against the aquifer and a gravel pack between wellscreen and aquifer may be necessary to prevent excessive movement of fine sand. The basis for calculating the correct slot width and gravel pack grading is sieve analysis of the aquifer, and it appears that this has not been carried out in the construction of the boreholes.

When boreholes are constructed using drilling mud to support the borehole walls there can be difficulty deciding where water is struck and where the static water level is. The drill cuttings returned with the mud circulation during drilling are collected and examined; sand sections and clayey sections are identified, and because a wellscreen is required to support the borehole wall and to allow water to be pumped, the grain size of the sand samples is measured by sieve analysis to ensure that the correct slot width wellscreen is chosen. Some aquifers may contain particles of fine sand which requires the use of fine slot width wellscreen against the whole aquifer. This may have relatively little open area and is also expensive so that a gravel pack of coarser grains may therefore be placed around the wellscreen. This allows the use of a wellscreen having a larger open area and also permits the removal of the finest sand particles from the aquifer during development. Thus overall a zone of relatively high permeability is created around the well which reduces water entrance velocity so that fine sand particles are not generally mobilised by production pumping. The design of the borehole either by natural pack completion or by gravel pack completion as described is governed by the grain size distribution of the aquifer material.

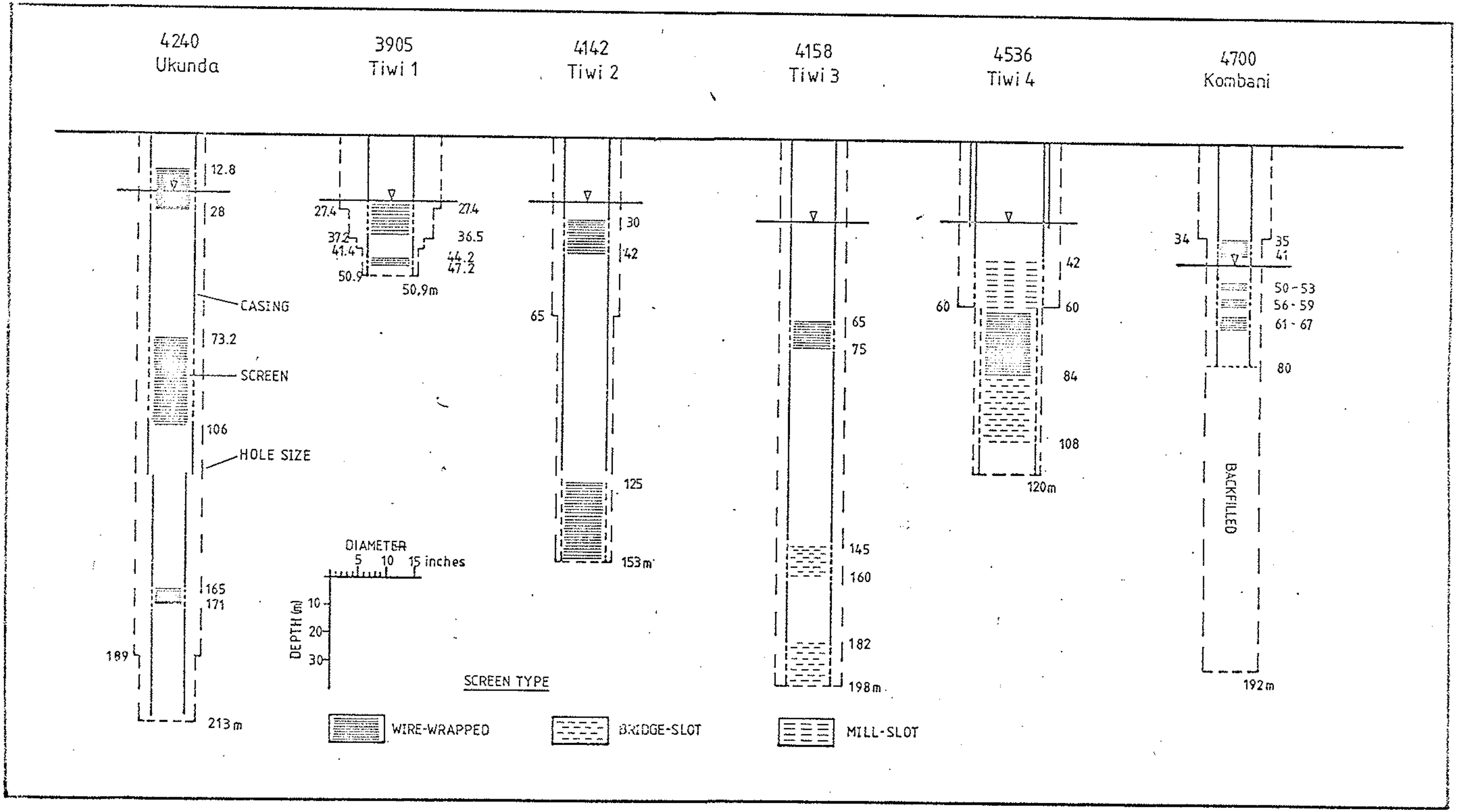

FIGURE 11 Tiwi borehole construction.

There are several well design criteria based on sieve analysis results in the published literature (Johnson UOP, 1970; Sharma and Chawla, 1977; Kruse, 1960; Hunter-Blair, 1968) and general recommendations arising from several sources are given below.

A. <u>Uniform aquifer</u> (UC < 3.0)*

If the uniformity coefficient is low (< 3.0) sand pumping must be avoided because a continuous unstable condition can exist which cannot be remedied by development. There are 3 options:

i) Natural pack construction - is possible if $d_{10} > 0.25$ mm. A wellscreen which retains 90% of the aquifer material (d_{10}) size would be selected. A minimum slot width of 0.01 inch (10 slot, 0.25 mm, wire wrapped screen) may be necessary.

ii) Gravel pack construction - if $d_{10} < 0.25$ mm a gravel pack construction is recommended because it is impractical to use less than 10 slot screen and maintain a large open area (often necessary if water has encrustation tendency). By using a gravel pack a larger wellscreen slot width (larger open area) can be used.

iii) In case (i) and the aquifer is <u>thick</u> it may be preferable or more economic to use bridge-slotted <u>pipe</u> with a gravel pack instead of wire-wrapped screen provided drilling costs for the large diameter do not exceed the cost of the wire wrapped screen, and where the water has an encrustation tendency a wider slot opening is definitely preferred. Well development will be less effective if bridge slotted screen is used however.

B. <u>Non-uniform aquifer</u> (Uc > 3.0)

If the aquifer is non-uniform (Uc > 3.0) sand pumping is less critical because some aquifer development is possible. There are several options.

i) Natural pack construction - is possible if $d_{10} > 0.25$ mm and the aquifer is not too heterogeneous.

ii) Gravel pack construction - will be necessary if $d_{10} < 0.25$ mm and is recommended if d_{50} is between 0.25 mm and 0.75 mm (Sharma and Chawla, 1977).

iii) Gravel pack construction - is preferred if the aquifer is very heterogeneous.

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* Uniformity coefficient Uc $= \frac{d_{60}}{d_{10}} \left(\frac{\text{sieve aperture passing 60\% of the grains}}{\text{sieve aperture passing 10\% of the grains}}\right)$

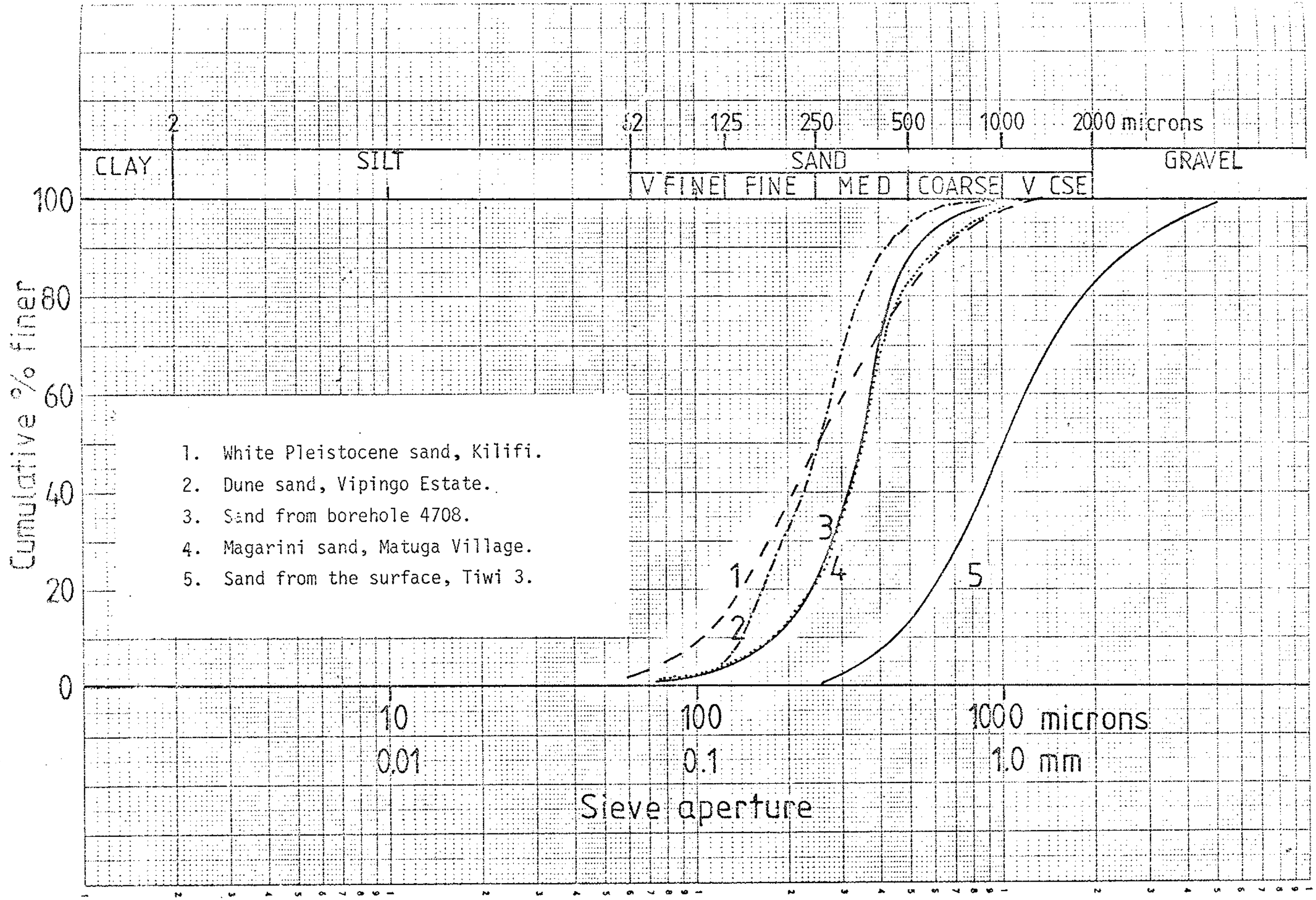

FIGURE 12 Grain size distribution curves.

When a uniform pack is used the wellscreen slot opening is usually chosen to retain all of the pack particles. When natural completion is adopted the slot width is usually chosen to retain 90% of the formation particles (i.e. the d_{10} size).

The gravel pack is placed as an envelope between the wellscreen and the aquifer after the screen is installed. It is important that it is placed uniformly without bridging of the particles or segregation of the grains. A tremie pipe is often used to place the gravel.

The grain size of the gravel pack is critically related to the aquifer grading. Use of too coarse a pack allows continuous sand pumpage (leading to subsidence and screen damage) and use of too fine a pack gives rise to blockage by invading fines. The gravel pack grading is therefore selected on the basis of the sieve analysis of the aquifer. Two types of pack are in current use. A graded pack contains a range of grain sizes (usually selected to parallel the aquifer grain size distribution curve) and a uniform pack contains similar sized grains (in practice $Uc < 2.0$).

The published criteria for selecting gravel pack grain size refer to pack : aquifer ratio (P : A) which is the ratio of grain sizes of the pack and the aquifer. Normally the d_{50} or d_{30} size are quoted. Those suggested by Johnson UOP (1970) are given below.

Uniform fine grained aquifer ($Uc < 3.0$) use 4 x d_{30} size
Medium-coarse grained aquifer ($Uc < 3.0$) use 6 x d_{30} size
Highly non-uniform aquifer ($Uc >> 3.0$) use 9 x d_{30} size which includes silt

Table of multipliers for gravel pack selection.

It is noted that the finest pack is generally required for fine grained uniform aquifers because no significant development will be possible.

Kruse (1960) gave experimental evidence to show that there is a limit to the P : A ratio beyond which the well will be unstable (allows sand pumping).

Aquifer	Gravel Pack	P : A Limiting Ratio
uniform	uniform	9.5
non-uniform	non-uniform	13.5
uniform	non-uniform	13.5
non-uniform	non-uniform	17.5

Note: uniform = $d_{60}/d_{10} < 2.0$

non-uniform = $d_{60}/d_{10} > 3.0$

Date	Time	Q (m^3/h)	Sand Content in Tank (g)	Sand Content of Water (ppm)	Remarks
BOREHOLE 4570 TIWI 3 (4)					
5/5/80	1715	24	352	352	fine and coarse white sand
6/5/80	1015	42	293	293	very fine white sand
7/5/80	1215	48	311	311	very fine sand and white coral
	1815	49	109	109	very fine sand and white coral
8/5/80	1215	52.5	44-51	44-51	very fine white sand
9/5/80	2015	54.6	27	27	very fine white sand
BOREHOLE 4708 TIWI 2 (2)					
11/2/80	1630	106	1650	1650	fine sand and coral, dirty white and brown
12/2/80	1630	149	100	100	fine sand and coral, dirty white and brown
13/2/80	0430	159	150	150	fine sand and coral, dirty white and brown
	1530	129	70	70	fine sand and coral, dirty white and brown
	1630	170	350	350	very fine white sand

TABLE 4. Sand Content observed during Pumping Boreholes 4570 and 4708.

The thickness (width) of the gravel pack is also important. It has been shown that a pack width of 5 grain diameters is all that is needed to retain formation particles but in practice a width of several inches is allowed for to ensure the pack completely surrounds the wellscreen. If the pack is too wide it will be difficult or impossible to remove the fines from the aquifer through the pack and a thickness of 3 inches is generally recommended to avoid this.

The Tiwi borehole drilling records show that 20 slot (0.50 mm) Johnson wellscreens were used in each borehole and a gravel pack was not used. It is however unlikely that the aquifer d_{10} size is as large as 0.50 mm (med/coarse sand) and that this material is uniformly present at each site so that the design of the Tiwi boreholes must be considered improper.

Samples of the formations presented in these drillings are not available but some information is given by the sieve analysis of the sand discharged during pumping and sand taken from the surface (Figure 12). It is not suggested that these samples are representative of the aquifer but they serve as an example of grain size distribution and perhaps indicate the limits. The median particle size (d_{50}) of the sand discharged during pumping is 0.38 mm (medium sand) and the effective size (d_{10}) is 0.18 mm (fine sand). It can be expected however that when a representative sample is obtained the effective size will be greater than 0.18 mm unless layers of fine sand are present at depth. Analysis of the coarser surface material shows the presence of particles up to 5 mm diameter and a d_{60} size of 1.2 mm so that the uniformity coefficient (d_{60}/d_{10}) of a proper sample is likely to exceed 3.0 and the aquifer is probably non-uniform. Use of a 20 slot screen (0.50 mm) in aquifers solely composed of these particles would pass 90% of the grains (fine sand sample) and 13% in the case of an aquifer comprised solely of the coarser grains.

The amount of sand discharge during pumping has been measured at borehole 4570 (Tiwi 3) and 4708 (Tiwi 2) during tests by the MOWD after the boreholes were completed. These results (Table 4) show that the sand content exceeds 100 ppm. Normally sand content can be expected to be highest immediately after switching on and to reduce during sustained pumping as the grains in the aquifer surrounding the wellscreen begin to bridge. The sustained sand content should be less than 20 ppm (Ahrens, 1968) and a quantity of 0.1 ppm would be noticeable in routine sampling. A sand content of 100 ppm from a high capacity borehole discharging 100 m^3/h would amount to 87.6 metric tons of sand removed from the aquifer in a year. Whilst this would be quite impracticable because of wear of the pump, the effect of continuous sand removal apart from additional maintenance work on the well and pump, can be collapse of the well or settlement of the wellhead. The mean particle size (d_{50}) of the sand discharged during the tests is less than 0.50 mm which suggests that the excess sand is not a result of damaged or broken screen, but is due to improper design. Larger particles (> 1.0 mm in size) were measured in the sample but proved to be fragments of rusted steel from the pump or rising main (see Figure 12).

There seems little doubt therefore that the continuous sand pumping of the Tiwi boreholes is due to the lack of a gravel pack and the use of two wide a slot width wellscreen in the presence of fine sand in the aquifer, and it is likely to represent a continuous unstable condition that cannot be remedied by development.

It is understood that borehole 4536 is in use without a gravel pack but there is indirect evidence to suggest that the aquifer is significantly coarser-grained at that site so that natural gravel pack completion is feasible. It is interesting to note in Figure 12 the close agreement in grain size distribution between the fine sand discharged from the aquifer during pumping (borehole 4708) and the sample of Magarini sand (dune sand) from Matuga village.

8.5.2 Well Development.

The process of well development where fine material, drilling fluid and drill cuttings are removed from the aquifer, the gravel pack and well-screen after drilling is particularly important in wells drilled in unconsolidated materials by mud rotary methods. Many drillers now use a degradeable drilling fluid instead of bentonite which produces better formation cutting returns, easier desanding, and allows more effective development. It can be difficult to remove bentonite from the aquifer during development, depending upon the screen design and development method used. Bentonite is a montmorrilonite clay which is often used. The use of a degradeable drilling fluid such as Johnsons Revert which 'reverts' to the viscocity of water by enzyme action helps to ensure that the formation does not remain 'mudded up' and unresponsive to development methods.

Well development serves two functions:

i) To stabilise the formation and well giving sand-free operation.

ii) To improve the permeability of the aquifer in a zone immediately surrounding the screen to ensure continued sand-free operation and high efficiency.

The length of time required for well development (it may be several hours or days) and the effect of the development is related to 4 factors.

(a) Size and sorting of the aquifer.

(b) Type of drilling fluid used.

(c) The screen type.

(d) The development method used.

If the aquifer is uniform and fine grained there can be no significant removal of 'fines' and little development will be possible. If the aquifer contains clay and is non-uniform, longer development time is required to remove the finer portions.

The design of the borehole may affect the effectivess of well development. Screens with limited open area (e.g. fine slot wire wrapped, bridge slotted, mill slotted pipe) and thick gravel packs, prevent access of the development method to the formation surrounding the screen. In this respect continuous slot wire wrapped screen appears to be preferred. (Some fibreglass slotted screen can be physically damaged by development jetting.)

There are several methods of well development in common use. These include overpumping, surging (block or valve surging with a percussion rig), compressed air development (airlift pumping and surging), water jetting using high velocity water jets and the use of chemicals to disperse or dissolve clays, or a combination of methods. Methods which concentrate the development on the screen (jetting and surging) are most efficient and recently the use of sectional development (by water or air) where the screen is isolated by blocks or packers, a section at a time, and subjected to development is an effective technique.

The few details concerning well development given in the Tiwi well records suggest that overpumping, backwashing and airlift pumping were used. The results do not appear to be satisfactory and the methods adopted were probably ineffective because some of the pump test results show a reduction in specific capacity during testing as a result of what must be movement of fines towards the wellscreen and 'packing off' or clogging of the aquifer or wellscreen by the particles. The results of pumping at borehole 3905, 4536 and 4708 however show that the aquifer has locally high transmissivity and properly designed and developed wells can be constructed to provide a valuable supply.

It is unlikely the Tiwi boreholes can be rehabilitated to stable sand-free operation by development. It would be feasible to install 4 inch wire-wrapped screens and gravel packs inside the existing boreholes with design based on analysis of the grain size of particles passed by the pump (Figure 12) but this is not satisfactory nor reliable and leaves no scope for installation of a pump unless a drop set screen is used. There is little prospect either that concentrated development will remove the fines. It might be possible to recover the screens although this is probably unlikely. However gamma logging of the boreholes should be carried out whilst there is access, and CCTV-inspection should be used to check their construction and to confirm that sand entry is not due to damaged or broken screen.

8.5.3 Pump Testing.

The record of pump testing of the Tiwi boreholes is confusing. This is not only because several boreholes are referred to by the same number in the records but because there are several inconsistencies. There are references to very high discharge rates and comments that in some tests all the drawdown occurred within 30 seconds and full recovery occurred within 90 seconds which is impossible. The records suggest that the measurements and testing are not adequate.

