Groundwater potential assessment of Rarotonga coastal plain

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ABSTRACT

On Rarotonga the existing water supply is served by a double ring-main distribution network which is fed by the capture of surface water catchments installed on the main streams of the island. The total demand includes domestic and commercial water requirements, agricultural applications (including irrigation of market gardening) and, it is suspected significant wastage through a leak-prone distribution network. During drought periods demand increases while the supply falls and it becomes difficult or impossible for the system to satisfy all existing uses.

Twenty geo-electrical soundings (Offset Wenner and Schlumberger methods), carried out on the plains all around the island, have indicated that there is a good quantity of largely unexploited groundwater in the coastal plain aquifers, which could provide a valuable source of water supply for agricultural purposes.

This report identifies zones with groundwater potential as well as indicates appropriate extraction technology in order to minimise salt-water intrusion risk. Because of the shallow water table and the proximity of the aquifer to the seashore the use of horizontal galleries may be the most appropriate technology. Galleries avoid the problems of excessive drawdown and consequent upconing of saline water, which can result from localised pumping of individual boreholes.

It is hoped that the construction of a demonstration horizontal gallery will be the next step of this project.

ACKNOWLEDGEMENTS

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The visit to Rarotonga was co-ordinated by Mr Ben Parakoti, Director of Water Works, Ministry of Works and Physical Planning. Field work was undertaken with the assistance of Water Works staff members, in particular Adrian Teotahi and Terence Bishop who participated in the resistivity survey work and undertook some data analysis and interpretation for the project.

Mr Peter Kemp, of the Muri Beachcomber Motel, provided access to his records of groundwater levels. Daily rainfall records were provided by Mr Kevin McGill of the National Institute of Water and Atmospheric Research (New Zealand).

INTRODUCTION

Background

Rarotonga in the Cook Islands depends upon several surface water catchments for its reticulated water supply. This system provides water for domestic, commercial, industrial and agricultural uses and, during periods of drought, is becoming increasingly unreliable. This unreliability is the result of a number of factors:

- the natural climatic variability which exposes the island to frequent low rainfall periods,
- the lack of any significant storage capacity in the water supply system and the small scale of the water supply catchments,
- the leakage and other losses from the reticulation system,
- the high per capita water usage.

There are a corresponding number of actions that can be taken to improve the current position and it is likely that none will be sufficient by itself. The measures that have been proposed in the past have included:

- the construction of surface water storage capacity,
- the development of further surface water catchments,
- the upgrading of the reticulation network through a programme of leak detection and control,
- the introduction of a demand management programme through metering and charging for use,
- the development of groundwater as a supplement to the reticulated supply.

The principal purpose of this SOPAC project was to assess the potential to use groundwater to supplement existing surface water resources. The project was carried out in January/February 1998 in response to a request by the Cook Islands Government and follows recommendations made after a previous SOPAC visit (Burke and Ricci, 1996).

Geology, Morphology and Hydrogeology of the Coastal Plain

The coastal fringe of Rarotonga consists of sediments derived from inland and sea deposition processes. Foothill terraces have formed from fans of strongly weathered volcanic alluvium while a narrow strip of beach deposits and coral debris surrounds the island. A depressed belt of swamp, underlain partly by coral sand and partly by fan gravels, occurs between the terraces and the coastal strip. The geological map in Figure 1 is based on the geological survey carried out by Wood and Hay (1970) and shows the following sediments/geological units encountered from the terraces to the sea:

Nikao Gravels

Bordering the volcanic hills are terraces of various heights, consisting of weathered volcanic gravels. These terraces have been divided (Grange and Fox, 1953) into low terraces (younger Nikao) and higher terraces (older Nikao), depending on their age of formation. Variations in the deposition process have resulted in a spatially diverse lithology. On the plain, the clay matrix is predominant and the upper layer of Nikao Gravels is strongly weathered to highly impervious clay, which in places tends to clay loam. At higher altitudes, volcanic rounded pebbles frequently appear in the clay matrix of this formation. Because of this variable composition, this deposit can be expected to have a range of hydrogeological properties. Where the clay matrix is predominant the deposit is likely to be quite impermeable. This usually occurs in the plain where the Nikao Gravels border the swamp area. At greater altitudes, usually in the fans where the Nikao Gravels have been re-sorted by river transport, the clayey sediment is less pervasive and water is able to circulate. A clear distinction between these different aspects of the Nikao Gravel is not straightforward and cannot be done from morphological evidence alone.

Swamp Deposits

Between the beach deposits and the Nikao Gravels are narrow and irregular swamp-like depressions, commonly used for growing taro. These are composed of fine sediments, mostly brown and grey mud, that make the bottom relatively impermeable. The water in the swamp is generally derived from precipitation, sub-surface runoff and springs, which appear at the foot of the gravel terraces. Slightly acid freshwater in the swamps may be responsible for dissolution of carbonate material thereby increasing swamp size.