A summary of the pumping test results from boreholes in the Pleistocene sediments, including those in the Tiwi area is given in Table 5, and a summary of transmissivity values from tests in the Tiwi area is presented in Table 6, but the testing has been generally inadequate to obtain precise T values.

Regular measurements of water level during testing were made by the MOWD Geology Section at borehole 4570 and borehole 4708 (during the tests to observe the sand content discharged). The discharge rate during these tests was varied to observe the effect on the sand content so that precise analysis of the drawdown plot is not possible, nor was the change in rate appropriate for step-drawdown analysis, but the recovery measurements can be analysed. This is shown in Figure 13 where the

Borehole	Date	Discharge (m^3/h)	Drawdown (m)	Specific Capacity $m^3/h/m$	EC (Micromhos)	Remarks
3905 (Tiwi 1)	1973	67.7	6.09	11.1	450	
4141 (Tiwi 2)	2-7-75	272-363[1]	0.00	-	-	see note 1
4708 (Tiwi 2)	8-1-80	360[1]	3.20	-	450	
	10-1-80	270	2.80	-	450	
	11-14-2-80	139.6[2]	4.056	34.42	-	sand content measured
4158A (Tiwi 3)	7-9-75	272[1]	8.90	-	-	
	2-78	45-68	4.20	10.7-16.2	1000	after 'cleaning'
4158B (Tiwi 3)	-	273[1]	9.00	-	450	
	3-5-78	16.36[2]	20.00	0.82	-	
4470 (Tiwi 3)	8-11-5-78	12-19.8	5.19-16	2.3-1.2	-	
4570 (Tiwi 3)	5-9-5-80	24	4.44	5.4	650	sand content measured
4536 (Tiwi 4)	12-9-78	42-109	5.14-14.66	8.17-7.43	450-700	higher EC at higher Q
4240 Ukunda	13-6-78	48	5	9.6	400-2700[3]	see note 3
4700 Kombani		7.56	1.67	4.5	-	Austromineral b/h
3904 Shamu Ukunda	9-2-73	10.90	7.02	1.55	420	
	15-2-73	13.6	5.06	2.69	420	
3906 Ngombeni	12-1-73	4.81	13.72	0.35	-	
2575 Vipingo Estate	1956	0.65	4.87	0.14	-	
		9.80	0.60	16.07	-	
		14.15	1.22	11.60	-	
2572 Vipingo Estate	1956	10.98	1.5	7.2	3500	
4137 Vipingo Estate	25-5-75	1.5	1.73	0.8	-	
3053 Vipingo Estate	1960	14.70	2.12	6.9	-	
3042 Vipingo Estate	1960	13.60	1.52	8.97	1700	
3173 Vipingo Estate	6-6-62	15.15	1.22	12.42	1760	
3174 Vipingo Estate	8-5-62	10	0.31	32.2	~2000	
		22.7	0.91	24.8	-	
3254 Kilifi Plantation	30-8-63	4.3	3.05	1.42	-	

1 This is an improbable pumping rate for a pump fitting inside 8 inch casing.

2 As measured by MOWD.

3 Estimated from chemical analysis.

TABLE 5. Summary of pumping tests in the Pleistocene sandy aquifer.

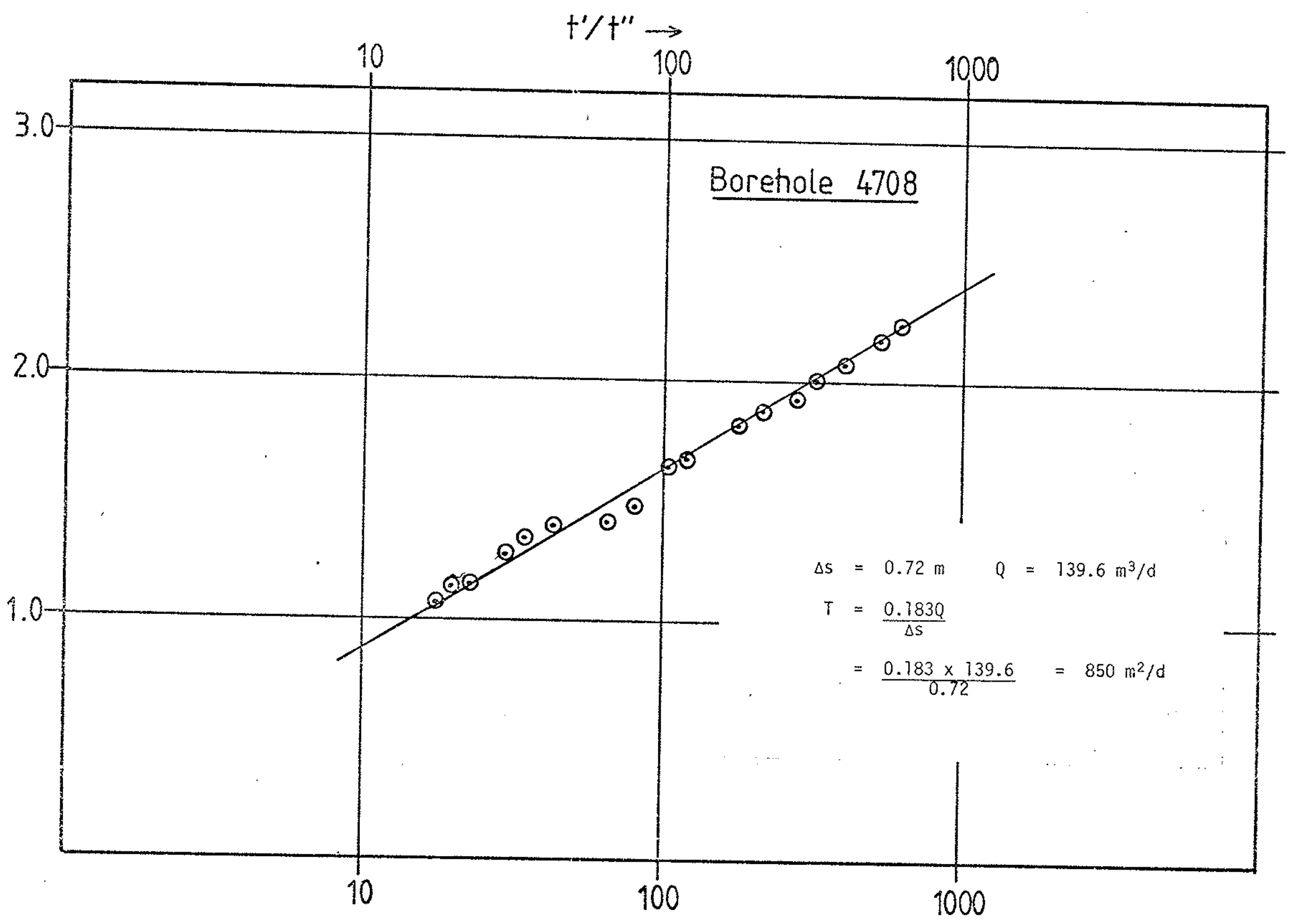

FIGURE 13 Residual drawdown plot, borehole 4708 (Tiwi 2).

residual drawdown plot of borehole 4708 gives a transmissivity of 850 m^2/d although it could be as high as 2000 m^2/d. Drawdown measurements in borehole 4142 used as an observation well during a short period of pumping in borehole 4708 (r = 16.75 m) in November 1980 and curve matching to watertable type-curves (Figure 14) gives a much higher transmissivity (3500 m^2/d) which is likely to be more appropriate and gives an indication that well losses are adversely affecting the pumping well analsyis.

Carefully controlled pumping tests of adequate duration should be carried out to obtain precise values of transmissivity and storage in the Tiwi area presently supplying water to public supply. A carefully controlled pumping test could easily be run at borehole 3905 during the normal schedule of pumping*, and water level measurements could be made in the observation well (r = 9.70 m) in borehole 4708 and 4121 (r = ∿ 200 m). This should be carried out for at least 6 days, preferably longer, after a period of shutdown of the production pump (for whatever reason).

The radius of influence during pumping is given by :

$$Re = 1.5 \sqrt{\frac{Tt}{S}}$$

where T = transmissivity (m^2/d)

t = duration of pumping (d)

S = Storage coefficient

from which it is seen that the observation wells at 200 m would be affected after about 250 minutes (T = 1000 m^2/d, S = 1%)**.

The calculated values of transmissivity from the testing in the Tiwi area are given in Table 6.

General recommendations for suitable pump testing procedures are given in section 10.

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* Such a test was planned in November 1980 but unfortunately before the test could start the pump was damaged and could not be removed from the well.

** The calculated values for storage coefficient (specific yield) from the short test at 4142 are imprecise because of the limitations of the short period of testing but an early specific yield of 9.3×10^{-3} is indicated. A longer test of several days is required to obtain the late specific yield which influences the drawdown during production pumping.

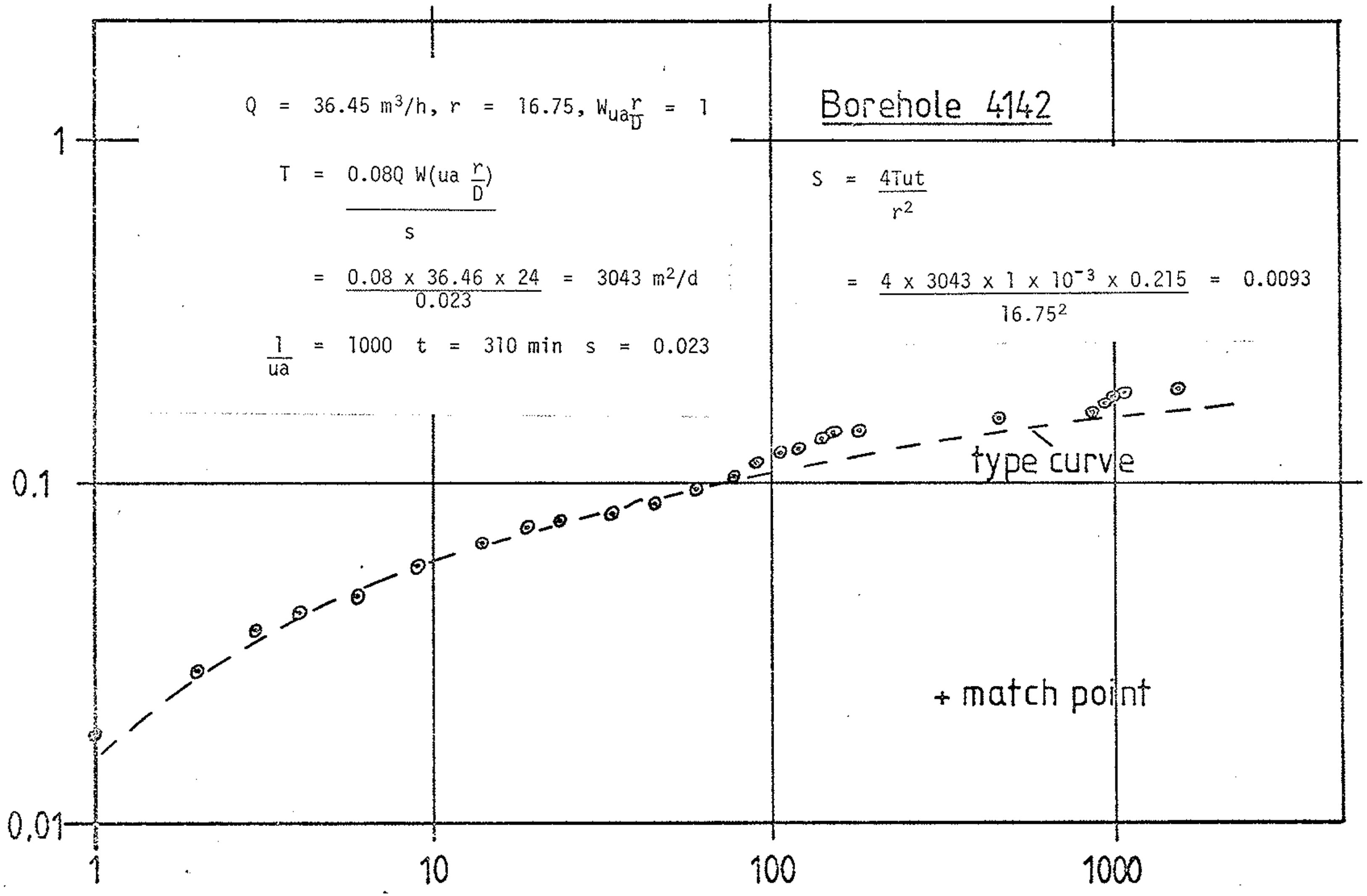

FIGURE 14 Pumping test analysis borehole 4142 (Tiwi 2).

Borehole	Transmissivity (m^2/d)	Method of Analysis
4570	850	Theis Recovery
4708	850-2000	Theis Recovery and Jacob Drawdown
4142	1890-3500	Theis Recovery, Jacob Draw-down, Theis Curve Matching
4536	235-480	Jacob Drawdown

Table 6. Summary of pumping test results, Tiwi boreholes.

8.5.4 Geophysical Studies.

The Tiwi area has been subject of much surface geophysical work to locate groundwater. An early resistivity survey (1968) by Gentle used the Wenner configuration and the field curves from measurements on coral outcrop, and the sandy facies were interpreted with the use of 4 layer masters. In all measurements resistivity decreased with depth, and significantly this effect was observed at the inland margin of the Coastal Plain where the loose deposits overlie Jurassic shales.

Both electrical resistivity (Schlumberger) and seismic refraction measurements were made more recently by Austromineral who carried out a hydrogeophysical survey of the South Coast as part of a 1 years extension to the Kenya/Austria Mineral Exploration Project. During this period a combined airborne magnetic and radiometric survey was also flown over selected areas of the country by Terra Surveys Ltd. under a Canadian Government (CIDA) contract, and an electromagnetic INPUT (induced pulse transient) survey was flown over the Coast.

The principle of the INPUT method is given in Telford et al., (1976). It consists of a transmitter loop attached to an aircraft and a receiver towed at the end of a cable. In operation pulses of electromagnetic energy from the transmitter generate secondary electromagnetic fields in the ground which are related to conductivity and are detected by the receiver. Because the primary field is pulsed the secondary magnetic field decays exponentially. The amplitude of the decay curve is sampled at 6 points (6 channels) over 100 microsecond intervals during the period of decay (2 milliseconds) after the pulse. Poor conductors show low amplitude responses which decay rapidly so that they may be absent in the higher channels (5, 6) and good conductors may appear on all channels.

By plotting the response amplitude and position a contoured map of ground 'conductivity' is produced as shown in Figure 9 and 10 where areas of 'low conductivity' (high resistivity) have been selected as target areas for groundwater exploration.

The INPUT mpa of the South Coast in Figure 9 and 10 shows steeper contours at either side of a trough of low conductivity. Terra Surveys have traced a suggested saline interface through the more easterly (dashed line of amplitude 7 units chosen) and they infer a geological boundary for the more inland steepening of the contours (dashed and dotted line).

The boundaries of the geological units have also been included in Figure 9 and 10 and they show that the zone of low conductivity coincides with the outcrop of the sandy facies and the Magarini Formation particularly well.

It is assumed that the contours in the Figures represent a weighted average 'conductivity' between surface and the depth of investigation, and the interpreted saline interface shown does not imply saline water is present at the watertable. It is hydrogeologically unlikely that the reef structure will be saturated with saline water at the watertable at the indicated distance inland. (The aquifer must discharge through the reef complex, freshwater springs are observed at the coast, and water in boreholes 2558, 2761, 4421 and 4441 is potable). The interpretation must therefore relate to the interface at depth. Similarly amplitude values > 7.0 are not taken to imply saline water, for the best quality groundwater of the South Coast area ($\sim$ 300 micromhos) is found at Tembo Springs where contour values > 10.0 are shown.

It is important therefore to appreciate the depth of penetration of the method. There is little doubt that the high amplitude obtained inland At Tembo Spring is a response to conductive Jurassic shale present at shallow depth under the Magarini Formation and not to saline water at the watertable.

Borehole evidence to indicate the depth of any saline interface is, at present, quite limited. There are at least 10 m of freshwater at borehole 4421 in the reef limestone near Ukunda (Figure10) and 160+ m of freshwater at borehole 4158B (Tiwi 3) which is very close to the assumed interface on the INPUT map. Similarly present in the aquifer throughout the area is a clay layer 40-50 m below watertable which may influence the responses. The results of surface resistivity and seismic measurements made by Gentle and Austromineral may indicate the depth of saline saturation within the reef structure to compare with the INPUT map, but these measurements have not been available.

Resistivity measurements made at two sites during this survey in the zone of 'low conductivity' (at borehole 4536 and at Tiwi 3 site) show that the aquifer is overlain by 20-30 m of Pleistocene sand having an unsaturated resistivity of 1000 ohm.m which is an order of magnitude higher than the aquifer resistivity (90 ohm.m) some 20-30 m below. It is important therefore to demonstrate that the low INPUT conductivity does relate to the aquifer rather than merely to the unsaturated overlying sand of low conductivity. There are examples outside the South Coast area where low INPUT conductivity is matched by (reported) saline water, e.g. at Kilifi and a critical assessment of the INPUT results is required.

No resistivity measurements were made on the reef limestone outcrop in the present survey but freshwater-saturated reef limestone can be expected to have a resistivity within the range 20-300 ohm.m and its saline-saturated equivalent will be < 10 ohm.m. The Jurassic shale can also be expected to be < 10 ohm.m. A strong resistivity contrast will therefore exist when passing from the reef limestone (20-300 ohm.m) to the sandy facies (1000 ohm.m overlying 90 ohm.m) and the Jurassic shales (< 10 ohm.m). This resistivity contrast is identified by the INPUT measurements.

Some drilling of the reef limestone to identify the saline interface to compare with interpretations of interface depth from surface resistivity and INPUT measurements is required, and a map of apparent resistivity constructed from the existing resistivity measurements for comparison with the INPUT map would be particularly useful. INPUT measurements in other geological environments where such a resistivity contrast does not exist are likely to be more difficult to interpret.

8.5.5 Hydrogeology of the Tiwi Area.

Figure 8 is a schematic cross-section to illustrate the hydrogeology of the Tiwi area but the section can equally well describe the general hydrogeology of the coastal sediments.

The aquifer is shown to comprise several units including Magarini Formation, Kilindini sands (the sandy facies proper) and the Pleistocene reef. Rainfall on the unconfined outcrop area (and further inland and fed to the outcrop area by streams) recharges a water table which slopes gently to the coast where groundwater discharges. There is likely to be a transfer of groundwater from Magarini Formation to the sandy facies and from the sandy facies to the reef and the hydraulic gradient is expected to change in these units are shown. The position of boreholes on the Coastal Plain and dugwells on the reef structure is indicated schematically. A saline water interface is also shown to occupy the reef structure at depth and in plan view the various creeks which cut the aquifer may also be expected to be sources of saline intrusion.

The presence of a saline water boundary in the discharge areas means that a reduction in the throughflow whether by increased abstraction from boreholes or through less annual recharge will permit landward advance of the interface and a deterioration in water quality can be expected. With excessive abstraction the saline interface may come to occupy large portions of the aquifer and lead to salination or reduction of the supply in a process that cannot be reversed.

It is important therefore that the discharge water quality from abstraction wells (electrical conductivity or chloride content supplemented by regular chemical analysis) is monitored to observe any changes that may take place. It is important also that downhole measurements of electrical conductivity (or depth sample collection) be made in observation wells having access to the aquifer being pumped, to observe at depth the effect of pumping, particularly in areas close to sources of saline contamination. It is also important that wellfields should have a network of observation wells to allow water levels to be measured continuously so that the effect of abstraction on water levels can be observed. Periodic measurements of water level and water quality are taken at borehole 3905 and 4536 but it is recommended that they be analysed by plotting a hydrograph or a Piper diagram. It is also recommended that recorders should be used to observe changes in water level both in the wellfield (at borehole 3905 observation well for example) and outside the wellfield, at borehole 4158B (Tiwi 3 site) for example, where there is full penetration of the aquifer (see Figure 15).

8.5.5.1 Water Level Fluctuations.

Groundwater levels in boreholes are affected by several factors including recharge, discharge (natural and pumping) barometric pressure and tidal loading. In coastal areas such as this where the aquifer is in hydraulic connection with the Ocean, boreholes and wells close to the coast may exhibit fluctuations in water level due to changes in level of the adjacent surface water. Analysis of these regular changes in borehole water level combined with comparison of tidal fluctuations of sea level can give the hydraulic properties of the aquifer which can be compared with those obtained from pumping test results. The computation methods are shown in Appendix 4.

Water levels in boreholes and wells are affected by seasonal factors and the measurement of water levels during a season show the patterns of recharge and storage changes. In an unconfined aquifer, such as the Tiwi aquifer, the water level change multiplied by the specific yield gives the amount of groundwater entering or leaving storage, which together with the quantity of abstraction is likely to represent the bulk of the recharge.

Water level measurements are not generally available for any boreholes or dugwells on the Kenya coast to show the seasonal change in level that occurs but because of the marked seasonal rains (long rains April, May; short rains October, November) the pattern of water level change is expected to be similar to the rainfall record (and riverflow record) shown in Figure 2 and this is confirmed by a hydrograph of borehole water level in the Ganda Wellfield given by Bestow (1958) the only record of seasonal change in level that has been located.

The measurement of water level in boreholes and wells forms the basis for groundwater resources calculations and provides the basic data for construction of water table and piezometric maps and is thus basic information for hydrogeological studies.

8.5.5.2 Saline Intrusion.

Freshwater in permeable coastal sands and oceanic islands typically occurs as a wedge or lens overlying more saline water of oceanic origin. The contact between freshwater and the saline water forms the base of the freshwater layer and the water table forms the upper surface (see Figure 8). Because of the general fixed density difference of the two fluids the height of the watertable above MSL is related to the depth of saline water below MSL. The relationship is described as the Ghyben-Herzberg relationship and is given by:

$$\text{Interface depth } (x) = \frac{h}{s-1}$$

where h = watertable elevation above MSL

s = seawater density/freshwater density

A value of s of 1.025 is usually used so that the interface predicted by this relationship is at a constant depth 40 times the measured watertable elevation above MSL. The relationship assumes that the water is static but in fact freshwater is continuously escaping to the sea so that in practice there is a deviation from the relationship. The boundary between fresh groundwater and the underlying seawater is a zone of dispersion where the salinity grades continuously from that of freshwater to that of seawater. The zone of dispersion may be quite thin or it may be thick and extend right to the watertable as for example in parts of Bermuda and other oceanic islands. The Ghyben-Herzberg interface depth is taken as the mid-line of the transition zone, where the relative salinity* is 50%

The shape and position of the interface and the zone of dispersion, is a function of the volume of freshwater discharging from the aquifer. A reduction in the amount of discharge, whether by a lack of recharge in a dry year, or by abstraction (pumping) results in a consequent change in the interface position. Thus any abstraction will affect the interface position and proper management is required to ensure that abstraction is not excessive.

The effect of excessive abstraction may be twofold. The reduction in natural discharge permits landward advance of the interface. This may progressively affect wells close to the coast so that they cannot be used, and, if abstraction is locally excessive actual up-coning of the saline water interface may occur under the point of abstraction. The former passive intrusion may take many years to equilibrate with the new abstraction but the up-coning process is more rapid particularly in thin freshwater lenses where the saline water is near the surface. It can be shown that boreholes abstracting from above a saline interface should be as shallow as convenient (see Appendix 5), and it is important that pumping water levels are not taken below MSL otherwise up-coning and landward advance of the interface will occur more rapidly.

At present there is only indirect evidence of the presence of saline water at depth in the Tiwi area. This is from the Ukunda borehole (4240) and from the geophysical measurements.

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* $$E = \frac{C - C_1}{C_s - C_1}$$

where E = relative salinity (%)

C = conductivity of sample

C_1 = conductivity of freshwater lens

C_s = conductivity of seawater

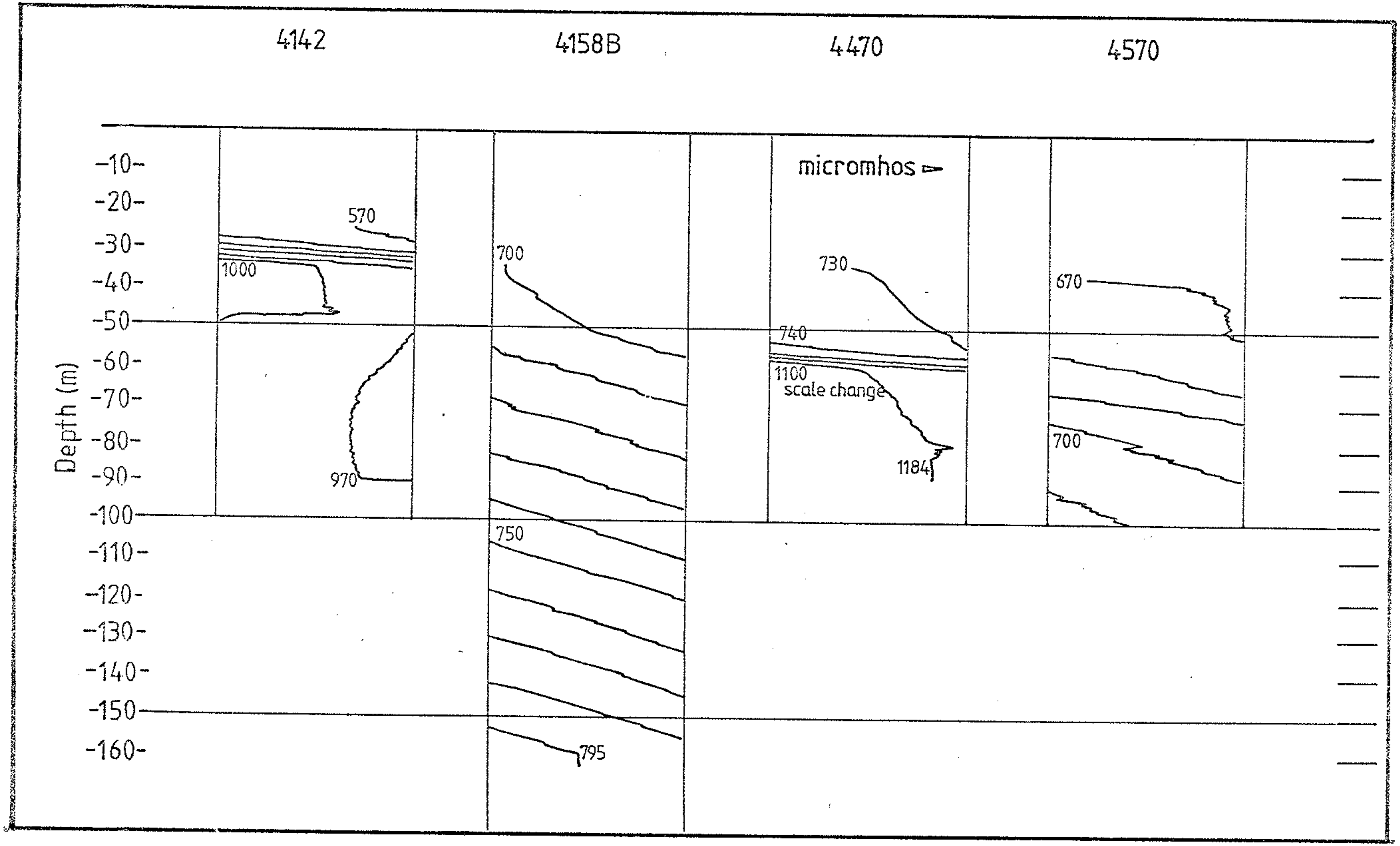

FIGURE 15. Conductivity logs borehole 4121, 4158B, 4470, 4570.

The Ukunda boreholes was constructed in May 1976 and is 213 m deep. Its construction (Figure 11) shows that the only open area (screened) is from 12.8-28 m, 73-100, 165-171 and 189-211 m. The Contractor originally recorded a SWL at 11 m, but this was in error (due to the mud rotary method of drilling) and the actual SWL was 21 m. However during pump testing (13/6/78) there is a comment that all the drawdown occurred within the first 3 minutes and the conductivity increased from 400-700-800-1100-1200 micromhos in the first 6 minutes, then remained steady. Later reports suggest the well pumped saline water and was taken out of service.

Chemical analysis of water from the first test shows a TDS of 1494 mg/l and Cl content of 560 mg/l which is close to the recommended limits for drinking water. However I suspect the deterioration in quality reported (no actual analyses located)* is merely related to the incorrect well design. The history of Tiwi wells apart from inadequate development and improper design (lack of gravel pack) is also one of inadequate pump test measurements and I suspect that during pumping of the Ukunda borehole, water level dropped below the top screen - only 2 m of which is saturated so that the water was obtained only from the lower screened intervals which must be of poorer quality. This is also supported by the observation that more sand was discharged at lower pumping rates (upper aquifer contributing). Unfortunately the Ukunda borehole is blocked with rocks 8 m below surface and no conductivity log could be made to confirm the water quality at depth, but a saline interface or a transition zone can be inferred within this borehole. The borehole should be cleaned out by percussion rig to allow a conductivity log to be made. Dugwells at Ukunda show that water quality at the watertable is good (670 micromhos) and about the same as in the Tiwi area which might be expected.

Conductivity logs made in borehole 4121 and 4158B during the survey (Figure 15) show that poor quality water (600-700 micromhos) is present to at least 190 m below surface (4158B) which is a substantial thickness, so that it is unlikely that a saline interface will be present at shallow depth in the aquifer. A saline interface at depth is more likely closer to the coast in the reef limestone or close to the creek lines where the sandy aquifer can be expected to discharge. Conductivity measurements at the watertable in dugwells on the limestone outcrop closer to the coast (Kenya Calcium Products Factory) do show higher values (1330-1550 micromhos).

The poor quality water reported from some drillings in the reef limestone should be interpreted with caution. Drilling which has penetrated a zone of dispersion at depth will often show poor quality water during pumping yet a perfectly acceptable and reliable supply of potable water can be obtained from shallow wells penetrating only the freshwater portion.

Direct measurement of the saline interface and zone of dispersion can be made by conductivity logging if there are sufficient boreholes close to the coast which penetrate the zone of dispersion or the interface. Periodic measurements in these will serve to monitor the landward advance

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* An analysis on a sample after 600 mins pumping (30/12/77) at Q = 18 m^3/h gives TDS = 1040 and Cl = 300 mg/l which is of acceptable standard for drinking water.

of the interface. It may be possible to interpret the resistivity measurements in terms of saline saturation but boreholes are likely to be required to confirm or calibrate the interpretations.

8.5.6 Groundwater Chemistry.

Chemical analyses of groundwater from the Cainozoic rocks are listed in Table 7, and Figure 16 is a tri-linear (Piper) diagram which summarises the chemistry of all the analyses including the Karroo groundwaters and also serves for hydrogeochemical classification.

The Tiwi waters are distinct in Figure 16. They are Ca-HCO_3 type and have a TDE (total determined equivalents) range of 8.9-11.6 meq/l. The Vipingo Estate and Ganda Wellfield waters show an increase in sodium and chloride, compared to the Tiwi water and a TDE range of 29-60 meq/l. The few complete Karroo groundwater analyses are Na-Cl type water with a significantly higher TDE range of 49-242 meq/l.

Saline water contamination of coastal groundwater would be normally indicated by an increase in chloride, in sodium and a decrease in bicarbonate and Ca/Mg ratio. (Seawater has relatively low HCO_3 (140 mg/l) and low Ca/Mg ratio (0.18-0.19 meq/l). The Vipingo Estate and Ganda Wellfield waters plot in a position of increased Na and Cl relative to the Tiwi waters although it is not known if they originally had a similar composition. Water from the Ribe borehole (4215) which is located on Kambe Limestone between Karroo rock outcrop and the Cainozoic sediments, occupies an intermediate position in Figure 16.

The tri-linear diagram is useful to show changes in composition with time or to indicate the mixing of groundwaters. Deterioration of the Tiwi water by overpumping (and up-coning of saline interface of drawing in of poor quality water from the Jurassic rocks) can be expected to show a trend towards NaCl in the direction of seawater plotted on the diagram. Depth-samples of water progressively closer to the saline interface should also show the same trend so that routine chemical analyses should be plotted to monitor any such deterioration.

Table 2 and 7 list the major anions and cations and indicate the ionic charge balance of the water analysed. This is a check on the analysis and a charge balance of zero ± 3% would be acceptable. Some analysis are not acceptable hence ionic ratios and total dissolved solids content are not given in the tables for these analyses.

The Tiwi waters are without exception of acceptable quality for domestic purposes. They are low in total dissolved solids and are marginally better quality than Mzima Spring water. The Vipingo Estate waters have relatively high salinity, higher sodium and higher chloride content but with the exception of 2572, are of adequate drinking water standard. The reasons for the higher salinity compared with the Tiwi waters should be investigated and may be due to initial differences or may be due to the borehole design. The Ganda Wellfield waters are suitable for public supply.

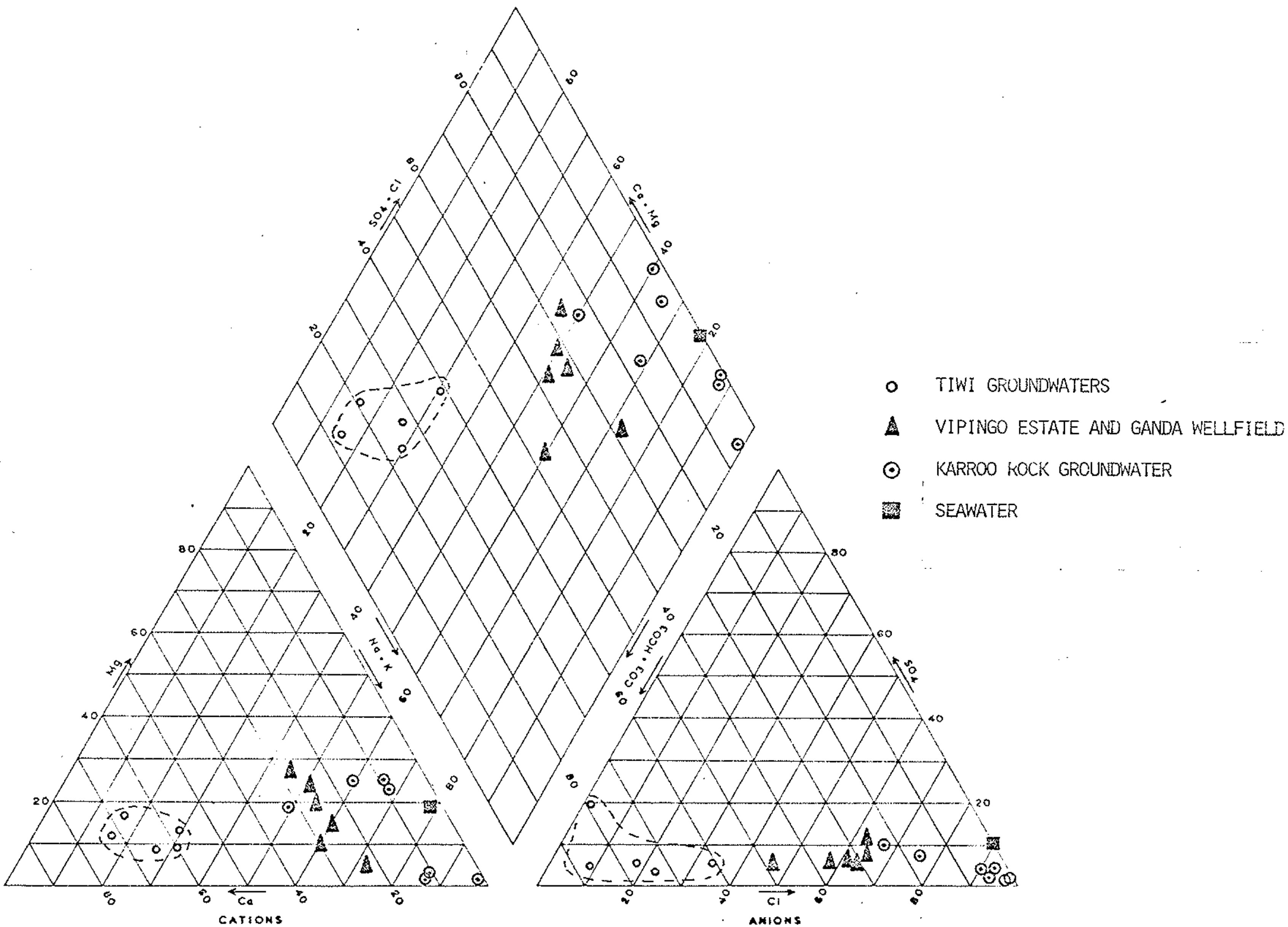

FIGURE 16 Tri-linear diagram representing chemical analyses of groundwaters.

8.5.7 Groundwater Resources.

A preliminary analysis of the resources of the Tiwi aquifer can be made using information already available but is rather imprecise because of the limitation of the data.

Because the aquifer is unconfined throughflow may be obtained from the Dupuit equation:

$$q = \frac{K(h_1^2 - h_2^2)}{2L}$$

where q = discharge from the aquifer per unit width (m^3/d)

K = permeability (m/d) = T/h

h_1 = saturated thickness of the aquifer at $x = 0$

h_2 = saturated thickness of the aquifer at $x = L$

Substituting values appropriate to the Tiwi wells:

(K = 33 m/d ($T = \sim 1000\ m^2$), h_1 = 30 m, h_2 = 26 m, L = 3000 m) gives $q = 1.23\ m^3/d$. Multiplying by the assumed width of aquifer (15 km) gives a total discharge of 18450 m^3/day. No allowance is made for gain or loss of water to the watertable by infiltration or evaporation. Present abstraction is about 4000 m^3/d.

Becuase the aquifer is unconfined this figure can be compared with the area of outcrop of the aquifer to relate the discharge to recharge. If the area of the aquifer is assumed to be 15 km x 2 km then the discharge represents 225 mm/year or about 17% of the annual rainfall which would be reasonable. The actual outcrop area is probably much larger than indicated and no account is made of lateral inflow from surface water so that the percentage of annual rainfall is likely to be much less. It should be noted however that the saturated thickness of the aquifer is considerably greater than 30 m and the transmissivity > 1000 m^2/d in the Tiwi area, so that the groundwater flow of some sections will be much greater. Precise measurement of water levels and aquifer properties are required to obtain a precise analysis, but these preliminary calculations indicate there is scope for about 5 more production wells. It should also be noted that the aquifer has significant unused storage giving scope for artificial recharge.

8.6 Vipingo Estate Area.

There are at present 14 boreholes on the Vipingo Estate area, some 30 km north of Mombasa (Figure 5). These include boreholes 1722, 2572, 2575, 2608, 3042, 3053, 3173, 3174, 3862, 3863, 4137 and 4526. The earliest, borehole 1722 was drilled in March 1952 to a depth of 60 m and penetrated grey clay and gravel with water obtained from 'blue coral'. It is probable that this description refers to Baratumu Formation and the water was said to be 'slightly mineralised'. The later drillings (2572 and 2575) in 1956 describe soft coral, loose sand and water and give high specific capacities (7.2 $m^3/h/m$, 2572) which are more typical of the sandy facies of the Pleistocene reef. Borehole 3173 drilled in 1962 to 45 m penetrated coral, sand and water and describes flowing sand entering the borehole during drilling. It has a high specific capacity (12.4 $m^3/h/m$) and was constructed using slotted casing and not wellscreen. The water quality was good (TDS = 1470 mg/l), but the sand content discharged was high.

Most if not all the Vipingo Estate boreholes are completed with slotted casing and not wellscreen. Borehole 4137 (Figure 5) which was drilled in 1975 penetrated coral and sand overlying a green-blue clay at 71 m. The borehole was tested on 25.5.1975 when a low specific capacity (0.8 $m^3/h/m$) was obtained. The pumping water level was 32.18 m. The borehole is however lined with blank casing to 43.01 m which would appear to case off part of the aquifer which may be partly responsible for its low capacity.

The clay present at 71 m (about 40 m below water level) is of interest because a similar clay is recognised at 40-50 m below watertable in the Tiwi area of the South Coast so that it may represent a significant continuous horizon and could be readily identified by gamma logging.

The drilling descriptions of the Vipingo holes suggest the presence of Baratumu Formation or Baratumu-derived sediments of low permeability in some areas and these may be responsible for the poorer quality water observed at some sites although other factors may be important. Geophysical borehole logging of some of the boreholes is strongly recommended to observe the salinity at depth and to identify the clay portions in order to assist in the construction of geological cross-sections which are necessary if the geometry of the aquifer is to be understood. In general terms the hydrogeology would appear to be similar to that of the Tiwi area.

It is not certain how many of the boreholes on the Estate are actually in production at the present time, perhaps 2 or 3. The abstraction which is used in the decortication of sisal has been estimated to be approximately 0.213 MCM/year (24 m^3/h). The design of the boreholes is such that no access is available to measure water levels. It would be useful if future boreholes incorporate an access tube or permit measurement of water level so that the decline associated with abstraction can be monitored.