Beach Ridges (Aroa Sands)

The large ridge that fringes the Rarotonga coastal plain is composed mainly of unconsolidated carbonate sand and gravel. Wood and Hay (1970) map this zone as a single unit named “Aroa Sands”. The sands occur mainly on the south and west coast beaches, while elsewhere gravel is the predominant component. These sediments are mainly composed of bioclastic, primarily coral, carbonates but significant amounts of volcanic material may occur, especially at the mouths of the larger streams (Avana, Matavera, Turangi, and Tupapa). The relation between the carbonate sediments and the volcanic derived gravels has not been determined everywhere. The inland boundary is sometimes hidden by the swamp area and, as a result, it is difficult to define the inland extent of the sands. Previous workers (Clement and Bourguet 1992, Binnie and Partners 1984) have noted groundwater occurrence in this formation. Though the permeability could be expected to vary slightly from place to place, depending on grain size and matrix composition, it is more homogeneous than the Nikao Gravels.

Stream alluvium and reworked sediments

Large streams, especially in the north and east part of the island, maintain direct channels to the sea. They are bordered by narrow flood plains but extensive well-developed estuaries are absent. The alluvial deposits are usually composed of round boulders and fine sediments reworked by stream transport. As a general rule, the amount of fine sediment is related to the transport energy; as transport energy weakens more fine sediments are deposited. In the north and east part of the island, between the Avana and Takuvaine streams, the inner part of the coastal plain is partly comprised of sediments which have been reworked by the action of streams and floods. Richmond (1990) has mapped the extent of these deposits at a scale of 1:10,000. The distinction between reworked sediments and coastal terraces (Nikao Gravels) is based more on the geological feature of the deposits rather than on the formation process. Stream alluvium deposits can yield useable quantities of water because of their high permeability. In the past, these deposits have been exploited with infiltration galleries located in the stream beds. The hydrological potential of the fans is also likely to be good, especially where permeable deposits (such as gravel and sand) have been accumulated.

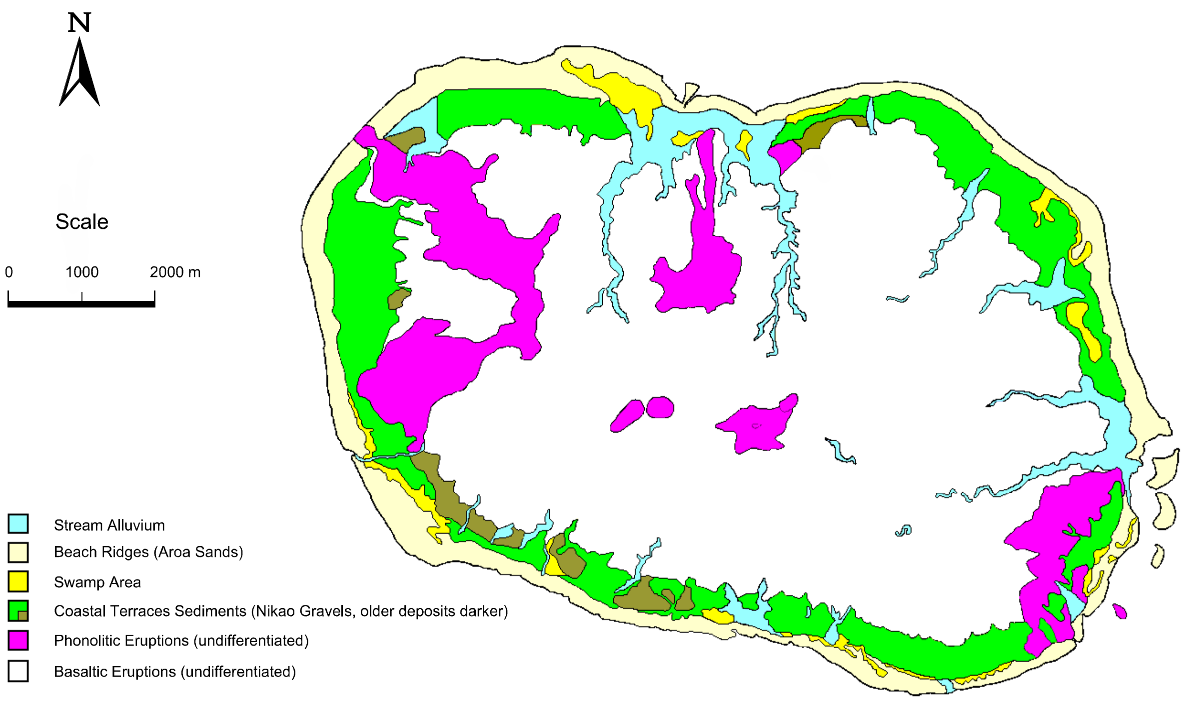

Figure 1: Simplified geologic map of the coastal fringe of Rarotonga

Hydrology and Climate

Thompson (1986) provides a description of the rainfall distribution over Rarotonga. Mean annual rainfall is highest in the centre of the island with over 4000mm reported. On the coastal margins conditions are driest in the north-west of the island (2000mm) and wettest in the south (3000mm).

The variability of rainfall recharge can be illustrated using the rainfall records from the Rarotonga Airfield for which daily data is available since 1929. For this investigation daily water budget calculations have been made using the following assumptions:

- surface runoff can be neglected
- daily evaporation estimated from the monthly total figures given by Thompson (1986)
- soil moisture holding capacity of 125 mm

The resulting temporal pattern of recharge is shown as an annual series in Figure 2. The calculated average annual recharge from rainfall is 640 mm which is approximately 33% of the average annual rainfall. However the variability of rainfall produces a corresponding variability in recharge and in some years it appears that negligible recharge may occur; e.g. in 1950, 1982, 1983 & 1987 the calculated annual recharge was less than 25% of the mean. This variability in recharge must be considered when planning to develop groundwater resources. The smaller the resource the more susceptible it will be to short-term fluctuations in recharge rates.

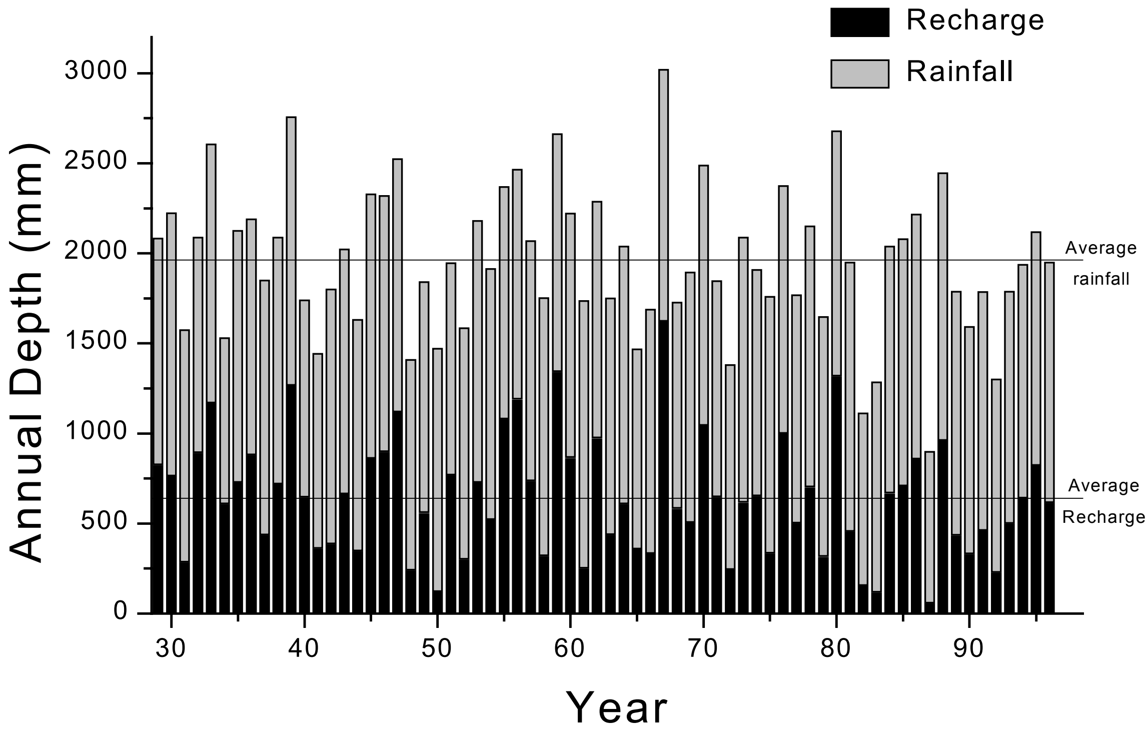

Figure 2: Measured rainfall and estimated recharge for Rarotonga Airport.

There appears to have been no long-term program of groundwater level monitoring on Rarotonga. However, from February 1997 groundwater levels have been recorded at a shallow well at Muri Beach on the south east of the island (Appendix 4). Part of that record is plotted in Figure 3 together with daily rainfall data from Totokoitu on the south of the island. Though there are other complicating factors, it is clear that rainfall is having an effect on groundwater levels. There appears to be a lag of several days between the occurrence of heavy rain and the subsequent increase in groundwater levels. In the sandy deposits at the Muri Beach well local recharge could be expected to have a relatively rapid effect. The recorded response to the high rainfall in mid-September suggests that local recharge may produce a response within 1 or 2 days. The larger response, which occurred 1 week after that rainfall, is presumably the result of lateral inflow and illustrates the potential for recharge of the coastal margins from inland areas.