Several dugwells were visited in the Vipingo area. A little south of Kikambala (20 km north of Mombasa) there are three high-producing dugwells constructed in the sandy facies of the reef complex which provide irrigation water. One such at the farm owned by M K Patel (Figure 5) is 3 m diameter and penetrates coral and sand and is used for 9 hours per day. Measurement of the water trajectory from the pump indicated a discharge of about 50 m^3/h and water quality was good (980 micromhos). Similar quality water is present in the dugwell (3 m dia.) used for public supply next to the Total Petrol Station on the main road. The well has 3 iron rails and is lined for 2-3 m only after which the coral reef can be seen. The SWL (20/11/80) was 21.280 m below casing top and the water table conductivity was 1100 micromhos.

Poorer quality water (EC = 2000) is found in the Public Well penetrating the coral reef near the MOW Shariani Road Camp (Figure 6). SWL in November 1980 was 21.500 m below casing. A borehole at Hedge Farm near to the Total Petrol Station (4 inch diameter) gives poor quality water (EC = 2320 micromhos) but this may be simply due to a construction that penetrates too deeply into a transition zone in the coral reef.

Similarly the borehole at the Vipingo Health Centre with poor quality water (EC = 2300 micromhos) may be too deep but no drilling details were available.

Several boreholes have been constructed between the Sinawe River and Kilifi Creek including borehole 4358 (200 m) and 4382 (298 m). These moderately deep boreholes provide lithological details of the Cainozoic section down to inferred Jurassic shale at 235 m (borehole 4382) and are boreholes that should be geophysically logged. Details of their construction and lithology are given in Appendix 1. The section in borehole 4358 could be Pleistocene throughout and a conglomerate of hard quartzitic pebbles described at 192-200 m should perhaps be compared with the similar description of quartz-hard consolidated conglomerate between 174 and 177 m in the Ukunda borehole (4240) south of Mombasa.

Their construction according to the record appears unusual. Borehole 4382 is lined with blank casing from 0-170 m and borehole 4358 has blank casing from 0-50 m. The SWL is given as 1 m(?) (borehole 4382) and 26 m (borehole 4358) and the lithological descriptions would suggest the aquifer is unconfined so that much of the aquifer appears to be cased out. The aquifer in borehole 4382 (17-21 m) was said to be salty but no measurements of water quality during drilling are given so that it is possible a thin lens of freshwater could have been cased out. The borehole was tested on 15-9-1977 with perforated casing between 170 and 298 m but the test measurements are confusing.

The section penetrated in borehole 4358 is very similar to those described in the Tiwi area. The drilling record reports that water was struck at 60 m but a static water level of 26 m is recorded. There is no description of clay or other material above 60 m that is likely to confine the aquifer so that it must be concluded that the aquifer is at 26 m and is unconfined and the drilling method (mud rotary) has confused its identification.

The borehole was tested when 200 m deep on 21-7-77 and gave a (reported) specific capacity of 12.5 $m^3/h/m$ and a discharge water conductivity of 8000 micromhos. (Water pumped from the borehole in the storage tank was 13000 micromhos in November 1980). Unless the water during drilling of these borehole was saline right from the watertable it is not possible from the records available to say if a layer of freshwater exists close to the watertable from these drilling results. Borehole 3303 which was drilled in the same area in 1964 to a depth of 60 m and penetrated 'good quality' water between 18 and 48 m and borehole 3254 and 3258 nearby which penetrated 'good quality' water suggest that a lens of freshwater could have been cased out, and this is supported by the observation of the driller that during pump test 'the initial water quality was good but got worse gradually'.

It is recommended that these boreholes should be geophysically logged using natural gamma and conductivity/temperature measurements to record the salinity.

There is a need for further critical assessment of drilling results in the area between Mombasa and Kilifi and for collection of basic data. Such a study should include a well inventory, measurement of water levels and water quality in existing boreholes and dugwells, measurement of abstraction and the construction of geological cross-sections similar to the one presented in Figure 8. The methodology recommended for a study of the Tiwi area (section 10) could be uaed.

8.7 The Kilifi-Malindi Area.

The groundwater prospects of the Cainozoic sediments in the Kilifi-Malindi area appear to be relatively poor. Although not studied in great detail the Roka Development Scheme boreholes (3175-3207) are all shallow (6 m) penetrating coral, sand and silt and variable quality but often saline water and their well yields are all given as 1.36 m^3/d from which it can be assumed that permeability is very low.

Borehole 1866 drilled 4 km from Kilifi in 1952 to 83 m penetrated yellow sandstone and blue clay which is probably Baratumu or Marafa Formation. The specific capacity was typically low (1.3 $m^3/h/m$) and the water was very saline (TDS = 17300 mg/l reported). The sandy facies in the area between Kilifi and Malindi is not generally as coarse-grained as it is at the locations further south and the permeability is correspondingly lower. This may be a result of the remoteness of a well-developed Coastal Range as a source of coarse material, compared to locations further south and the affect of the Vitengeni-Rare drainage. Shallow lagoon conditions suitable for gypsum formation must have existed in this area and the lagoon sediments are fine-grained and clayey. A shallow layer of freshwater does however exist as indicated by the dugwell water quality. The Mtondia public well is 13.10 m deep and has a SWL of 12.93 m and a conductivity of 1250 micromhos. Further north at Penda Kula freshwater (EC = 1000 micromhos) is literally spooned from dug pits in the sands adjacent to Mida Creek. If the pits are deepened the water quality deteriorates.

A simple well inventory which includes measurements of water quality and depth-sampling or conductivity logging of boreholes in the area will indicate the extent of non-potable water.

8.8 Ganda Wellfield Area.

The Ganda Wellfield, approximately 6 km west of Malindi (Figure 17) produces a small quantity of water for Malindi, Gede and Watamu. Only two boreholes C986 and C848 were in operation when visited in November 1980 although there are a relatively large number of production wells in the wellfield. Their total output is presently 480 m^3/d (12 m^3/h from 986; 8 m^3/h from 848).

The Wellfield was constructed in 1950 following an appraisal of groundwater potential of the area which revealed that a dugwell in Ganda village, constructed in 1930, produced good quality (195 mg/l TDS) water in 'large quantity'. In 1947 and 1948 five boreholes (848, 849, 860, 881 and 969 were drilled. These penetrated a sequence of clays and sands and reports of water struck in water-worn gravels and coarse pebbles in 848, 860 and 986 suggest that an unconfined aquifer is present in Old Sabaki River deposits probably of Pleistocene age. These overlie calcareous sands identified as Baratumu Formation (by fossil evidence) of lower permeability.

A detailed groundwater investigation was carried out by Bestow in 1958 when 10 further exploration holes were drilled. A large number of wellhead elevations were measured so that water level contours could be drawn and a water level map was presented with the report (Bestow, 1958). These are reproduced in Figure 17. The water levels show that the Sabaki River is effluent and the Ganda Wellfield discharges towards the Sabaki and is probably recharged by local rainfall. A recharge 'mound' in the sandy facies at the junction with Magarini Formation outcrop is suggested.

The shape of the contours reflects the shape of the reef structure which would appear to be responsible for the 'ponding up' of the water levels in the Ganda area.

The details of the geology interpreted from the drilling results given by Bestow (1958) show that the aquifer consists of gravel in the zone of high yields (boreholes 860, 986, 848, Q/s (860) = 8.9 $m^3/h/m$) which rests upon and passes horizontally into calcareous sandstones of the Baratumu Formation which is of lower productivity.

No pump test measurements are available for analysis but had tests been conducted they would have shown that the storage coefficient (specific yield) is very low. Bestow in his report drew attention to the decline in water level within the wellfield during its short period of operation (1949-1958) during which time the Mere Springs, reported to have discharged at 136 m^3/h (a useful source of supply?) ceased to flow. (The flowing elevation is 11.00 m above MSL). Measurements of water level by Bestow supplemented by more recent ones are listed in Table 8 and they demonstrate that the abstraction, of about 400 m^3/d, (which has varied little over the years of operation) is exceeding the current recharge so that groundwater is being mined by present abstraction.

The effect of a declining water level is a reduction in well yield through dewatering of the aquifer and where the main aquifer is a gravel overlying lower permeability sands, as in this case, dewatering of the gravel layer will lead to a serious reduction in yield and accelerated water level decline controlled by the specific yield of the underlying sands.

The decline in well yield has been recognised during operation but it has been associated with what was thought to be deterioration of the condition of the well or 'clogging', so that several wells were cleaned (848, 860) and new wells were drilled to replace failed ones. Other wells were deepened to chase the declining water level (860) in an attempt to obtain better yields. The measured water level decline between 1949 and 1980 in borehole 860 has been 10 m, and in borehole 881 has been 6 m.

If it is assumed that no recharge occurs it is possible to use the Theis relationship to calculate approximately the hydraulic properties of the aquifer which would combine to produce such a decline provided abstraction is known. The Theis relationship is as follows:

$$u = \frac{r^2 S}{4Tt}$$

$$s = \frac{Q}{4\pi T} W(u)$$

where r = radial distance from pump well to observation well (m)

S = storativity (storage coefficient)

T = aquifer transmissivity (m^2/d)

Q = discharge rate (m^3/d)

t = duration of pumping (days)

W(u) = well function of u (obtained from tables)

s = drawdown (m)

For borehole 860 assuming:

$T = 250\ m^2/d$

$t = 10950$ days

$S = 0.001$

$r = 0.1$ m

$u = 9.13 \times 10^{-13}$ $\quad$ $W(u) = 27.145$

$Q = 450\ m^3/d$ $\quad$ $s = 3.88$ m

The actual observed water level fall is 10 m so that T and S will be significantly less. Calculation shows that when S is $< 1 \times 10^{-6}$ (a confined aquifer value) drawdown is only 4.87 m so that T must be reduced to $< 250\ m^2/d$ to obtain a fall of 10 m. Using $T = 100\ m^3/d$ and $S = 0.001$ and 0.0001, drawdown of 9.39 m and 10.21 m are obtained which are close to that observed. The effect of recharge is to reduce the decline so that the estimated hydraulic properties will tend to be over-estimates. Proper pump testing should however be used to obtain precise values, and such testing should be carried out prior to significant development. Monitoring of water levels during development can then be compared with those predicted by analysis. The water level in borehole 848 has fallen to within the Baratumu Formation and pump testing now will obtain the hydraulic properties of the Baratumu Formation. A pumping test could be carried out at borehole 986 by taking water level measurements whilst pumping borehole 860 (31 m away). Given similar properties to those above the observation well would be affected after about 10 minutes.

Chemical analysis of water from borehole 860 and 3859 is given in Table 7 where it is compared with Vipingo Estate water. Wellfields which experience a significant decline in water level often show changes in water chemistry which will be apparent by comparison of time-series samples. Records of periodic sampling and analysis were not located but these should be studied to observe if there have been significant changes.

A decision on the recent recommendation by Wellfield Consulting Services (January 1980) to rehabilitate the Ganda Wellfield should take account that the decline in well yield is not simply due to screen clogging but due to a dewatering of the aquifer. Any replacement drilling would therefore need to be deeper and production would be obtained largely from the Baratumu Formation which is of low productivity. Pump testing of existing boreholes penetrating Baratumu Formation will enable calculations to be made of the drawdown that can be expected for a given abstraction. It can then be seen if pumping water levels will be below MSL which should be avoided.

Borehole	Elevation of casing top (m. above MSL)	Water level (m)	Date	Notes
848	41.82	28.04	1958	
		34.57	Jan 1976	Baratumu Formation from 33 m
		-	Nov 1980	PWL 40.09 m EC = 1600 Q = 8 m^3/h
860	-	26.10	1949	Well top elevation must be similar to 969
		30.77	1958	(r = 31 m)
		33.70	March 1976	EC = 1525 Deepened from 29.5-41 m
		36.07	Nov 1980	
881	-	19.80	1949	When drilled
		25.03	Nov 1980	32.6 m deep. Baratumu Formation from 18 m
969	40.62	26.12	1958	
986	39.28	30.84	1958	
		-	Nov 1980	No WL measurement possible EC = 1600 Q = 8 m^3/h
4025		26.21	July 1974	
		31.885	Nov 1980	41.35 m deep

Table 8. Water level measurements, Ganda Wellfield boreholes.

8.9 Summary and Conclusions.

1. The Cainozoic sediments of the coastal region have greater groundwater potential than the Karroo rocks further inland. The sediments having the highest groundwater potential are the Pleistocene reef complex sands which contain an unconfined aquifer at shallow depth along most of the coast.

2. High-yielding boreholes and wells tap this aquifer in the Mombasa-Ukunda area on the South Coast and at Kikambala and Vipingo between Mombasa and Kilifi. North of Kilifi the well yields are lower and the water quality deteriorates and there is some evidence that this is due to a change in the nature and grain-size of the Pleistocene sediments.

3. A simple hydrogeological model can be used to describe the occurrence of groundwater over much of the coastal area. The aquifer occurs at shallow depth and is unconfined. It is recharged at outcrop by rainfall and by surface run-off from adjacent areas. The watertable is expected to slope gently to the coast and groundwater discharges to the sea through the Pleistocene reef and to the creeks from other formations. A saline interface must exist in the discharge areas close to the coast. The older Cainozoic sediments generally contain poor quality water and deep drilling to investigate these formations below the Pleistocene sediments is unlikely to find better well yields and such drilling is also to be avoided in view of possible saline intrusion.

4. Large resistivity contrasts are to be found in the Cainozoic sediments and the underlying rocks so that electrical resistivity exploration methods can be employed with advantage to identify the rock units and particularly to differentiate the effect of freshwater- or saline water-saturation. An airborne geophysical INPUT survey has demarcated the outcrop of the sandy facies from that of the Pleistocene reef structure and has located areas of low conductivity which in this particular environment may be associated with groundwater.

5. There is a general need for a critical assessment of drilling results and the collection of basic hydrogeologcial data throughout the area studied. There are many boreholes and dugwells along the coast where simple information can be collected. They should be visited and located accurately on the topographic maps, and measurements made to form a well inventory. Regular records of water level and water quality in selected wells could be kept which will be valuable to future hydrogeological analysis and studies.

6. Specific recommendations for a suitable programme of work to investigate the aquifer in the South Coast area are given in Section 10.

9. GENERAL RECOMMENDATIONS

The Report has focussed attention on two main aspects:

(i) The specific identification of an area of the Coast where assistance is required to develop and manage groundwater abstraction (see Section 10).

(ii) The more general requirement for hydrogeological advice to the MOWD in certain aspects of hydrogeology and to assist their groundwater studies.

1. The MOWD Geology Section groundwater studies are presently directed towards exploration and geophysical survey. Drilling and wellsite work are routine activities and there is little resources assessment. There is an increasing need for further analysis, compilation and appraisal of these results in combination with other studies in order to view groundwater on a larger scale and to form a basis for regional resources studies.

2. There is a special need for advice on the running and analysis of pumping tests. Present analysis is inadequate and this has led to difficulties and unnecessary expense.

3. There is a need for specialist advice in the field of geophysical methods appropriate for groundwater exploration, and their interpretation. The present analysis of resistivity measurements would be considerably extended if standard methods of interpretation were used.

4. There is a need for some specialist advice in the techniques of operation and maintenance of geophysical logging equipment and the interpretation of borehole logs so that effective use of equipment can be made.

These requirements may be largely met by the proposed groundwater resources studies soon to commence with Dutch cooperation, and by the proposed (this Report, Section 10) South Coast Groundwater Resources Project. These studies aim to provide on-the-job training which is regarded as being generally the most effective.

The MOWD may however wish to decide whether they require the longer-term and more general services of an experienced hydrogeologist to head-up and organise the activities of the proposed Water Research Section, and the services of a geophysicist to give immediate advice on techniques and interpretation of geophysical methods.

PROPOSALS FOR A SOUTH COAST GROUNDWATER RESOURCES PROJECT

10. PROJECT PROPOSALS

Detailed project proposals for a suitable programme of exploration and development of the promising South Coast sandy aquifer are given below. They stress the resources aspect which is important if development is to proceed without fear of saline contamination, and they stress the importance of correct well design to ensure efficient operation and long life.

10.1 Scope of Proposed Study.

In order to quantify the groundwater resources of the Tiwi aquifer (and the same aquifers at other locations on the south coast) more and precise information is required than is available at present. Information is required to show boundaries of the aquifer (geologically, hydraulically and chemically), its hydraulic properties (T and S) from carefully controlled pumping tests of adequate duration, the seasonal change in water level, water table maps, and recharge, both from direct infiltration, and from lateral inflow of groundwater or surface run-off.

A suitable programme of work should include the following measurements and activities:

10.1.1 Data Collection.

(a) Collection and review of geological data relating to the aquifer within the coastal area.

(b) Collection and review of relevant drilling records.

(c) Collection of rainfall and evaporation records.

(d) Collection of data on groundwater abstraction from producing boreholes and dugwells, current and historical data.

(e) Collection of existing streamflow and springflow measurements relevant to the area of study.

(f) Measurement of water levels in existing dugwells, boreholes and observation wells as part of a monthly hydrograph network.

(g) Continuous measurement of water level in selected boreholes using water level recorders.

(h) Drilling programme. Drilling of exploration/observation and test/production boreholes.

(j) Geophysical logging of existing and Project boreholes.

(k) Test pumping of existing and Project test boreholes.

(l) Measurement of electrical conductivity and chemical content of water of existing dugwells and boreholes and Project boreholes.

(m) Monitoring of the freshwater/saline water interface in appropriate boreholes close to the coast and creek lines.

10.1.2 Data Analysis.

(a) Production of water level contour maps, water level fluctuation maps and depth-to-water maps.

(b) Description of the groundwater system showing areas of recharge and discharge and a description of the groundwater flow patterns.

(c) Analysis of the surface geophysical measurements in terms of aquifer units and salinity.

(d) Calculation of volumes in storage.

(e) Determination of the hydraulic properties of the aquifer, transmissivity, storage, diffusivity, leakage, etc.

(f) Presentation of a groundwater balance for the Project area.

(g) Calculation of the aquifer safe yield.

(h) Construction of a numerical model of the aquifer system and modelling of the freshwater/saline water interface.

(i) Consideration of the potential and applicability of artificial recharge techniques to augment the resources.

10.2 Area of Proposed Study.

The area of study is outlined in Figure 18. It includes the Coastal Plain from Likoni to the Ramisi River (60 km) and will include investigation of the Pleistocene reef, the sandy aquifer and the Magarini Formation. The area is about 350 km^2 and coarse-grained quartz sands, derived from the Shimba Hills, immediately inland of the Project area, are expected to form the aquifer. Elsewhere and on the North Coast the lagoonal sand deposits tend to be finer-grained and more clayey, and less productive aquifers so that the presence of the Shimba Hills as a source of high-energy deposition has hydrogeological significance. It is anticipated that the study would concentrate on the Waa, Tiwi, Diani and Muhaka areas where there is already much information and would later extend to other areas where there is less existing data.

10.3 Programme of Work.

10.3.1 Well Inventory.

There are many dugwells on the Coastal Plain which are being used or have been used, as traditional water supplies. The water in the dugwell represents the exposed water table and inventory of all dugwells is an important part of a resource study.

The Geology Section of the Coast Province Water Branch of MOWD could start an inventory of dugwells in the Tiwi-Waa area which would be of use to the Project, and could later extend it to include other wells on the coast. The information required includes:

(a) Accurate location on the 1 : 50,000 toposheets - this is basic information, air photos would be needed to differentiate wells in some areas.

(b) Elevation of measuring point (m above MSL) - in those wells chosen for the Hydrograph network (see below) it is important that the datum point elevation is accurately measured. Because of the general flat topography and shallow hydraulic gradients these elevations should be made by surveyor and not altimeter.

(c) Well depth (m) - can be measured using water level indicator probe.

(d) Depth to water (m) - using electric probe or graduated tape and read to the nearest millimeter. (Repeat measurements to be made from the same measuring point).

(e) Well diameter (m) - noting any reduction at depth.

(f) Well construction features - lined, unlined, circular, square, concrete coping, iron rail, etc.

(g) Electrical conductivity of water - at the water table as routine, and in wells close to the coast, a depth sample from the bottom of the well for comparison.

(h) Measured or estimated abstraction - required for throughflow adjustment. Measured pump discharge or number of buckets and volume. The abstraction may or may not be significant depending upon the area (alternative piped supplies).

(j) Description of rock penetrated - e.g. sands, limestone, clays and measurement of unit thickness (using water level probe again).