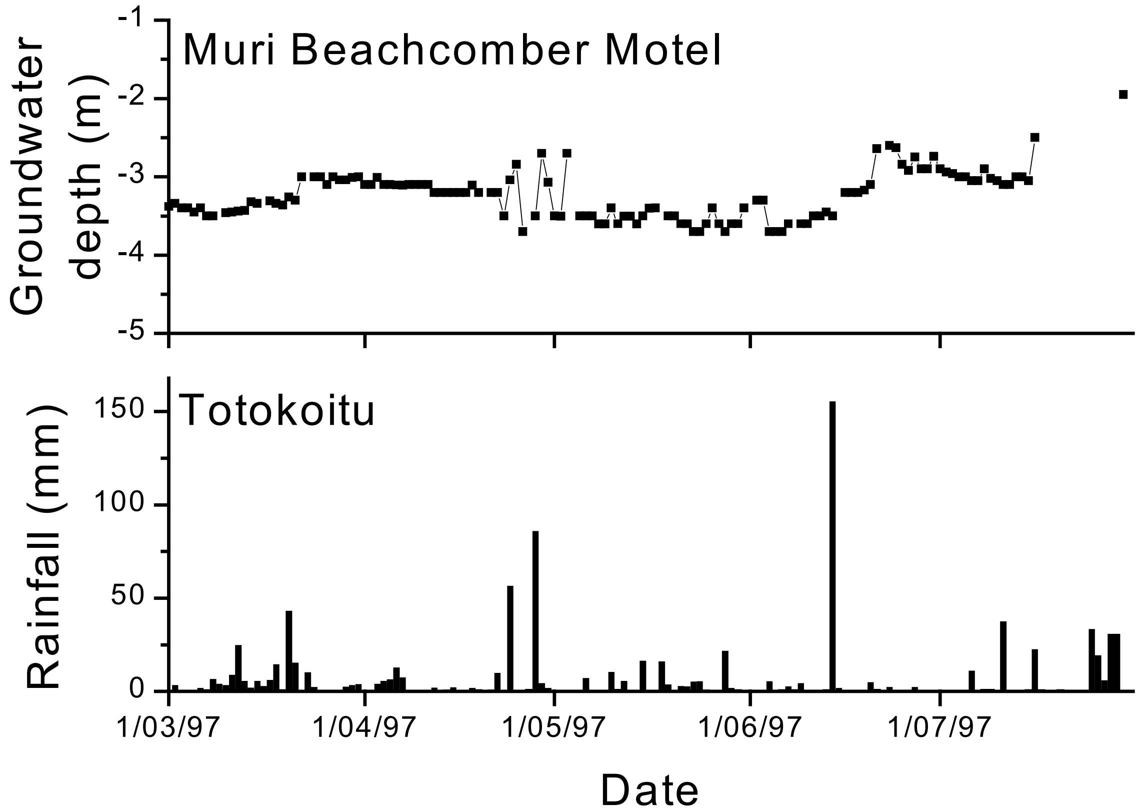

Figure 3: Groundwater depth at Muri Beach and daily rainfall at Totokoitu.

Previous groundwater studies

A number of previous investigations of Rarotonga's water resources have involved consideration of the potential for groundwater development. Binnie & Partners (1984) report on the water resources of Rarotonga focused on the needs for a public water supply and concluded that the groundwater was unlikely to provide the required yields or storage volume. Nevertheless they noted the potential for farmers to reduce their dependence on the public supply system and proposed investigation drilling in six areas of the island – largely within the Aroa sands. Aquifer properties and development potential were assessed for four geological units as follows:

- ***Stream Alluvium.*** Moderate potential for development over limited areas near major watercourses with a serious hazard of pollution.
- ***Aroa Sands.*** Good potential on inland edge of outcrop and with high yields except where aquifer thickness creates constraints.
- ***Nikao Gravels.*** Generally poor potential and suitable for only small-scale development.
- ***Volcanic Rocks***. Development potential expected to be generally poor.

Waterhouse and Petty (1986) report on the hydrogeology of six islands in the Southern Cook Islands and summarise the findings from an extended drilling programme to investigate subsurface geology. Binnie & Partners (1984) had previously used their unpublished data. In relation to Rarotonga, Waterhouse and Petty concluded that the Late Pleistocene-Holocene gravels, sand, coral, and undifferentiated alluvium could yield worthwhile quantities of ground water. However, they indicated that the quantity and quality would vary from place to place, depending upon depth of borehole and proximity to the coast, swamps, and inhabited areas.

Clement and Bourget (1992) undertook an assessment of the surface water and groundwater resources of Rarotonga. They identified the coastal plain as a good source of groundwater and, amongst a range of measures, proposed groundwater development by shallow wells in the coastal plain. Their preliminary estimate of groundwater resources in the coastal plain indicated a flow of approximately 550 l/sec through about 32 km of coastal line (equivalent to an average of about 1 to 2 l/sec for every 100 metres of beach length).

Burke & Ricci (1996) undertook an assessment of the exploitation of groundwater resources and prepared a plan for the development and management of existing aquifers. The first phase of that plan included a proposal to carry out a geophysical survey of the Nikao Gravels and Aroa Sands together with borehole drilling and testing.

METHODS

This project primarily involved a geophysical survey designed to determine the depth to groundwater and, where possible, to underlying salt water in the Aroa Sands and the Nikao Gravels on the coastal margins of Rarotonga. In addition, hydrological and meteorological data were analysed in an attempt to provide a perspective on the nature of drought events in Rarotonga.

Geophysical Survey

Knowledge of the location of the interface between saline and fresh groundwater is of far-reaching importance for island water resource management. Geophysical methods have proved to be particularly well suited for this purpose, since the electric resistivity of the aquifer is strongly influenced by the ions dissolved in the groundwater and results in marked contrasts between the properties of unsaturated, fresh-water saturated and salt-water saturated media. Surface resistivity methods are based on the concept that the apparent resistivity of the ground can be measured by inducing an electrical current at the ground surface using a standard array of electrodes (two current and two potential electrodes). Resistivity soundings involve measurements of apparent resistivity over a range of electrode spacings in order to obtain an indication of how resistivity changes with depth. Interpretation of these soundings can establish the depths to a sequence of different layers with different electrical resistivity.