10.3.2 Water Level Measurements (Hydrograph Network).

A water level measurement network (Hydrograph Network) should be set up to study water level changes in the Tiwi aquifer. This should include measurements in selected dugwells of even distribution (identified in the well inventory above) and existing accessible boreholes. Boreholes where water level can be measured include 4142, 4158B, 4700 and the observation well 9.70 m from 3905 (Tiwi 1). It is recommended that water levels be measured at least monthly (same period each month say 1-5th of each month). A 2 inch nipple and pipe cap should be fitted to the casing top of existing boreholes with welded caps, (e.g. 4158B and 4700) so that the water level can be measured easily.

The Project will require continuous measurement of water level in selected observation wells, including in boreholes drilled in the reef structure (to establish hydraulic gradients and tidal fluctuations). Six water level recorders will be required. Computations to obtain aquifer diffusivity (T/S) from the groundwater tidal fluctuations should be made.

10.3.3 Run-off Measurement and Rainfall.

It may be necessary to obtain flow measurements of rivers which enter the Coastal Plain and the Mgarini outcrop in the study area for the water balance calculation. The largest stream is the Mwachema although there are several smaller streams. The cooperation and advice of the Hydrology Section would be required.

A Dines-pattern tilting syphon recording raingauge should be installed on the Coastal Plain to give a continuous record of rainfall events.

10.3.4 Exploration Drilling.

It is expected that the costs of drilling, testing, back-up services and equipment required for the drilling programme including the cost of casing and screen, would be provided by the MOWD.

The aim of the drilling and testing programme is to provide additional information on the limits of the aquifer, its hydraulic properties and to provide access for monitoring the saline interface. Dual-purpose exploration/observation and test/production type boreholes would be required. If the existing deep boreholes are geophysically logged information can be obtained that will be of use to the drilling programme and it will be probably unnecessary to drill to the same depth (200 m) in the proposed study. It is estimated that 15 boreholes of say maximum depth 100 m, would be required.

These boreholes are required for various purposes in the different aquifer units including:

(a) The sandy aquifer proper

(b) The Magarini Formation

(c) The Pleistocene reef structure

(d) Formations close to creek lines and the coast

The design of the boreholes is critically related to the construction method and their intended use or uses. The programme requires approximately 10 dual-purpose exploration/observation boreholes of small diameter and 5 dual-purpose test/production boreholes of larger size.

10.3.4.1 Exploration/Observation Boreholes

This borehole type is required for initial exploration to determine lithology, water level and water quality and should be completed suitable for use as an observation well during pump testing (a test well would be drilled nearby if the productivity is good) - it should therefore be screened at the same screened intervals as the pumped well. It would be a slim hole and gravel pack construction would not normally be possible.

A recently announced screen with an attached pre-fabricated gravel pack (Laing screen)* could be tried in these wells. If successful it would have the advantage that the well could be pumped for production purposes if necessary.

Where no significant aquifers are penetrated by the exploration boreholes, they should be left as observation wells to monitor water levels, or if the boreholes are constructed in the reef limestone or other formations close to the coast and penetrate a saline interface they should be converted to a piezometer installation to monitor the saline interface and tidal fluctuations of water level.

The boreholes would have to be drilled approximately 8 inches diameter and completed with 6 inch diameter casing and screen to allow access to water level recorder floats ($4\frac{1}{2}$ inches), piezometer pipes (say 2 inches) and to permit geophysical logging.

Exploration boreholes will be required in the Magarini Formation to define the inland extent of saturated aquifer and to investigate its groundwater potential, but extensive exploration of the Magarini Formation is not envisaged at this stage.

Exploration boreholes in the reef limestone are particularly necessary. Information is required on reef thickness, lithology (calcareous or sandy layers) on hydraulic gradients, water level fluctuations, and the position of the freshwater/saline water interface or 'saline front'. Borehole drilled to the interface may have to be completed open to only one level to avoid possible exaggerated dispersion of the interface in the borehole itself. Several boreholes open to separate levels may therefore be required at one site. To reduce the amount of drilling required for this purpose it is hoped that the geophysical measurements from existing studies can be of use to locate the saline interface in other areas.

10.3.4.2 Test/Production Boreholes.

Test/production boreholes would be constructed in the sandy aquifer at sites appropriate for use, where exploration holes indicate significant aquifers. The preliminary resources calculation indicates there is scope for about 5 more production wells (of about 100 m^3/h). The existing producing boreholes are completed with 8 inch casing and screen which is too small for the installed production pumps ($7-7\frac{1}{2}$ inches) and the well capacity. A completed diameter of 10-12 inches is therefore recommended. The test wells will probably need to be gravel packed so that allowance should be made for a 3 inch thick pack, between wellscreen and aquifer. The top-hole portion will therefore require to be of 18-20 inches diameter.

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* A pre-fabricated screen/gravel pack of textile material available with a range of slot widths 0.05-.65 mm from Geotextiles Ltd., a subsidiary of John Laing.

Borehole 3905 shows that high yields (80 m^3/h) can be obtained from 20-30 m of saturated aquifer so that the test well depth may only need to be 50-60 m, and deep drilling particularly close to a saline interface should be avoided.

10.3.4.3 Drilling Methods.

It is strongly recommended that the test/production boreholes are drilled by percussion method if this is possible. This is to avoid any possible 'mudding up' of the formation by using a rotary method and drilling fluid and also to obtain better formation samples for sieve analysis. It is appreciated though that this may not be possible.

The requirements for a gravel pack and large completion size mean that a large construction diameter is required preferably an in-line construction. The deepest percussion boreholes drilled are 3904 and 3906 which were 76 m deep but completed with only 6 inch and 5 inch casing and screen.

A rotary method may therefore be necessary so that it is strongly recommended that a biodegradable drilling fluid such as Johnsons Revert be used in place of bentonite to minimise 'formation damage' by the drilling fluid.

The exploration boreholes may be drilled by rotary method and Revert, except that exploration boreboles in the reef limestone could be drilled by percussion method (straight percussion or down-hole-hammer drilling) if there is no sand. It may be feasible to complete them through the saline interface open hole. Current thinking is that open hole construction could lead to wrong interpretation of the interface position due to dispersion so that some experiment would be required.

During drilling, by whatever method adopted, the penetration rate should be carefully recorded. This information when reliably collected is a very useful guide to lithology and helps the selection of well design.

Possible drilling problems are flowing sand and drive casing removal (percussion method). Fine sand could enter and flow up the borehole during drilling which would have to be contained by keeping the drive casing full of water to exert a positive head. Water levels in the area of study are 25-30 m below surface which gives ample positive head. Depending upon the clay content of the sands penetrated some experiment with drive casing removal for construction of the test/ production wells would be required.

10.3.4.4 Drilling Requirements.

As a guide to the quantities and sizes of casing and screen required for the suggested drilling programme a suggested listing is given below:

i) Exploration/observation boreholes - 10 required.

Rotary drilling 8 inches to TD 100 m allowing 6 inch completion without gravel pack.

Percussion drilling or rotary drilling (consolidated reef limestone areas only) to TD (100 m) allowing 6 inch completion casing screen or open hole.

Completion assembly (10 wells)

6 inch blank casing 700 m
6 inch wellscreen (Laing screen recommended) 300 m
Piezometer pipe (2 or 3 inch GI or screw coupled PVC) 500 m

ii) Test/production boreholes - 5 required.

Preferably percussion drilled or rotary/Revert 18-18+ inches diameter to 60 m. Gravel packing and completion casing and wire-wrapped screen 10 or 12 inches.

Drive casing (percussion method) 18-20 inches 60 m.

Completion assembly (5 wells)

10 or 12 inch blank casing 200 m
10 or 12 inch wire wrapped wellscreen 100 m

iii) Wellscreen and gravel pack.

The choice of wellscreen design and material is related to the intended use and properties of the water. A wire-wrapped screen is recommended because of its advantages for well development and a minimum slot size of 0.25 mm may be required which is not available in other designs. Steel, fibreglass and plastic wire-wrapped screens are available. Some fibreglass screens can be damaged by water jetting during development. Stainless steel screen would normally be used for public supply wells because of its corrosion resistance and strength.

Screen slot width of 0.25 mm (10 slot) may be required for observation well completion (no gravel pack) if Laing screen is not used. A slot width range from 0.25 mm-1.5 mm (60 slot) would be required for use with a gravel pack.

Gravel pack material might be expected to be within the range 1-6 mm and material suitable for gravel packs (quartz grains) is available at the surface at some locations, e.g. Tiwi 3 so that a suitable pack could be obtained by sieving.

iv) Drilling rig.

The DANDO 800 combination top-drive rotary/percussion rig recently acquired by the MOWD is particularly suitable for this work. It can operate as a rotary rig, straight percussion or downhole hammer rig depending upon the ancillaries connected.

10.3.4.5 Sampling.

Accurate sampling of the aquifer forms the basis of the well design, the choice of screen slot width and gravel pack grading. It is very important therefore to have the sampling carried out or supervised at all times by experienced and qualified personnel familiar with the problems. Sand samples should be bagged in the field before sieving in the laboratory and afterwards recombined and stored for reference and future use (e.g. density measurement) at HQ.

Because a saline water interface can be expected in some drilling close to the coast, measurement of water conductivity or chloride content of water from the bailer or from the cutting return, should be made at regular intervals during the drilling. This is particularly important in the reef limestone where after drilling repeat sampling in the borehole may not be representative of the salinity stratification in the aquifer.

10.3.4.6 Well Development.

Well development is vital to the successful completion of the production wells. It is believed that the most effective development technique will be sectional development in which the screen is isolated a metre or so at a time, by packers or surge blocks and the development technique is concentrated on that interval only.

Because water level is approximately 30 m below surface there would be insufficient submergence in a 60 m well for an efficient air-lift operation so that a jet-pump would be required for development work.

Development tools such as surge blocks, jetting nozzles and associated equipment are available or could be made in Kenya. The inflatable packers are not available in Kenya and would have to be obtained from outside.

It is unlikely that the existing Tiwi boreholes which pump sand could be developed to continuous sand-free operation. However well development techniques could perhaps be tried on one of the boreholes following a CCTV-inspection to check its construction.

10.3.5 Geophysical Borehole Logging and Closed-Ciruit (CCTV) Inspection.

It would be normal practice in boreholes drilled in unconsolidated rocks by mud rotary drilling, to confirm the position requiring screen or blank casing by geophysical borehole logging of the mud-filled hole. Point resistance (PR) and short- and long-normal resistivity (SN, LN) lateral resistivity (LAT), spontaneous potential (SP) and gamma logs would be run as a routine.

The resistivity of a formation (ρf) is related to the formation factor (F) and the pore fluid resistivity (ρw) as follows:

$$\rho f = F \rho w$$

If the formation consists of electrically inert grains such as quartz or feldspar (e.g. the Tiwi aquifer) the formation factor is relatively constant and changes in formation resistivity are related to changes in pore water salinity. Thus saline-saturated sands display lower resistivity than freshwater-saturated sands and resistivity logging can be used to identify saline interfaces.

If the pore water salinity is constant (e.g. Tiwi 3, Figure 15), changes in formation resistivity are related to porosity through the formation factor which is variably related as indicated below:

$$F = \frac{1}{\phi m}$$ (Archie, 1942) where m = a cementation factor

$$F = \frac{0.81}{\phi^2}$$ in sands, $$F = \frac{1}{\phi^2}$$ in compacted formations

$$F = \frac{1.05}{\phi^{1.47}}$$ (Barker and Worthington, 1973)

thus resistivity logs may give an indication of porosity. Lower resistivities indicating higher porosities. There is a relationship between median grain size and porosity so that sieve analysis is also important to resistivity log interpretation.

The clay content of the sands is hydrogeologically important; it reduces permeability and where layers exist they may represent confining beds separating aquifers. Clay is readily detected on SP and resistivity logs but is best indicated by the gamma logs which develop strong peaks alongside clay layers.

In percussion drilled boreholes steel drive casing instead of mud is left in place before running in the completion assembly to support the borehole wall. Resistivity and SP logs are therefore not possible and only gamma can be used. However the samples of the formation obtained by percussion drilling are usually better than rotary samples so that the lack of resistivity information may not be too serious.

It is recommended that the Project should use a small portable logging system with facilities for gamma, resistivity, conductivity/temperature, flowmeter measurements and depth-sampling. These latter are required to observe changes in salinity with depth and to pin-point levels of water inflow into the borehole. A suitable logging system for these measurements is the EMEX system, which apart from the logging reel, is contained within one package the size of a brief-case and can be easily operated by a hydrogeologist.

As a priority, all existing boreholes on the South Coast that have access should be logged using gamma and conductivity/temperature and possibly CCTV. This will establish the clay layers and will indicate where freswater/saline water interfaces are present and will confirm construction. Boreholes that can be logged without removal of pumps include 3905 observation well, 4142, 4158B, 4470, 4700 and 4240 (if the latter is cleared of rocks).

CCTV inspection and flowmeter logging of the existing sand pumping boreholes will indicate the level of water and sand entry.

CCTV inspection equipment will be required by the Project to check the existing borehole construction (screen location, condition of screen - corroded, encrusted, damaged, etc.) and the levels of sand and water entry and is equipment that is particularly useful to the MOWD who need to check the construction of other boreholes drilled by Private Contractor. The CCTV inspection could alternatively be provided as a service to the Project using IGS borehole television equipment during a visit by a well logging expert, if it is not purchased outright. A visit by a well logging expert to demonstrate the operation of the CCTV equipment would be necessary in either event and is also necessary to commission the Project logging equipment and to discuss the role of a well logging unit with the Geology Section of the MOWD in general.

10.3.6 Pump Testing.

The aim of the pump testing is to obtain the hydraulic properties of the aquifer (T, S, Sy, vertical permeability, Kv, of overlying semi-pervious layers) and to indicate radial anisotropy and boundaries. This information is required in resource calculations and for management purposes.

Constant rate testing of the test/production wells using observation wells is therefore required.

Inspection of the lithological logs and pumping test measurements indicates that unconfined or semi-confined aquifers can be expected, and pump testing of existing boreholes (e.g. 3905 as discussed) will give an indication of the likely duration of test to obtain specific yield, and suitable radial location of observation wells. Observation wells should fully penetrate the aquifer and have rapid response (pumping can be used to ensure this) or be located a radial distance at least 1.5 x aquifer thickness x $\sqrt{Kh/Kv}$ to avoid complicating effects of partial penetration.

Water level measurements should be made before and after the test to establish the background trend and measurements of drawdown and recovery during the test should be made by graduated electric sounder. Observation well measurements could be made by water level recorder with suitable gearing. The data should be fitted to type curves. The pumping rate during the test should be measured by in-line flowmeter or orifice plate and should not vary by > 10%. It is likely that testing of the unconfined portions will take several days or weeks and the discharge water should accordingly be fed to supply or conducted sufficiently away to avoid recharging the aquifer.

Samples of water should be collected at suitable intervals (conveniently 10, 100, 1000, 10000 minutes) to observe any chemical trends. This is particularly important if a saline interface is present or production is from several layers with different waters.

10.3.7 Water Chemistry.

Samples of groundwater and surface water will be required for analysis as a routine during the Project and it is expected that satisfactory analyses would be obtained by the MOWD chemistry and pollution control section. Specialised analysis such as stable isotope and tritium if required, would need to be done outside Kenya.

It is important that the water samples are collected properly. Standard IGS practice is to use polyethylene bottles that have been rinsed in HCl and distilled water. Bottles are sample-rinsed in the field and the sample is collected in two bottles. One sample is filtered through a 0.45 micron filter and acidified with reagent-quality HCl or HNO_3 to a pH < 3.0 to stabilise the valency and the other sample is filtered but unacidified for chloride or nitrate, bicarbonate and sulphate determination.

Bicarbonate and pH should be measured in the field. Carbonate equilibrium can therefore be studied to determine the possible encrustation effect on the wellscreen. The effect of groundwater on the wellscreen may be one of corrosion of encrustation. Calcium bicarbonate and sulphate are generally responsible for encrustation of screens (particularly where limestone is present in the aquifer, e.g. Tiwi aquifer). Corrosion is a chemical action of water on metals. It can enlarge wellscreen slot width and be responsible for sand pumping or damage to the screen. The factors which encourage corrosion are dissolved gases (O_2, CO_2, H_2S) increased EC ($>$ 1500 micromhos) and low pH (< 7.0). The corrosion tendency of groundwater can be estimated by use of a Corrater instrument.

10.3.8 Transport.

It is expected transport and transport costs would be provided by the MOWD. Landrovers or similar vehicles would be required by the Project Hydrogeologist for the duration of the project and for short periods by visiting experts. Support vehicles for the drilling operation are also required.

It is also important that the Project hydrogeologist and visiting experts be given permission to drive their official vehicle, if they wish to do so, in addition to having a driver assigned.

10.3.9 Housing and Schools.

It is expected that the resident Project hydrogeologist would be housed in Mombasa where there is excellent housing and schools and for all facilities. There is a possibility that CPWB staff housing, reserved for staff of the Sabaki Pipeline scheme, will be available. There is an excellent range of hotel accomodation available for visiting experts.

10.3.9 Staff and Equipment Costs.

A. STAFF.

	Man Months
Hydrogeologist (SSO or PSO grade)	18
Well Development Expert (driller) (2 visits)	3
Well Logging Expert (1 visit)	1.5
Geophysicist Desk Study, UK (SSO grade)	2
and field visit to Kenya	2

B. EQUIPMENT.

	£ Sterling
i) Geophysical borehole logger.	
EMEX unit comprising control unit, recorder, winch 300 m cable, and probes to enable gamma, conductivity/temperature, depth-sampling, impeller flow measurements, point resistance and resistivity.	5000
Borehole television camera, TELESPEC 800 or equivalent 300 m cable	7000-10000
OR, return airfreight of IGS television camera system. (not including visit costs of expert)	600
ii) Water level measurement.	
Munro 1H95 water level recorder with fibre pen, pulley and $4\frac{1}{2}$ inch float. (6 required)	2400
5 m tape, monthly clocks (4) weekly clocks (4) time gears 2, 4, 8, 32 day traverse range gears 1 : 1 ratio x 6 1 : 5 ratio x 3 and charts (500)	850
Ott-type water level indicator (100 m tape) (2)	320
iii) Sampling (drilling)	
Set of Endecott wire mesh sieves	500
Test sieve shaker, brushes, charts	say 300
Electronic torsion balance	1000
Sieve mesh for gravel pack compilation	50
Unconsolidated formation sampler device	1000
iv) Sampling (chemistry)	
Field Bicarbonate measurement (Hach kit)	100
Field filtration kit	100
Specific ion meter (Orion) with pH, Eh, dissolved oxygen and sulphide electrodes.	1030

£ Sterling

iv) Continued.

Electrical conductivity meter pHOX-type		115
Isotope analyses and tritium determinations	say	400
Corrater - corrosion tendency indicator		600

v) Well Development.

Double packer assembly and jet pump for sectional pumping	8000

vi) Pump Testing.

Digital stopwatch - Casio AQ 2000 or MQ-11 or equivalent	20
Flowmeter, 3 inch in-line Kent meter	300

Note: Local costs including transport, counterpart services, water level measurement programme (pre- and post-Project) and pump testing are not included.

It is estimated that the drilling costs if the boreholes were to be constructed by private drilling contractor would be of the order of £200,000 (KS 3400,000, based on an 'all in' cost of £130/KS2266 per metre.

The approximate cost of Johnson screen and Revert drilling fluid for the proposed programme is:

Johnson Screen (18-8 stainless steel)

	10 inch diameter	100 m	9500
or	(12 inch diameter	100 m	11700)

Johnson Revert 16 x 120 kg drums sufficient for 1500 m of drilling	3000

Laing Screen for observation wells

Complete well assembly 6" PVC 70 m blank 30 m Laing screen 0.25 mm slot, 10 wells	25850
Screen section only 10 wells	11100
Screen sleeve only (for use on perforated pipe not supplied)	2025

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APPENDICES

APPENDIX 1 Selected Borehole Logs.

APPENDIX 2 Report on the use of the MOWD HYDROLOGGER in Coastal Boreholes

APPENDIX 3 The History of Exploration Drilling on the Kenya Coast

APPENDIX 4 Tidal Fluctuation and Time Lag Analysis.

APPENDIX 5 Up-coning of the Saline Interface.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 689 Location Mrere Toposheet

Date drilling started 13-6-48
Date drilling completed 17-7-48
Drilled depth 76m
Elevation of casing top
which is
Water struck 35.9 m 71.9
R W L m
Main aquifer at

Hole diameter

300 mm from 0 m to 10.6 m
255 mm from 10.6 m to 33.5 m
200 mm from 33.5 m to 76 m

Casing and Screen

Type	Size	From	To	Notes
	150	0.00	33.5	Blank
		33.5	76	open hole

From	To	Lithological Details
0.00	8.84	sandy detritus and weathered sandstone
8.84	14.63	quartzy sandstone and grit
14.63	22.25	red and purple clay
22.25	31.39	light buff sandy shale
31.39	41.45	quartzy sandstone
41.45	44.19	purple sandy shale with green and purple streaks.
44.19	76.20	light grey sandstone with sandy shale bands

Remarks:

Tested after drilling at 24.5 m³/h for 44 hours (no measurements given) Tested during cleaning in 1973 with SWL = 29.56 PWL 31.08 Q = 29.22 m³/h Q/s = 19.2 water said to be good quality.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 848 Location Ganda Wellfield Toposheet Malindi 193/1

Date drilling started 18-2-49

Date drilling completed 14-3-49

Drilled depth 45m

Elevation of casing top 41.82m

which is

Water struck 28 m

R W L 28.04 m

Main aquifer at

Hole diameter

200 mm from 0 m to 44.2m

150 mm from 44.2m to 45.7 m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	200mm	0	39.01	

From	To	Lithological Details
0.00	3.00	Light brown sand
3.00	29.56	red sand and clay
29.56	33.53	white sand
33.53	39.00	sand and lumps of coral
39.00	44.19	coral
44.19	45.72	blue clay and limestone

Remarks:

SWL Jan 1976 34.57m

PWL Oct 1980 40.09m

Borehole 'cleaned' January 1976 and test pumped

$Q = 4.09 m^3/h$, SWL = 34.57 PWL = 35.40m. $Q/s = 0.24 m^3/h/m$.

KENYA COAST GROUNDWATER STUDY

BOREHOLE DETAILS

Borehole Number 860 Location Ganda Wellfield Toposheet Malindi 193/1

Date drilling started 26-4-49

Date drilling completed 12-5-49

Drilled depth 41 m

Elevation of casing top ~ 40m

which is

Water struck 27.43 m

R W L 26.10 m

Main aquifer at

Hole diameter

200 mm from 0 m to 39.6 m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	200mm	0	15.24	Blank
		15.24	27.43	Perforated ?

Borehole deepened (1976) to 41m

From	To	Lithological Details
0.00	0.66	soil
0.66	4.57	brown sand
4.57	8.23	red sand and clay
8.23	15.00	brown sand and clay
15.00	22.50	brown sand and clay, harder
22.50	24.50	as above but soft.
24.50	28.34	gravel and clay, water struck
28.34	29.56	coarse gravel
29.56	39.62	gravel

Remarks: Water level after drilling (1949) = 26.10m

SWL (1958) = 30.77m

(1976) = 33.70 EC = 1525 micromhos Q/s = 8.9 m³/h/m.

(1980) = 36.07

Borehole deepened in 1976 from 29.5m to 41m.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 982 Location Vitengeni Toposheet 192/3

Date drilling started 1949

Date drilling completed 1949

Drilled depth 121.92 m

Elevation of casing top

which is

Water struck m

R W L 7.175 m

Main aquifer at 76-85m

Hole diameter

252 mm from 0 m to 18.2 m

200 mm from 18.2 m to 30.4 m

150 mm from 30.4 m to 121.9 m

Casing and Screen

Type	Size	From	To	Notes
	150	0.00	18.28	Blank
		18.28	121.92	open hole

From	To	Lithological Details
0.00	10.00	sand and clay
10.00	13.41	sandstone
13.41	20.00	clay with murram
20.00	45.70	shale
45.70	51.81	clay
51.81	91.44	shale
91.44	121.92	sandstone

Remarks:

No chemical data available but said to be 'salty'.
No drawdown measurements given.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 1047 Location Kaloleni Toposheet 198/3

Date drilling started 7-2-1950

Date drilling completed 23-2-1950

Drilled depth 152 m

Elevation of casing top

which is

Water struck 10, 32, 143 m

R W L 6.1 m

Main aquifer at

Hole diameter

200 mm from 0 m to 15.2 m

150 mm from 15.2 m to 152 m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	150mm	0.00	16.3	Blank
		16.3	152	open hole

From	To	Lithological Details
0.00	3.048	clay
3.04	32.30	sandstone
32.30	59.74	sandstone and grey shale layers
59.74	64.00	brown shale
64.00	68.58	grey shale
68.58	152.0	sandstone, grey shale layers

Remarks:

No pump test record. Water said to be slightly saline
Borehole visited 19/9/80. SWL 5.435m below casing top.
Blockage at 7m, salty taste.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 2501 Location Jaribuni Toposheet Bamba 198/1

Date drilling started

Date drilling completed

Drilled depth 148m

Elevation of casing top

which is

Water struck m

R W L 140.8 m

Main aquifer at 140.8 – 148 ?

Hole diameter

150 mm from 0 m to 148 m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	150mm	0.00	23.16	Blank

From	To	Lithological Details
0.00	19.50	Red sandy soil
19.50	24.38	medium hard sandstone
24.38	28.34	soft sandy stone
28.34	29.26	cavity
29.26	38.71	Hard sandstone
38.71	57.91	medium hard sandstone
57.91	63.09	Hard sandstone
63.09	97.50	soft calcareous sandstone
97.50	100.00	cavity
100.00	118.26	medium hard sandstone
118.26	122.8	clay
122.8	144.4	hard sandstone
144.4	145	sand and water
145	148	med. hard sandstone.

Remarks:

Drilled by percussion, probably Mazeras sandstone from 19.50 m. Pump tested for 24 hours. Q = 6.45m³, SWL = 18.9 PWL = 19.9. No record of water quality but said to be slightly mineralised.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 2575 Location Vipingo Estate Toposheet Vipingo 198/4

Date drilling started 26-10-56

Date drilling completed 2-11-56

Drilled depth 40.84 m

Elevation of casing top

which is

Water struck 32.6 m

R W L 28.6 m

Main aquifer at

Hole diameter

mm from m to m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
Borehole		backfilled		to 33.8m

From	To	Lithological Details
0.00	0.61 m	soil
0.61	6.10m	medium hard coral
6.10	12.20	medium hard coral
12.20	30.48	soft coral
30.48	32.00	medium hard coral
32.00	34.44	sand and water
34.44	40.84	sandy clay

Remarks:

Sand flowing into hole at 32.61m

Pump tested when 33.8m depth Q/s = 0.14 m³/h/m

Tested with blank casing raised Q/s = 16.1 m³/h/m

No record of water quality

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 3173 Location Vipingo Estate Toposheet 198/4

Date drilling started 18-5-62

Date drilling completed 4-6-62

Drilled depth 44.8 m

Elevation of casing top

which is

Water struck 27.43 m

R W L 24.38 m

Main aquifer at

Hole diameter

203 mm from 0 m to 44.8 m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	203mm	0	24.4	Blank

From	To	Lithological Details
0.00	6.09	Soil and coral boulders
6.09	15.24	Mostly coral
15.24	27.43	Coral
27.43	29.26	Sand and water
29.26	44.8	loose coral and sand

Remarks: Much sand flowing in below casing. Casing driven to 40.2m and 1m of slotted 150mm pipe with base plate inserted inside 203mm casing.
Pump tested 6-6-62 Q/s = 12.4 m^3/h/m TDS: 1470 mg/l.

KENYA COAST GROUNDWATER STUDY | BOREHOLE DETAILS

Borehole Number 3254 | Location Kilifi Plantation | Toposheet 198/2

Date drilling started 26-7-63

Date drilling completed 3-8-63

Drilled depth 15.31m

Elevation of casing top

which is

Water struck 13.4 m

R W L 8.5 m

Main aquifer at

Hole diameter

150 mm from 0 m to 15.2 m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes

From	To	Lithological Details
0.00	3.00	sandy soil
3.00	9.14	clayey soil
9.14	12.14	coral
12.14	13.20	soft coral
13.20	15.20	Sand and water

Remarks:

Water said to be 'good quality', but no measurements available.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 3258 Location Kilifi Plantation Toposheet 198/2

Date drilling started 21-3-63

Date drilling completed 25.4-63

Drilled depth 37.5m

Elevation of casing top

which is

Water struck 33.5 m

R W L 29.87 m

Main aquifer at

Hole diameter

150 mm from 0 m to 37.5 m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	150mm	0	24.38	Blank
	150mm	24.38	36.57	Perforated

From	To	Lithological Details
0.00	6.09	sandy clay
6.09	18.27	soft coral
18.27	35.05	blue clay
35.05	36.05	sand and water
36.05	37.5	clay ?

Remarks:

Pump tested 22-4-63

Test 1 SWL 29.87 PWL 36.57 Q falling during test

Test 2 SWL 29.87 PWL 35.96 Q = 0.81 m^3/h

Water said to be 'good quality'.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 3303 Location Kilifi Toposheet 198/2

Date drilling started 21-4-64

Date drilling completed 2-6-64

Drilled depth 60.35m

Elevation of casing top

which is

Water struck 18.2 m

R W L 48.7 18.8 m

Main aquifer at

Hole diameter

152 mm from 0 m to 60.3 m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	150mm	0	51.2m	Blank
		51.2	60.35	Perforated

From	To	Lithological Details
0.00	18.20	coral and clay in bands
18.20	48.76	clays
48.76	54.86	sand and water
54.86	60.35	sand and clay

Remarks:

Water struck at 18.2 and 48.7m and said to be 'good quality'

Pump tested Q/s = 0.117 m³/h/m with yield reducing during test.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 3661 Location Changambe School Toposheet Mazeras 198/3

Date drilling started March 1970

Date drilling completed

Drilled depth 186.2m

Elevation of casing top

which is

Water struck 30.48 – 36m m

R W L +0.15 m

Main aquifer at below 21.6m

Hole diameter

74 mm from 0 m to 186 m — Inclined diamond-drilled hole.

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	63.5mm	+1.05m	24.38	

From	To	Lithological Details
0.00	10.67	Overburden
10.67	21.64	Calcareous siltstone (Jurassic shale)
21.64	23.16	Fault gouge and breccia
23.16	186.2	Mazeras sandstone and siltstone.

Remarks:

Inclined (50° from horizontal) diamond-drilled mineral exploration hole drilled by Mines and Geology Department near Mazeras escarpment. Water struck depth also given as 45.7m. Artesian borehole, aquifer confined by Jurassic shale. Good quality (TDS = 920 mg/l)

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 3904 Location Shamu Ukunda Toposheet Ukunda 201/3

Date drilling started 28-1-73

Date drilling completed 24-2-73

Drilled depth 76.21m

Elevation of casing top

which is

Water struck 20.42 m

R W L 15.54 m

Main aquifer at 19.81-24.39m

Hole diameter

304 mm from 0 m to 9.1 m

254 mm from 9.1 m to 76.2 m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	250mm	0	24.08	Blank
	152	0	20.73	Blank
1mm slot	152	20.73	26.82	Screen (Bridge slot)
		26.82	54.87	Blank

All casings withdrawn

From	To	Lithological Details
0.00	9.14m	red sandy clay
9.14	13.10	yellow brown sandy clay
13.10	19.81	stiff brown / yellow laminated clay
19.81	21.34	fine coral sand
21.34	24.39	sandy coral
24.39	43.29	stiff yellow sandy clay
43.29	76.21	grey-yellow sandy clay

Remarks: Percussion drilled. EC = 420 chemical analysis 16/5/73 does not balance.

Pump tested 9-2-73 SWL = 15.54 PWL = 22.56 Q/s = 1.55 $m^3/h/m$

Pump tested 15-2-73 SWL = 15.54 PWL = 25.60 Q/s = 1.35 $m^3/h/m$

All casing withdrawn.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 3905 Location Tiwi Toposheet Mombasa 201/1

(Tiwi 1)

Date drilling started 26-2-73

Date drilling completed 7-4-73

Drilled depth 50.91m

Elevation of casing top —

which is

Water struck 27.43 m

R W L 25.36 m

Main aquifer at
27.44 – 36.58
44.2 – 47.25

Hole diameter

457 mm from 0 m to 27.4 m
381 mm from 27.4 m to 37.2 m
304 mm from 37.2 m to 41.4 m
254 41.4 50.9

Casing and Screen

Type	Size	From	To	Notes
	200mm	GL	27.43	Blank
10 slot	152	27.43	36.58	Johnson Screen
		36.58	44.20	Blank
15 slot	152	44.2	47.25	Johnson Screen
		47.25	50.91	Blank

From	To	Lithological Details
0.00	5.18m	Brown clayey sandy soil
5.18	27.43	Coral formation
27.43	30.48	Coral mixed with white and brown fine to medium sand
30.48	36.58	Brown clayey silty fine to medium sand
36.58	41.46	Stiff brown silty clay sand.
41.46	44.20	Stiff black clay
44.20	47.25	medium to coarse sand
47.25	50.91	Brown fine – medium clayey sand.

Remarks:

Water struck 27.43 m.

SWL = 25.36 m (1973) 25.29 (12-6-78)

Gravel pack used. PWL 31.30 m (12-6-78)

Q/s = 11.1 m^3/h/m. EC = 440 micromhos (11/5/73)

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 3906 Location Ngombeni Toposheet Mombasa 201/1

Date drilling started 27-12-72

Date drilling completed 20-1-73

Drilled depth 76.21m

Elevation of casing top

which is

Water struck m

R W L 35.97 m

Main aquifer at

Hole diameter

305 mm	from 0 m	to 15.2 m
254 mm	from 15.2 m	to 39.6 m
203 mm	from 39.6 m	to 76.21 m

Casing and Screen

Type	Size	From	To	Notes
	152mm	0	30.48	Blank
10 slot	127	30.48	33.53	Johnson screen
	152	33.52	51.82	Blank
10 slot	127	51.82	54.87	Johnson screen
	152	54.87	70.12	Blank

From	To	Lithological Details
0.00	13.70	Brown silty clay sand soil
13.70	14.63	Coral sand
14.63	15.24	Coral sandy clay
15.24	16.76	coral sand and quartz gravels
16.76	27.43	Coral
27.43	31.40	yellow silty sandy clay (caving)
31.40	33.5	light brown clayey silty fine sand
33.5	38.10	Hard dry laminated clay
38.10	76.2	shaly clay

Remarks:

Borehole drilled by percussion method. Quartz sand and coral section is unsaturated at this location. Pump tested 12-1-1973 Q/s = 0.35m³/h/m. No measurements of water quality given, but said to be good to taste. Section tested is 51-54 (shaly clay).

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4137 Location Vipingo Estate Toposheet Vipingo 198/4

Date drilling started 1975

Date drilling completed 1975

Drilled depth 74.4 m

Elevation of casing top

which is

Water struck 32, 48, 62+ m

R W L 30.45 m

Main aquifer at 30.45–71 m

Hole diameter

252 mm from 0 m to 43 m

202 mm from 43 m to 70 m

152 mm from 70 m to 74.4 m

Casing and Screen

Type	Size	From	To	Notes
	152mm	+2.7	43.01	Blank

From	To	Lithological Details
0.00	4.00	Dark brown soil
4.00	24.00	brown soil with sand
24.00	30.00	white fine sand
30.00	42.00	coral formation
42.00	48.00	white fine sand
48.00	50.00	brown sand, some cementation
50.00	62.00	white fine sand
62.00	71.00	coarse brown sand and clay
71.00	74.4	green blue clay

Remarks:

Would appear to be completed open hole? Bottom 7.5m is backfilled with gravel. Tested on 25-5-75

$Q/s = 0.8 m^3/h/m$.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4141 Location Bamba Toposheet Bamba 198/1

- Date drilling started: 10-12-74
- Date drilling completed: 10-5-75
- Drilled depth: 310.9m
- Elevation of casing top:
- which is:
- Water struck: 50 m with RWL 22.8
- R W L: 96 m (main aquifer)
- Main aquifer at: 207.3-310.9 ?

Hole diameter

- 317 mm from 0 m to 10.7 m
- 246 mm from 10.7 m to 23 m
- 220 mm from 23 m to 137 m
- 170 137 310.9 m

Casing and Screen

Type	Size	From	To	Notes
	200mm	0	15.2m	Blank
		15.2	122	Blank
		122	140	slotted
	125mm	137.2	152	Blank
		152	178	slotted
		178	206	Blank

continued →

From	To	Lithological Details
0.00	4.00	Loose material
4.00	207.00	Hard abraisive sandstone with interbedded graywacke and thin red layers
207.00	226.00	Loose quartz sand, medium grained and light coloured
226.00	310.00	Hard abrasive sandstone and fine consolidated conglomerate layers.

Remarks: 0-90m said to be saline and cemented off. Temperature and conductivity log run 20-11-80. Present depth 255m with obstruction at 101m. CCTV inspection recommended. EC ranges from 3100 (watertable) to 3575 (at 242m). Two pumping tests carried out. No recovery after first test and test invalid. Second test 3-11-76 shows SWL 96.3 m and pumping period of 9 hours but only 4 measurements of water level given.

Borehole Number 4141 Location Bamba Toposheet 198/1

(continued)

Date drilling started

Date drilling completed

Drilled depth

Elevation of casing top

which is

Water struck m

R W L m

Main aquifer at

Hole diameter

mm from m to m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	125mm	206	226	Johnson Screen
		226	244	Blank
		244	256	Slotted
		256	274	Blank
		274	292	Slotted
		292	TD	Blank

From	To	Lithological Details

Remarks:

Second test water EC given as 1200 μmhos. SWL (20-11-80) is 34.743m below 200m casing top. Borehole P91 adjacent struck water at 85m with RWL 33.5m and EC = 11400 μmhos. Borehole completed open hole 13.5m — 86.25m.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4142 Location Tiwi Toposheet Mombasa 201/1

(Tiwi 2)

Date drilling started 10-5-75

Date drilling completed 30-11-75

Drilled depth 153m

Elevation of casing top —

which is

Water struck 30-31 m EC=850

R W L 23.2 m

Main aquifer at

Hole diameter

311 mm from 0 m to 65 m

260 mm from 65 m to 153 m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	311mm	0	3m	Blank
	203	0	30	Blank
20slot		30	42	Johnson Screen
	203	40	120	Blank
20 slot		125	153	Johnson Screen

From	To	Lithological Details
0.00	10.00	sands – clay – loose coral boulders
10.00	30.00	clays – corals – silts – sands
30.00	40.00	very coarse sands (gravels)
40.00	85.00	corals – fine sands
85.00	120.00	clays – fine sands
120.00	153.00	medium and fine sands.

Remarks:
40-113 m lost circulation
Water struck 30-31m. EC= 850 micromhos t= 22°C
Note records indicate a gap between 120 and 125m.
SWL after drilling 23.2 m Conductivity log shows
EC ranges from 570-1060 micromhos. Present depth 88m

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4158'B' Location Tiwi (site 3) Toposheet Mombasa 201/1

Date drilling started 12-11-75

Date drilling completed 22-11-75

Drilled depth 198m

Elevation of casing top –

which is

Water struck 31 m

R W L 30.1 m

Main aquifer at

Hole diameter

311 mm from 0 m to 198 m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	203mm	0	65m	Blank
		65	75	?
		75	145	Blank
20 slot		145	160	Rosco-Moss screen
		160	183	Blank
20 slot		182	198	Johnson Screen

From	To	Lithological Details
0.00	6.00	Brown calcareous sand
6.00	9.00	white-brown limestone
9.00	12.00	Grey-brown calcareous sand
12.00	21.00	Grey-brown kankar
21.00	27.00	Grey coarse-grained calcareous sand
27.00	30.00	Grey limestone
31.00	40.00	Calcareous sand
39.00	45.00	Calcareous sand + kankar
45.00	51.00	Calcareous sand
51.00	57.00	dark brown fine-medium calcareous sand
57.00	66.00	Grey calcareous sand with specs of rose garnet

continued →

Remarks:

Water struck 31m RWL 30.1m Aquifer cased out.

EC after drilling 450 micromhos

Drilled to replace 4158A drilled 3m away which filled with sand.

Present depth 170m Conductivity log run 17-11-80.

continued.

Borehole Number 4158'B' Location Tiwi (site 3) Toposheet

Date drilling started

Date drilling completed

Drilled depth

Elevation of casing top

which is

Water struck m

R W L m

Main aquifer at

Hole diameter

mm from m to m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes

From	To	Lithological Details
66.00	75.00	Grey calcareous sand mixed with sandstone and specs of rose garnet.
75.00	131.00	Grey marl
131.00	161.00	Grey coarse calcareous sand
161.00	182.00	Grey marl with specs of garnet
182.00	197.00	Grey coarse calcareous sand with specs of garnet.