The resistivity soundings undertaken in this survey used the “Offset Wenner” method (Barker, 1981) which is an improvement on the standard Wenner array. In addition, four Schlumberger array sounding were carried out. In the Offset Wenner method five electrode positions are used to measure two (offset) Wenner resistances and three additional resistances. The displacement (offset) of one of the Wenner array reduces undesirable spurious effects due to lateral underground resistivity variations. In addition, three additional resistance measurements allow calculation of the observation error, which gives an indication of the reliability of the measurement for each electrode spacing.

Soundings were carried out using an ABEM Terrameter SAS 300 supplemented, as required, with the SAS 2000 Booster. Field results obtained with the booster unit appeared unreliable and results obtained using the booster were not used in subsequent analysis. The Offset Wenner array was set up using the BGS-256 switch box and multi-core cables with steel spikes used as current and potential electrodes.

The purpose of the geophysical survey was to investigate the depth and thickness of freshwater in deposits of the coastal plain around the island. Since electrical resistivity methods perform at their best in a horizontal layered situation, all the soundings were oriented, as far as possible, parallel to the coastline. Soundings were usually carried out along one of the two roads that circle the island in order to obtain relatively easy access to the length of relatively clear ground required. In addition this made it possible to take advantage of elevation data available for some sections of road.

Drought Analysis

Drought is an unusual hazard as, by its very nature, its onset is gradual. As a drought develops water resource managers may be caught in the situation where it appears that they are not prepared for the situation. A drought index can provide a measure of the severity of a drought and can be used to inform the public and as a basis for specific drought management measures.

Drought can be defined in terms of plant water requirements, fire hazard, catchment yield, groundwater resources etc., and each requires a different basis on which to calculate a drought index. The Palmer Drought Severity Index (Palmer 1965) has been popular in the US as a measure of meteorological drought and requires data on precipitation, temperature and soil Available Water Content (AWC). However, despite its popularity and wide use within the US the Palmer Drought Severity Index has a number of limitations: in particular it does not accurately represent the hydrological impacts resulting from long term droughts.

The Standardised Precipitation Index (SPI) has been developed by McKee et al. (1993) to quantify precipitation deficits for different time scales. These time scales reflect the impact of drought on the availability of different water resources; soil moisture conditions could be expected to relate to an SPI calculated on a relatively short scale, whereas streamflow and groundwater conditions reflect longer time scales. As defined by McKee et al. (1993) the SPI is normalized so that wetter and drier climate can be represented in the same way. The classification of drought provided by McKee et al. (1993) is shown in Table 1

Table 1: Standardized Precipitation Index categories

SPI Value	Drought Category
0.00 to –0.99	Mild
-1.00 to –1.49	Moderate
-1.50 to –1.99	Severe
-2.00 or less	Extreme

RESULTS

Resistivity Interpretation

A total of 20 soundings were carried out at 18 sites. Appendix 1 provides full details of field observations for those soundings together with sounding curve plots and a summary of the interpretation. For the Offset Wenner soundings the plots also show the apparent resistivity for the offset arrays at each electrode spacing; effectively displaying the offset error. At two sites, where initial sounding results appeared unsatisfactory, duplicate soundings were made using Offset Wenner and Schlumberger arrays and the more reliable sounding used in the subsequent interpretation.

For each sounding it is possible to identify a layered earth model which explains the observed apparent resistivity variation with depth. The layers represent not only the geological variation but also identify the depth to fresh groundwater and to the interface with underlying salt-water. When interpreting individual soundings the choice of layered model has been constrained by other relevant information such as the ground elevation, the estimated or measured depth to the water table and any available drilling information. The interpretation also involved considering all soundings collectively in an attempt to correlate geological/hydrogeological layers between individual sites. This process has led to the identification of the following layer types or units:

Topsoil. This is the reworked thin portion (usually less than a metre) of upper ground. Depending on the matrix composition of this soil, the resistivity values range from 500 ohm*m (sandy matrix) to 30 ohm*m (clayey matrix). One sounding (located besides the airstrip) indicates a topsoil formed by backfill gravel used to drain and stabilise the ground.
Unsaturated. This represents a unit that does not contain free water. This does not mean that this unit must be totally dry, because some clayey sediment contains a percentage of capillary water. The presence of this capillary water in very fine sediments affect resistivity values and sometimes results in resistivity values equivalent to saturated conditions. In the unsaturated beach deposits (Aroa Sand) resistivity ranges from 200-600 ohm*m (when mostly sandy) to 1200-2400 ohm*m when gravel is predominant. The presence of clay in unsaturated sand deposits significantly lowers the resistivity value. When the layer is formed almost entirely of clay the resistivity value drops to a few ohm*m.

Saturated. This represents a unit where water is freely available and eventually could be extracted. The field results quite clearly indicate the distinction between freshwater-saturated and saltwater-saturated layers. Some differences in resistivity values were highlighted in freshwater-saturated layers, where the presence of fine sediments (clayey products of weathered volcanic rocks process) has reduced the resistivity. The fact that some low values of resistivity are due to the matrix composition, rather than the presence of brackish water, is confirmed by two soundings where water conductivity has been measured. In these cases water conductivity measurements indicate freshwater while geoelectrical modelled results suggest a water-saturated layer with relatively low resistivity.

Volcanic Basement. In some parts of the island the volcanic basement is shallower than elsewhere, located only a few metres below the soil surface. These rocks, dense and fine grained, outcrop mainly in the west side of the island and close to Muri. Soundings at these sites very clearly show the presence of dry massive rocks. The values given to these rocks accord with reference values for dry basalt (Milsom, 1996).

The resistivity ranges for the different conditions encountered in each of the layer types are summarised in Table 2. Commentary on the sounding interpretations is provided in Table A1-1 of Appendix 1 and individual sounding interpretations are summarised in Table 3. Where the presence of a freshwater layer has been inferred its properties have been highlighted. The sounding root mean square (RMS) error indicates how well the interpreted layered model explains the field observations. It is possible for several alternative models to explain field observations and the equivalence column in Table 3 indicates the severity of this factor for each model layer. An overview of the results is presented in Figure 4 showing the location of each sounding together with a representation of the interpreted model.

Table 2: Summary of interpreted resistivity values

LAYER TYPE	CONDITION	RESISTIVITY (ohm*m)
Top soil	Sandy	100 – 500
	Clayey	30 – 70
	Gravel (base course)	1200 – 2000
Unsaturated	Dry sand	200 – 600
	Dry sand and gravel (beach deposit)	1200 – 2400
	Sand and clay (depending on proportion)	20 – 120
	Clay	0.4 - 6
Saturated	Freshwater sand and gravel	150 – 200
	Freshwater sand	100 – 150
	Freshwater sand and clay	20 – 30
	Saltwater sand and gravel	2 – 10
Volcanic basement		300,000 – 600,000

Table 3: Resistivity sounding interpretations

Sounding RMS Error	**Depth** (m)	**Thickness** (m)	**Resistivity** (ohm-m)	**Equivalence**	**Lithology**	**Altitude** ***WT Depth***
RARO1	0	0.45	70	Minor	clayey top soil	4
2.95%	0.45	1.6	27.6	Minor	dry sand + clay	***2.05***
	2.05		20		freshwater sat. sand and clay	
RARO2	0	0.8	1800	Severe	top soil (gravel)	3.6
27.4%	0.8	0.6	400	Severe	dry sand	***1.4***
	1.4	7	28	Mild	freshwater sat. sand and clay	
	8.4		10000000		volcanic basement	
RARO3	0	2.5	250	Minor	dry sand	2.5
16.6%	2.5	4.9	140	Severe	freshwater sat. sand	***2.5***
	7.4	3.5	1.8	Severe	saltwater sat. sand	
	10.9		400000		volcanic basement	
RARO4	0	4.3	2240	Minor	dry sand and gravel	5.5
14.9%	4.3	5.2	135	Severe	freshwater sat. sand	***4.3***
	9.5	4.2	6.16	Severe	saltwater sat. sand	
	13.7		400000		volcanic basement	
RARO5	0	0.7	1050	Mild	dry sand and gravel	5.5
23.0%	0.7	3.2	2000	Severe	dry sand and gravel	***3.9***
	3.9	12	111	Mild	freshwater sat. sand	
	15.9	3.8	10	Severe	saltwater sat. sand	
	19		400000		volcanic basement	
RARO6	0	0.11	1420	Severe	top soil (gravel)	9.3
7.82%	0.11	8	23	Unique	clayey deposits	***9.21***
	8.11	1.1	0.63	Severe	very clayey horizon	
	9.21		156		freshwater sat. sand and gravel	