Remarks:

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4215 Location Ribe Toposheet Mazeras 198/3

Date drilling started

Date drilling completed 1976

Drilled depth 100m

Elevation of casing top

which is

Water struck 7 m

R W L 3.77 m

Main aquifer at

Hole diameter

mm from m to m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	152mm	0.00	30.5	Blank
		30.5	100	open hole

From	To	Lithological Details
0.00	2.00	sandy soil
2.00	8.00	sands
8.00	100.00	Kambe Limestone

Remarks:

Pump test relates to Kambe Limestone SWL = 3.77m

PWL = 48.44m Q = 6.3 m³/h. Q/s = 0.14 m³/h/m.

Chemical analysis (165) (19-11-80) TDS = 1446 mg/l EC = 2210

EC log shows range 1820–2320 micromhos. SP log confirms casing correct.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4240 Location Ukunda Toposheet Ukunda 201/3

Date drilling started 26-5-76

Date drilling completed 30-5-76

Drilled depth 213.4m

Elevation of casing top -

which is

Water struck m

R W L 21 m

Main aquifer at 12-30m, 73-106, 115-172, 176-214

Hole diameter

325 mm from 0 m to 189 m

264 mm from 189 m to 213.4m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	200mm	0.00	12.8m	Blank
20slot		12.8	28.00	Johnson Screen
		28.00	73.20	Blank
20slot	telescopic	73.20	100.60	Johnson Screen
	203	100.60	123.4	Blank
				continued →

From	To	Lithological Details
0	3.00m	surface material (sand)
3.00	28.00	corals
28.00	73.10	sands - clays.
73.10	88.40	fine to medium sands
88.40	101.00	greyish blue clay
110.00	116.00	clays - sands
116.00	137.5	fine to medium sands
137.5	174.0	medium sands
174.00	177.0	conglomerate quartzy, hard, unconsolidated
177.00	213.4	medium to fine grey sands

Remarks:

Chemical analysis 1976 gives TDS= 1694 mg/l Cl = 600 mg/l
analysis 30-12-77 after 600 mins pumping, TDS = 3034 mg/l

Pumping test (13-6-78) Q/s = 9.6 m^3/h/m. PWL = 26m.

Borehole taken out of service because of poor quality.

continued

Borehole Number 4240 Location Ukunda Toposheet Ukunda 201/3

Date drilling started 26-5-76

Date drilling completed 30-5-76

Drilled depth 213.4 m

Elevation of casing top

which is

Water struck m

R W L 21 m

Main aquifer at 12-30m
73-106
115-172
176-214

Hole diameter

mm from m to m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	152mm	123.4	165.2	Blank
20 slot	telescopic	165.2	171.3	Johnson Screen
	152	171.3	189	Blank
		189	211.4	Johnson Screen

From	To	Lithological Details

Remarks:

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4300 Location Vitengeni Toposheet 192/3

Date drilling started 5-1-77

Date drilling completed 9-3-77

Drilled depth 300m

Elevation of casing top

which is

Water struck m

R W L m

Main aquifer at

Hole diameter

252 mm from 0 m to 30 m

222 mm from 30 m to 300 m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	203mm	0	30m	Blank
	152	0	190	Blank
	152	190	202	Wellscreen
	152	202	220	Slotted
		220	300	open hole

Borehole backfilled to 220m

From	To	Lithological Details
0.00	5.00	surface material
5.00	190.00	Hard consolidated Mariakani SST. (actually to Mazeras Sandstone)
190.00	204.00	Loose sand
204.00	220.00	sand-conglomerate and some limestone, clay at 212m?
220.00	300.00	Hard consolidated Mazeras Sandstone and thin conglomerate layers.

Remarks: Borehole design is such that only open section to formation is 190-220m. Present depth is ~175m (21-11-80). Point resistance log records from 61m. Conductivity log (21-11-80) shows EC ranges from 5040-5530 μmhos. Pumptested twice. First test when 211m EC = 5000-6000 Q/s = 0.8 m³/h/m. Second test EC = ?1800 Q/s = 1.24 but no measurements of WL given. SWL (21-11-80) is 9.165m below 152mm casing. CCTV inspection recommended.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4358 Location Kilifi Toposheet 198/2

Date drilling started 18-6-77

Date drilling completed 27-6-77

Drilled depth 200 m

Elevation of casing top

which is

Water struck m

R W L 26 m

Main aquifer at 60 - 195m ?

Hole diameter

246 mm from 0 m to 200 m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
1	152mm	0	50m	Blank
		50	100	Slotted
		100	130	Blank
		130	160	Slotted
		160	200	Blank

From	To	Lithological Details
0.00	5.00	surface material
5.00	18.00	medium and v. coarse qtz and calcareous sands
18.00	20.00	Quartz gravel
20.00	30.00	V. coarse qtz sand and gravel (water struck)
30.00	45.00	V. coarse sands and gravel, loose coral.
45.00	80.00	V. coarse sands and gravel.
80.00	105.00	medium sands, quartz.
105.00	128.00	Fine and medium-grained sands, some clay.
128.00	165.00	Very coarse sands and gravels (qtz)

continued →

Remarks: Water said to be struck at 60m but RWL and lithology suggest it is much higher.

Pump tested 21-7-77 drawdown given as 4m at $Q = 50 m^3/h$. EC = 8000.

Rotary drilling

Borehole Number 4358 Location Kilifi Toposheet 198/2

.... continued

Date drilling started

Date drilling completed

Drilled depth

Elevation of casing top

which is

Water struck m

R W L m

Main aquifer at

Hole diameter

mm from m to m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes

From	To	Lithological Details
165.00	168.00	Medium grained sands
168.00	172.00	very coarse sands
172.00	178.00	fine - medium sands, some coarse sand.
178.00	182.00	sandy clays
182.00	192.00	fine and medium sands
192.00	200.00	very coarse sands, hard conglomerate with hard quartzitic pebbles.

Remarks:

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4382 Location Kilifi Toposheet 198/2

Date drilling started 29-7-77

Date drilling completed 18-9-77

Drilled depth 298 m

Elevation of casing top

which is

Water struck m

R W L 20m, 150 m

Main aquifer at 17-21 m
226-230 m

Hole diameter

246 mm from 0 m to 298 m
mm from m to m
mm from m to m

Casing and Screen

Type	Size	From	To	Notes
		0	170m	Blank
		170	298	Perforated ?

From	To	Lithological Details
0.00	5.00	surface material
5.00	127.00	v. coarse sand and gravels.
127.00	160.00	hard abrasive sandstone.
160.00	205.00	as above, with some sandy clay layers
205.00	235.00	hard brown sandy clay
235.00	296.00	Grey blue clay

Remarks: First aquifer said to be 'salty'
Pump tested 15-9-77 SWL given as 1m PWL 170m Q=7.8m³/h
Large quantity of fine sand entering perforated sections during development. EC said to be 3600 micromhos.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4443 Location Mapotea Toposheet 191/4

Date drilling started 1978

Date drilling completed

Drilled depth 72m

Elevation of casing top

which is

Water struck 45 m

R W L 15.3 m

Main aquifer at

Hole diameter

250 mm from 0 m to 16 m

200 mm from 16 m to 61 m

152 mm from 61 m to 72 m

Casing and Screen

Type	Size	From	To	Notes
	150mm	+0.5m	41.56	Blank
		41.56	58.59	Slotted
		58.59	64.59	Blank
		64.59	72.00	open hole

From	To	Lithological Details
0.00	16.00	Unconsolidated
16.00	44.00	Very hard grey rock
44.00	70.00	Hard grey coral
70.00	72.00	Light grey sandstone

Remarks:

Description of coral (44-70m) is unusual. Borehole pump tested SWL = 15m PWL 18.35m Q = 12 $m^3/h/m$.
Water said to be 'salty' and 'smelly' (probably H_2S)
$Q/s = 3.58 m^3/h/m$.

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4526 Location Shauri Moyo Toposheet 198/4

Date drilling started 30-5-78

Date drilling completed 30-6-78

Drilled depth 182 m

Elevation of casing top

which is

Water struck m

R W L m

Main aquifer at
seepage only at
108-116
128-132

Hole diameter

254 mm from 0 m to 81 m

203 mm from 81 m to 148 m

152 mm from 148 m to 182 m

Casing and Screen

Type	Size	From	To	Notes
All casing retrieved.				

From	To	Lithological Details
0.00	1.00	Black cotton soil
1.00	3.00	Brown limestone and clay
3.00	4.00	Weathered limestone
4.00	20.00	Stiff limestone
20.00	24.00	fine - medium sandy clay
24.00	32.00	compact clay (shale)
32.00	36.00	Weathered limestone
36.00	56.00	Grey limestone and clay
56.00	60.00	Dark sandy silty clay
60.00	108.00	Compact clay and gravel

continued →

Remarks:
A squeezing sandy clay at 151m made it difficult to drive casing.
Drilled by percussion.

Borehole Number 4526 Location Shawi Mayo Toposheet 198/4

...continued.

Date drilling started

Date drilling completed

Drilled depth

Elevation of casing top

which is

Water struck m

R W L m

Main aquifer at

Hole diameter

mm from m to m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes

From	To	Lithological Details
108.00	116.00	Fine to medium sandy clay
116.00	126.00	mottled clay with boulders
126.00	138.00	Dark sandy clay with limestone
138.00	162.00	Grey fissured clay
162.00	168.00	Fine to medium clayey sand
168.00	182.00	reddish brown sandy clay

Remarks:

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4536 Location Waa (Tiwi 4) Toposheet Mombasa 201/1

Date drilling started 19-6-78

Date drilling completed 2-8-78

Drilled depth 120m

Elevation of casing top

which is

Water struck m

R W L 29 m

Main aquifer at 30–100 m

Hole diameter

445 mm from 0 m to 60 m

315 mm from 60 m to 120 m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	356mm	0	30m	Blank
	305	0	42	Blank
	305	42	60	Slotted
	203	60	84	Johnson Screen
	203	84	108	~~Rosco-Moss Screen~~
		108	120	open hole

From	To	Lithological Details
0.00	28.00	Fine sand
28.00	33.00	Coral zone
33.00	35.00	Coral zone
35.00	46.00	very fine loose sands
46.00	48.00	very coarse white quartz sands
48.00	60.00	very coarse sand and gravel
60.00	88.00	corals and gravel
88.00	90.00	sand clay
90.00	120.00	quartz gravels, some coral

Remarks: Pump tested 12-9-78 Q/s = 8.17 – 7.43 m³/h/m

EC 450–700 (higher at higher Q)

PWL (22/9/80) 39.43m below casing top. (Q = 80m³/h)

Slotted section probably gravel-packed.

Used for supply (~ 80 m³/h) continuously.

KENYA COAST GROUNDWATER STUDY

BOREHOLE DETAILS

Borehole Number 4671 Location Baricho Toposheet Jilore 192/2

Date drilling started 6-8-79

Date drilling completed 19-9-79

Drilled depth 110 m

Elevation of casing top

which is

Water struck 66 m

R W L 60 m

Main aquifer at 66 – 67.8 m
84 – 86 m
86 – 96 m

Hole diameter

254 mm from 0 m to 110 m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	152mm	0.00	67m	Blank
	152	67.0	70.0	Johnson Screen
	152	70.0	88.0	Blank
	152	88.0	91.0	Johnson Screen
	152	91.0	100.0	Blank
	152	100.0	103.0	Johnson Screen
	152	103.0	110	Blank

From	To	Lithological Details
0.00	4.00	sandy soil
4.00	7.60	ferruginous sandstone
7.60	9.60	calcareous sandstone
9.60	15.60	sandstone (fresh)
15.60	16.60	calcareous sandstone
16.60	21.60	clayey sandstone
21.60	25.00	sandstone (fresh)
25.00	27.60	sandstone (fresh) with feldspar
27.60	30.3	clayey sandstone
30.30	32.6	calcareous sandstone
32.6	37.6	fresh sandstone
37.6	41.0	clayey sandstone

continued →

Remarks:

Gamma log run. Pump tested 20-10-79 SWL 59.3 m
PWL 62.3m Q/s = 2.8 m^3/h/m. t = 17 hours
Water said to be 'salty'.
Sandstone is Mazeras Sandstone.

Borehole Number 4671 Location Baricho Toposheet 192/2

(continued)

Date drilling started	
Date drilling completed	
Drilled depth	
Elevation of casing top which is	
Water struck	m
R W L	m
Main aquifer at	

Hole diameter

mm from m to m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes

From	To	Lithological Details
41.00	47	sandstone
47.00	49.3	clayey sandstone
49.3	51.6	slightly weathered sandstone
51.6	53.0	clay
53.0	63.0	clayey sandstone
63.0	67.8	sandstone
67.8	69.6	calcareous sandstone
69.6	70.6	sandstone
70.6	73.6	clayey sandstone
73.6	79.6	sandstone
79.6	84.0	clayey sandstone
84.0	86.0	calcareous sandstone (aquifer)

86.0–96.0 clayey sst (aquifer)

96–110 sandstone

Remarks:

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4700 Location Kombani Toposheet Mombasa 201/1

Date drilling started 17-10-79

Date drilling completed 24-10-79

Drilled depth 192m → 80m

Elevation of casing top

which is

Water struck 35 m

R W L 43.48 m

Main aquifer at

Hole diameter

336 mm from 0 m to 34 m

250 mm from 34 m to 192 m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	152mm	0	35	Blank
?	152	35	41	Johnson Screen
	|	41	50	Blank
	|	50	53	Johnson Screen
	|	53	56	Blank

continued →

From	To	Lithological Details
0.00	9.00	Fine to coarse sand
9.00	12.00	silty sand
12.00	18.00	quartzy sand
18.00	30.00	silty sand and gravel
30.00	36.00	coarse to fine sand with gravels.
36.00	42.00	coarse sand
42.00	57.00	poor sorted sand, gravel and clay
57.00	78.00	silty sand, yellowish

continued →

Remarks:

Gravel packed 53-56m, 59-61m, 67-80m.

Pump tested 10-12-79 Q/s = 4.5m³/h/m. Q = 7.2m³/h.

Gravel packing against blank casing ?

Borehole backfilled to 80m.

Borehole Number 4700 Location Kombani Toposheet Mombasa 201/1

Date drilling started	
Date drilling completed	
Drilled depth	
Elevation of casing top	
which is	
Water struck	m
R W L	m
Main aquifer at	

Hole diameter

mm from m to m
mm from m to m
mm from m to m

Casing and Screen

Type	Size	From	To	Notes
		56	59	Johnson Screen
		59	61	Blank
		61	67	Johnson Screen
		67	80	Blank

— Borehole backfilled to 80m —

From	To	Lithological Details
78.00	114.00	silty clayey sand
114.00	147.00	sandy silty clay
147.00	174.00	silty sand with shell fragments
174.00	180.00	poor sorted sand and clay
180.00	189.00	fine - coarse sand
189.00	193.00	v. coarse quartz sand.

Remarks:

KENYA COAST GROUNDWATER STUDY — BOREHOLE DETAILS

Borehole Number 4701 Location Matuga (Waa) Toposheet Mombasa 201/1

Date drilling started 12-11-79

Date drilling completed 5-12-79

Drilled depth 183.5m

Elevation of casing top

which is

Water struck 86 m

R W L not given m

Main aquifer at

Hole diameter

250 mm from 0 m to 18 m

200 mm from 18 m to TD m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	152mm	0	21	Johnson Screen
	152	21	128	Blank

From	To	Lithological Details
0.00	18.00	silty sand
18.00	30.00	coarse sand and gravel
30.00	36.00	medium-coarse sand
36.00	69.00	coarse sand and gravel
69.00	82.00	calcareous sand with clay
82.00	90.00	clayey sand with gravel
90.00	99.00	clayey sand
99.00	112.00	sandy clay with gravels
112.00	118.00	fine to coarse sand

continued →

Remarks:
Casing according to drilling record.
Casing stuck at 128m and could not be landed, borehole abandoned.

continued

Borehole Number 4701 Location Matuga (Waa) Toposheet Mombasa 201/1

Date drilling started

Date drilling completed

Drilled depth

Elevation of casing top

which is

Water struck m

R W L m

Main aquifer at

Hole diameter

mm from m to m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes

From	To	Lithological Details
118.00	127.00	shelly sandstone
127.00	157.00	coarse sand with compact silty clay
157.00	163.00	fine sand
163.00	172.00	poor sorted sand with gravel
172.00	178.00	medium-coarse sand
178.00	183.00	no samples

Remarks:

KENYA COAST GROUNDWATER STUDY

BOREHOLE DETAILS

Borehole Number 4708 Location Tiwi (site 2) Toposheet Mombasa 201/1

Date drilling started 9-11-79

Date drilling completed 11-1-80

Drilled depth 120m → 54m

Elevation of casing top

which is

Water struck m

R W L 24 m

Main aquifer at 24-60m

Hole diameter

445 mm from 0 m to 120 m

mm from m to m

mm from m to m

Casing and Screen

Type	Size	From	To	Notes
	305mm	0	12	Blank
20 slot	305	12	48	Johnson Screen
20 slot	254	48	51	Johnson Screen
20 slot	203	51	54	Johnson Screen

From	To	Lithological Details
0.00	2.00	fine sands
2.00	6.00	sandy clay, corals, quartz sand
6.00	30.00	quartz sands
30.00	60.00	coarse, medium and some fine sand
60.00	120.00	fine clay sands and grey clay formation

Remarks:

Pump tested 8-1-80 when backfilled depth (54m)
SWL = 24m PWL = 27.2 m Q = 360 m³/h ? EC = 450
Pump tested 10-1-80 Screen above the watertable.
Pump tested 11 & 14-2-80 Q = 139.6 m³/h, s = 4.056 Q/s = 34.4
Sand content measured.

APPENDIX 2

Report on the use of the MOWD HYDROLOGGER in coastal boreholes near Mombasa, 13-23 November 1980.

1. INTRODUCTION

The HYDROLOGGER geophysical logging system is based on an IGS logger designed for use in completed boreholes to investigate fissure flow by means of conductivity and temperature measurements (Robinson, 1974). It has subsequently been expanded to include gamma, point resistance, SP, short- and long-normal and lateral resistivity, flow-meter, depth-sampler and caliper measurements. A hand-operated winch is used and the logging cable is a 6-conductor PVC cable with a central steel strain-bearer.

The equipment is not as robust as systems using armoured logging cable and it is therefore not well suited for use in boreholes filled with drilling mud during drilling operations. It is however lightweight and the hand-operated winch is convenient to use to depths of 200 m or so in completed boreholes. The resistivity measurement is unusual in that the output is uncalibrated and is not quite linear. The lateral electrode configuration is not standard and a separate meter is connected to give the resistance measurement.

The MOWD HYDROLOGGER has facilities for measurement of natural gamma radiation, point resistance (also uncalibrated), spontaneous potential and caliper. During my visit IGS sent additional probes and modules to enable conductivity and temperature measurement and depth-sampling of the borehole water to be made and a discreet gamma control unit was also sent.

2. USE OF THE EQUIPMENT

The MOWD HYDROLOGGER was purchased in early 1978 and it has never been used. After charging the battery packs overnight I carried out pre-logging checks according to manufacturers instructions. During tests the gamma probe was found to be non-functional, and the well head tripod was found assembled back-to-front. Considering the possibility that the gamma probe had been damaged in shipping I replaced the scintillation crystal and photomultiplier tube and also the operating module (spares provided) without success so that the fault was probably in the probe circuitry.

The logger was installed on its sprung frame and mounted in a Land-rover station wagon and driven to Mombasa by which time the hinges had fallen off the doors and one of the bolts holding the nickel-cadmium cells in the battery pack had worked loose so that it was impossible to remove the battery pack without removing the bottom rack.

The gamma probe was used with a separate gamma control unit supplied by IGS. This effectively by-passed the logger circuitry and the continued non-operation of the probe confirmed a fault in its circuitry.

Point resistance logging was attempted without success. During this operation the measuring bridge indicated that measurements were being made but no input was received at the chart recorder which suggests a fault in the switching arrangement.

The various logging functions are switched into circuit using two rotary switches labelled 1-9 and A-X. The labels (or rather the spacing between the labels) were not placed against the actual switch positions correctly so that it was difficult to know what switch position was set without counting from one end.

Caliper logging was attempted without success. The caliper probe supplied was identical to one supplied to a Project in India, which also never worked because of inappropriate design. The caliper probe is however far too heavy and its repeated use would probably soon damage the logging cable.

During field operations the McMurdo press fit connector which is fitted loosely and connects with the battery pack terminals repeatedly fell loose because it is fixed in position by only two small screws.

More seriously there was a discrepancy between the rate of feed of the cable and the chart roll feed. A light-pulse drive system synchronises the paper feed with rate of cable wind but the paper feed consistently lagged behind the cable to give an error of 1 m in 20 m which is significant.