RARO7	0	1	69	Unique	top soil	6.5 - 7.5
6.02%	1		19.3		clayey deposits	
RARO8		4.98	1150	Minor	dry sand and gravel	5.5
12.7%	4.98	14.9	150	Severe	freshwater sat. sand	***4.98***
	19.88		13.12		saltwater sat. sand	
RARO9	0	0.34	145	Mild	sandy top soil	2.8 - 3.2
20.5%	0.34	1.5	600	Mild	dry sand	***1.84***
	1.84	7	45	Severe	freshwater sat. sand	
	8.84	20	12	Mild	saltwater sat. sand	
	28.5		400000		volcanic basement	
RARO10	0	0.8	510	Mild	sandy top soil	2.8
8.43%	0.8	1.4	600	Mild	dry sand	***2.2***
	2.2	14	148	Minor	freshwater sat. sand	
	16.2		5.7		saltwater sat. sand	
Sounding	**Depth**	**Thickness**	**Resistivity**	**Equivalence**	**Lithology**	**Altitude**
RMS Error	(m)	(m)	(ohm-m)			***WT Depth***
RARO11	0	0.32	494	Mild	sandy top soil	4.4
13.0%	0.32	2.5	1300	Mild	dry sand and gravel	***2.82***
	2.82	6.5	40	Severe	freshwater sat. sand	
	9.32		14		saltwater sat. sand	
RARO12	0	0.15	110	Severe	sandy top soil	3.7
41.0%	0.15	1.5	220	Severe	dry sand	***1.65***
	1.65	12	20	Severe	freshwater sat. sand	
	13.65		500000		volcanic basement	
RARO13	0	0.135	39	Severe	clayey top soil	7.6
4.28%	0.135	3.726	17	Unique	clayey layer	***5(?)***
	3.861	1.128	120	Severe	sandy clayey layer	
	4.989	0.15	0.33	Severe	very clayey layer	
	5.004		24		freshwater sat. sand and clay	
RARO14	0	0.31	60	Severe	clayey top soil	6.8
5.10%	0.31	4.9	24.6	Minor	sand and clay	***5.21***
	5.21	4.7	35	Extreme	freshwater sat. sand and clay	
	9.91		2.7		saltwater sat. sand	
RARO15	0	0.25	140	Severe	sandy top soil	9
7.24%	0.25	0.56	90	Severe	dry clayey top soil	
	0.81		23		sandy clayey layer	
RARO16	0	0.5	110	Severe	sandy top soil	10
5.36%	0.5	7.9	48	Minor	clayey deposit	***9.9***
	8.4	1.5	1.5	Severe	very clayey horizon	
	9.9		120		freshwater sat. sand and gravel	

RARO17	0	0.71	256	Severe	sandy top soil	2.8
9.55%	0.71	1.8	1300	Severe	dry sand	***2.5***
	2.51	6.4	90	Severe	freshwater sat. sand	
	8.91		10		saltwater sat. sand	
RARO18	0	0.13	125	Severe	sandy top soil	5.4
21.1%	0.13	5	330	Mild	dry sand	***5.13***
	5.13	10	150	Severe	freshwater sat. sand	
	15.13	5.8	2.2	Severe	saltwater sat. sand	
	20.8		400000		volcanic basement	

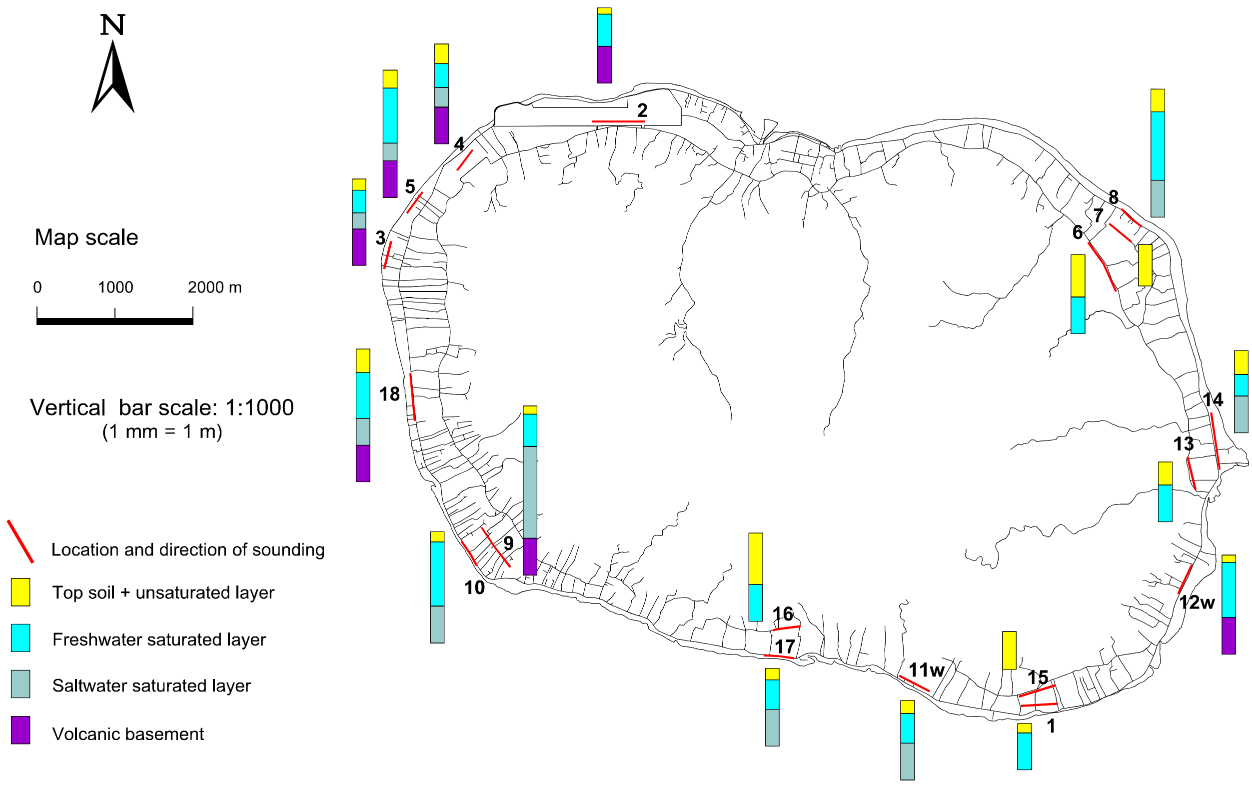

Figure 4: Location of resistivity soundings and simplified layered earth model interpretations