The depth indication is displayed digitally on the console in metres and decimetres, and is given in half-metre units by mechanical counters attached to the winch and tripod pulleys.

The digital display was not reliable because if the rate of wind was interrupted or the brake apllied it would count backwards. This is partly due to poor adjustment of an arm operating a micro-switch in the measuring head but the design is not practicable. The depth display on the mechanical counter on the tripod could not be read because the tripod leg was assembled back-to-front.

The multi-electrode resistivity measurement was not tried.

Conductivity and temperature measurements were made using a TCI probe supplied by IGS. These were satisfactory. Samples of water from different depths in the borehole were taken successfully using a 250 ml depth sampler and control unit supplied by IGS. A 1.25 ml sampler is also available.

3. RECOMMENDATIONS

1. The condition and operation of the HYDROLOGGER should be checked by a service engineer and in view that it has never been used before perhaps by the manufacturer.

2. The HYDROLOGGER is more suitable for use in completed boreholes without drilling mud although it can be used in mud-filled boreholes and a sinker bar is provided to ensure that the light-weight probes could be used.

3. It is particularly suitable for conductivity/temperature measurement, for flow meter measurement, depth-sampling and gamma logging. A 25 cm scintillation crystal is available. This is larger than the one used in the WIDCO 1200 probe and may be more suitable in some applications.

Additional equipment required to carry out these functions is listed below, prices are current as of January 1981.

		£	KS
(a)	<u>Conductivity/temperature measurement</u>.		
i)	Top Wayne Kerr bridge (detuned B642) to Hydrologger specifications	1950	33150
ii)	Conductivity/temperature probe TCI	415	7055
(b)	<u>Borehole flow meter measurement</u>.		
i)	70 mm Impeller Valeport flow meter	425	7225
ii)	Flowmeter counting module	630	10710
(c)	<u>Borehole depth-sampler</u>.		
i)	1.25 litre sampler	500	8500
ii)	Depth sampler sample/fine module	375	6375

4. Alternatively the MOWD may wish to consider other options. The WIDCO 1200 system could be expanded to include flowmeter, caliper, resistivity and temperature/conductivity, and many logging systems are now small portable units which can be carried on the seat of a car. These would be convenient to use in Kenya and do not require a special vehicle. One such is the EMEX system which has facilities for conductivity/temperature, gamma, flowmeter, point resistance, spontaneous potential and resistivity and uses the HYDROLOGGER winch. It is contained in a package the size of a briefcase.

5. If the MOWD decide to carry out geophysical borehole logging as a routine, a geophysical logging unit with responsibility for borehole logging would need to be set up within Groundwater Division and staff assigned to operate the equipment and carry out the service. There is at present no expertise in geophysical well logging within the MOWD and the services of a well logging expert should therefore be obtained to advise on suitable equipment, obtaining geophysical logs and their interpretation.

APPENDIX 3

Summary of Exploration Drilling in the Coastal Area.

A large amount of exploration drilling has been carried out in the coastal region at various times. The MOWD maintain detailed records of recent exploration drilling and their records also include details of the early drilling under the then Ministry of Works and Ministry of Agriculture. Most of the information relating to the coastal region boreholes has not been summarised chronologically before so that there are likely to be several gaps where records were not consulted or were available.

The earliest record of drilling in the area studied appears to be in 1905 when boreholes were drilled in the Karroo rocks at Mile 42/10 on the railway near Samburu (to 160 m) and at Mile 44/2 (to 407 m) to explore for coal. Coal seams were known to occur in the same age rocks in Tanzania, Madagascar and South Africa but no coal was reported from these drillings which must have penetrated Maji ya Chumvi Formation or Taru Formation.*

1929 In 1929 boreholes P48, 51, 54, 58, 67 and 75** were drilled at Kilifi. Borehole 48, 51 and 67 penetrated coral and running sand and borehole 67 was said to be saline. Borehole 58 was relatively deep (183 m).

1930 In 1930 borehole P91 was drilled at Bamba (86 m). This penetrated 'sandstone' (Mariakani Sandstone) and water was struck at 85 m. An analysis given in March 1973 indicates a moderately saline (TDS 7562 mg/l) sodium chloride type water.

1930-32 Between 1930 and 1932 P103, 133, 159 and 174 were drilled in the Karroo rocks near Mariakani. These with exception of P159 were saline water although water in P159 was said to be potable. There is no record of well yield or drawdown measurement. Between 1942 and 1943 eight boreholes were constructed for the Army between Mackinnon Road and Mariakani. These were C178, 184, 189, 190, 191, 232 and 236. They were either saline or dry. Borehole 213 at Mazeras, found significantly 'fair quality' water (no measurements given). Also in 1942, borehole C181, 182 and 183 were drilled on Mombasa island penetrating reef limestone and potable water.

1944 In 1944, four boreholes C243, 317, 318 and 319 were drilled close to the Pemba River near Mrere Headworks where spring water was taken for public supply. They struck saline water in the lower layers of the Mazeras Sandstone and probably the Mariakani Sandstone. Later boreholes 689, 742, 749, 808, 838, 857 and 890 were drilled to augment the piped supply to Mombasa, nearer to the spring intake where 'better quality' water (no analysis available) was found. Measurements made during 'cleaning operations'

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* Borehole C319 near Mrere Headworks (Shimba Hills) drilled in 1944 penetrated a thin coal seam between 23 m and 24 m depth.

** All P-series boreholes were drilled between 1928 and 1934.

in 1973 give a high specific capacity (19.2 $m^3/h/m$) in borehole 689, but water quality was generally poor (2440 mg/l TDS).

1948-49 Between 1948 and 1949 six boreholes were drilled in the Karroo rocks by the PWD on the main Mombasa-Nairobi road between Mazeras and Samburu. These boreholes C658, 668, 700, 764 and 797 were saline, only 763 was reported to be 'fair quality'.

In 1949 several boreholes were constructed in the Ganda Wellfield area. They were C848, 850, 860, 881, 969 and 986. They had relatively good quality water (EC ∿ 1500 micromhos) and good specific capacities (> 5 $m^3/h/m$). Borehole 982 (Vitengeni), 996 (Kijego) and 997 (Kwa Dadu) were drilled in the Karroo rocks, and boreholes 971-974 were drilled at Shimo La Tewa, near Mtwapa Creek. These penetrated good quality water and show high yields from the loose sands on the Coastal Plain. These boreholes, and the Ganda Wellfield drillings, with exception of the Kilifi drilling in 1929, were the first strong indication of the groundwater potential of the loose sand deposits of the Coastal Plain.

1950-55 Between 1950 and 1955 borehole 1035 (Tsangatsina) 1047 and 1048 (Kaloleni) and borehole 1106 (Kwa Dem) were drilled into the Mariakani Formation. Borehole 1035 and 1106 are still in use. Groundwater in these drillings was slightly saline and this is confirmed by the recent analyses. Borehole 1073 at Chonyi in the Mazeras Sandstone had low specific capacity (0.027 $m^3/h/m$) but was reported to have 'good quality' water.

In 1950 a deep borehole (unnumbered) was drilled for coal exploration near Maji ya Chumvi station. It was drilled to 1030 m and penetrated an aquifer at 45 m (artesian) and at 880 m with, reported, only slightly saline water (2305 mg/l TDS). Borehole 1079 and 1087 (Sokoke) and 1159 and 1160 were constructed at the Dida Sawmill penetrating Magarini Formation.

Borehole 1722 was constructed at Vipingo Estate in 1952. It penetrated coral and sandstone on the Coastal Plain with a reported yield of 700 m^3/d of 'slightly mineralised' water, and borehole 2177 and 2178 at Gede were also reported 'slightly saline'.

1956 Borehole 2518 was drilled near Marafa on Magarini Formation. The borehole penetrated Marafa Formation and possibly Baratumu Formation but was dry to 122 m. Borehole 2525, 2531 and 2552 drilled near Malindi (Kisima Farm) penetrated loose sand and water.

Further drilling at the Vipingo Estate took place in 1956. Borehole 2572, 2575 and 2608 penetrated sand and water and describe problems with flowing sand. An increase in salinity at depth was identified in borehole 2608.

1958 Further exploration/production boreholes were installed in the Ganda Wellfield in 1958. Borehole 2765-72, 2814 (Malindi), 2892 and 2893 (Ganda) were constructed. Also recorded as drilled in 1958 are boreholes 2555 and 2558 at Diani south of Mombasa, the first boreholes to be drilled on the South Coast. These were located on the Pleistocene reef and produced moderate yields

(330 m^3/d) and good quality water. Borehole C2558 penetrated 45 m of reef complex before entering what is described as sandy shale. From the depth of penetration the sandy shale referred to is more likely to be Baratumu Foemation than Jurassic shale. This borehole was visited in November to obtain gamma and resistivity logs but was found to be blocked near the surface.

Borehole C2807 near Port Reitz was drilled in May 1958 to a depth of 57 m and has a log which suggests the section penetrated was all shale. The water was said to have a high salt content (although no measurements were taken). This borehole was visited on 16 October 1980 when the water was found to be of good quality (600 micromhos) at the watertable which was 8.500 m below casing top. A dune sand, probably Magarini Formation, overlies Jurassic shale at this locality and it is likely that the freshwater is from a thin section of Magarini Formation not recorded on the log. Water at greater depth, in the Jurassic may be saline (and this could be checked by conductivity measurement of depth samples.

1960 In 1960 there was exploration of the South Coast at Ukunda (C3011) and Ramisi (C3020), and further development at Vipingo Estate (3042 and 3053). Borehole 3011 is located about 500 m from the shore and penetrates 62.5 m+ of coral limestone. The reef limestone is therefore at least 62.5 m thick. Other boreholes do not penetrate entire coral sections because located further inland they penetrate the sandy facies of the reef. The evidence from boreholes in the sandy facies indicates that coral or coral debris is not generally found beyond about 85 m depth. Borehole 3042 and 3053 at Vipingo Estate penetrated the sandy facies and have high specific capacities (6.9-8.9 m^3/h/m).

1962 Further drilling at Vipingo Estate in 1962 (boreholes C3173, C3174) showed even higher specific capacities (12.4-32 m^3/h/m) in the sandy facies of the Pleistocene reef complex and moderate quality (EC = 1760-2000 micromhos).

1963-64 In 1963 borehole C3254 and 3258 (Kilifi Plantation) penetrated coral, sand and water and in 1964 borehole 3287, north of Malindi penetrated coral, with sand and water with reported good quality. Borehole 3303 (Kilifi Plantation) penetrated the same lithology.

1970 In 1970 borehole C3661 was drilled by the Mines and Geology Department close to the Mazeras escarpment as an inclined mineral exploration hole. It struck water of good quality (EC = 1330 micromhos October 1980) with artesian flow, one of the few boreholes in the Karroo rocks having water of potable standard.

1971-72 The MOWD Drilling Section investigated the lower reaches of the Sabaki alluvium in a area close to Malindi, downstream of the Baricho intake by drilling in June-August 1972. Four boreholes C3845, 3846, 3854 and 3858 were drilled to about 30 m depth. Groundwater in three of these was saline (1660-5930 TDS) and only in borehole 3846 was the water of potable quality. Its specific capacity was 5.95 m^3/h/m. It is not clear from the drilling records available whether in fact these boreholes also penetrated the underlying Marafa beds, which are known to contain poor quality water. More recently (1978) borehole C4477 was drilled into Sabaki alluvium near Garashi. Water was struck at 6 m and 38-40 m and is reported to be again saline. There is however no conductivity measurement or analysis available or an indication of the quality of the 6 m aquifer which might be expected to be of good quality similar to the river water. Sabaki river water at Baricho has a conductivity of 700 micromhos, measured in November 1980.

Deeper drilling in the Ganda Wellfield (borehole 3859 to 59 m) now took place and further drilling at Vipingo Estate (boreholes 3862, 3863) was carried out.

1973 Boreholes 3904, 3905 and 3906 were drilled in the Tiwi-Ukunda area on the South Coast, borehole 3905 showing high specific capacity and very good quality water obtained from the loose sands. Borehole 3889 penetrated 46 m of Mazeras Sandstone and reported good quality water was struck at 28 m.

1974 In 1974 borehole 4025 and 4026 were drilled into Pleistocene lagoonal sediments near Malindi with low specific capacity (1.14 $m^3/h/m$, borehole 4026) but good quality.

1975 In 1975 borehole 4137 was drilled at Vipingo Estate and penetrated the Pleistocene lagoon sediments, coral, fine white sand and clay, and possibly Baratumu Formation at the base (74.4 m). It has low specific capacity but its construction appears to be partly responsible for the low yield.

Between December 1974 and May 1975 borehole 4141 was drilled in Mariakani Sandstone to 310 m at Bamba close to borehole P91. Borehole P91 which was drilled in 1930 struck water at 85 m (SWL 33 m) which was of poor quality (EC = 11400 micromhos, TDS = 7562 mg/l and Zn = 2 mg/l). Borehole 4141 was perhaps the first mud rotary drilled borehole in the Karroo rocks. Its construction included surprisingly Johnson wellscreen which was placed against a main aquifer of 'loose sand' at 207-226 m depth, although loose sediments have not been described in other Karroo drillings. A pumping test was carried out but the measurements were not satisfactory.

Borehole 4142 was drilled at Tiwi site number 2 close to the site of borehole 3905 (Tiwi number 1). It was reported to be very high yielding (363 m^3/h is recorded) and probably the highest yielding borehole in the country. Borehole 4158 was also drilled at Tiwi (Tiwi number 3 site) and borehole 4166 was drilled at Lunga Lunga near the Tanzania border.

1976 In 1976 borehole 4215 was drilled at Ribe close to the Mazeras escarpment. It penetrated Mazeras sands overlying Kambe Limestone which contained a low productivity aquifer ($Q/s = 0.14\ m^3/h/m$). Borehole 4240 was drilled at Ukunda in the sandy facies to 213 m and is the deepest borehole in the sandy facies on the South Coast, and it is likely to have penetrated poor quality water at depth.

1977 In 1977 a further deep mud rotary borehole (4300) was drilled to 300 m depth, at Vitengeni close to borehole 982. It penetrated Middle Mazeras Sandstone although the driller records Mariakani Sandstone. Borehole 982 was drilled in 1949 to a depth of 122 m.

The main aquifer was said to be at 76-85 m in a shale horizon, and the borehole was completed open hole from 18 m. The water is reported to be saline. Borehole 4300 is by contrast lined with blank casing to 190 m although water was struck at 25.9 m and SWL was 17 m. A 'collapsing zone' is referred to between 190 and 220 m and a wellscreen, and slotted casing with gravel pack completion is recorded for this interval. The section immediately below (220-TD) was completed, surprisingly, open hole. The borehole was tested when drilled depth was 211 m and again at full depth. The second test was said to be of 24 hours duration but no measurements of water level are given and in both tests the recovery was said to be complete within 25-30 minutes which is very unusual. Subsequent attempts to pump water from the borehole at pumping rates less than those tested have drawn water level down to pump suction. The water quality is also poor (5190 micromhos when visited in November 1980) which compares with a figure of 1800 micromhos given during pump testing.

Also drilled in 1977 were borehole 4354 at Perani School, Lunga Lunga, borehole 4358 and 4382 at Kilifi and borehole 4421 and 4441 penetrating the Pleistocene reef at Leisure Lodge on the South Coast. Borehole 4422 was also drilled to 300 m at Ganze. Although not visited its construction appears to be similar to the Bamba and Vitengeni boreholes. It reports blank casing to 207 m and Johnson screen against a 'loose sand' aquifer between 207 and 219 m.

1978 In 1978 borehole 4474 and 4477 were constructed at Malindi and Garashi near the Sabaki River. Borehole 4536 was constructed in the sandy facies aquifer at Waa, on the South Coast, near Tiwi, and known as Tiwi number 4 it supplies water for public supply.

1979 In 1979 the MOWD Drilling section carried out an investigation of the groundwater potential of the strata in the vicinity of the Lango Baya Fault which is the Mazeras boundary fault. Boreholes 4671 and 4673 penetrated Mazeras Sandstones and shale. Water was struck at 63 m in 4671 and was reported to be saline. Borehole 4675 penetrated a sequence of clays, gravels and clays that does not relate to the sequence found in the other boreholes so that the assumed extension of the Lango Baya Fault probably lies between boreholes 4673 and 4675.

Borehole 4570, the fourth borehole at Tiwi 3 site, and borehole 4708, the second attempt at Tiwi 2 site, were constructed in 1979, and exploration boreholes 4700 (Kombani) and 4701 (Matuga) were drilled by the Austromineral Project on the South coast. All proved good quality water.

1980 In 1980 borehole 4773 was drilled at Tiribe near Kwale and penetrated Mazeras sandstone with slightly saline water (TDS = 1925 mg/l) and had low productivity.

There are likely to be several gaps in this brief summary of the exploration drilling due to absence of records and also because the boreholes in the Karroo rocks on the South Coast were not studied in any detail. The great majority of the drilling has been carried out by percussion methods and only recently has the hydraulic rotary method been used as at Bamba, Vitengeni, Ganze, Kilifi and at Tiwi. The results of the rotary drilling have to be considered carefully.

APPENDIX 4

Tidal Fluctuation and Time Lag Analysis.

The aquifer diffusivity $(\frac{T}{S})$ can be obtained from a knowledge of the fluctuation ratio and lag in time of occurrence of a given tidal peak or low in a borehole a known distance from the coastline.

$$\frac{S}{T} = \left(\frac{1}{x} \ln \frac{sg}{2so}\right)^2 \frac{tp}{\pi}$$

$$\frac{S}{T} = \frac{4\pi tl^2}{tp\,x^2} = \frac{Ss}{K}$$

where:

- x = distance from coastline
- $\frac{sg}{2so}$ = fluctuation ratio = $\frac{\text{groundwater level change}}{\text{ocean level change}}$
- tp = tidal period (semi-diurnal = 745 mins, dirunal = 1490 mins)
- tl = time lag
- Ss = specific storage $(\frac{S}{m})$ unit $(\frac{1}{L})$
- K = hydraulic conductivity
- S = coefficient of storage
- m = aquifer thickness

In some aquifers the water level in the borehole does not respond immediately to changes in pore pressure in the aquifer so that the water level change is delayed and damped and a correction has to be made to take this into account. Details of the correction procedure are given in Carr and Van der Kamp (1969). In practice the correction is only necessary where hydraulic conductivity is low (< 0.3 m/day).

APPENDIX 5

UP-CONING OF THE SALINE INTERFACE

The rise in conductivity in coastal wells after prolonged pumping may be a result of up-coning of the saline interface beneath the point of abstraction.

Up-coning is caused by a mounding of the interface towards the well in response to the reduced head and measurements in observation wells where this has occurred confirm that it is cone-shaped, like an inverted con-of-depression. If pumping is excessive the u-coned interface will eventually reach the base of the well and salinate the supply.

Several studies describing the complex up-coning process are available (Bear and Dagan, 1964; Schmorak and Mercado,1969). For the case of a pumping well partially penetrating a relatively thick aquifer Bear and Dagan (op. cit) have the following expression describing the up-coning of the interface as a function of time

$$Z(t)_{r=0} = \frac{Q}{2\pi(\Delta\rho/\rho_f)k_x d} \quad (1 - \frac{1}{1+\rho^1})$$

$$\text{where } \rho^1 = \frac{(\Delta\rho/\rho_f)k_z t}{2nd}$$

Z	=	rise of interface above its initial position
Q	=	pumping rate
$\Delta\rho/\rho_f$	=	dimensionless density difference between the two fluids
d	=	distance between base of well and interface at $t = 0$
r	=	distance from the pumping well
n	=	porosity of the aquifer
k_z,k_x	=	vertical and horizontal permeability
t	=	time elapsed since start of pumping

From which it is seen that the rise of the interface is directly proportional to the pumping rate and hence the drawdown. Practical studies by Schmoral and Mercado (1969) have shown that the linear relation between Z and Q is limited to a certain critical rise Z_{cr} above which the intruded cone is said to be unstable and will rapidly jump to the well causing saline water to be pumped. A review of the literature suggests that the critical point is reached when $Z > d/3-d/4$. That is to say if the interface rises more than $\frac{1}{3}$ to $\frac{1}{4}$ the distance from the bottom of the well to the original non-pumping interface depth the cone will become unstable and rapid salination will occur. The depth of the well should therefore be as shallow as convenient.

The maximum pumping rate such that will not cause $Z > Z_{cr}$ is given by:

$$Q_{max} < 2\pi d Z_{cr} (\Delta\rho/\rho_f) k_x$$

where $Z_{cr}/d < 0.25$

so that it is important to obtain the depth to the interface and the horizontal permeability by drilling and testing.