Drought Index calculations

A variation of the Standardized Precipitation Index, without normalization, has been calculated using 69 years of monthly rainfall from Rarotonga Airfield. This has been done in order to simplify the calculation but still allows valid comparison of drought conditions, for the same site, at different times and over different time scales. The results obtained from the analysis are shown in Figure 5 for three month, six month and twelve month time scales. The horizontal dotted lines in each section of the figure correspond to the drought categories listed in Table 1 (i.e. Mild-Moderate-Severe). For all three time scales the drought conditions experienced in 1982-83 produced a record low drought index (at around 650 months from the start of records) which reached the 'Extreme Drought' category for the 6 and 12 month time scales. The figure illustrates the significance of time scale when considering drought impacts: as the time scale increases, droughts of a given severity occur less frequently and are more persistent.

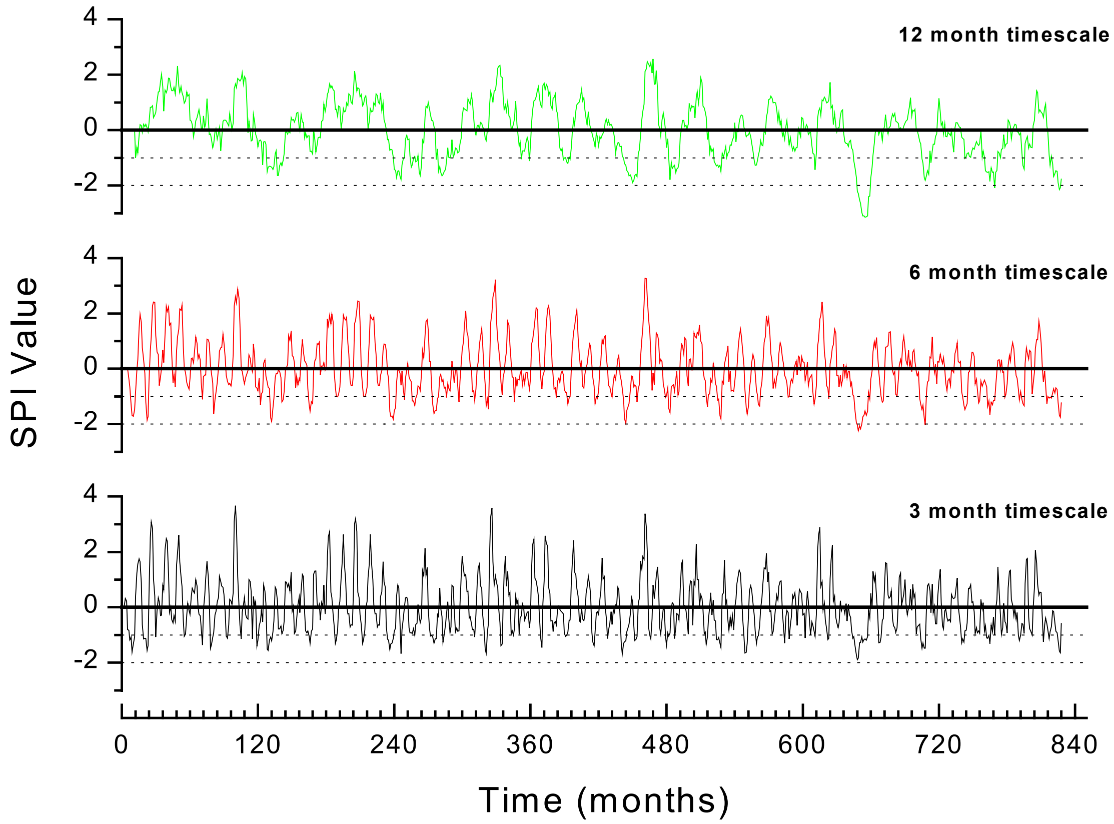

Figure 5: Standardised Precipitation Index for three alternative time scales

In the context of the management of Rarotonga's water supply a drought index should, ideally, reflect the appropriate time scale for surface catchment yields, use long term rainfall records which reflect rainfall patterns over the supply catchments and should be simple to calculate. Some of these requirements can not be achieved with the available climatic and hydrologic data for the island. Until further data are available and the necessary studies undertaken it should be possible to use the long-term rainfall from Rarotonga Airfield to provide a measure of drought. A simpler, rather ad hoc, alternative to the SPI Drought Index may provide a useful starting point.

A simple weighted sum of recent monthly rainfall totals is proposed as a drought measure. The measure considered is defined here as:

$$\mathbf{DI_i = P_{i-1} + 0.9 * P_{i-2} + 0.8 * P_{i-3} + \ldots\ldots\ldots + 0.1 * P_{i-10}} \qquad \textbf{Equation 1}$$

where DI_i = Weighted Sum Drought Index for month i
P_{i-1} = Precipitation in month (i –1) etc.

This simple drought index closely matches the behaviour of the Standardized Precipitation Index calculated for a 6-month time scale. The two indices are compared in Figure 6 for a selected 100 months of the 69-year record.

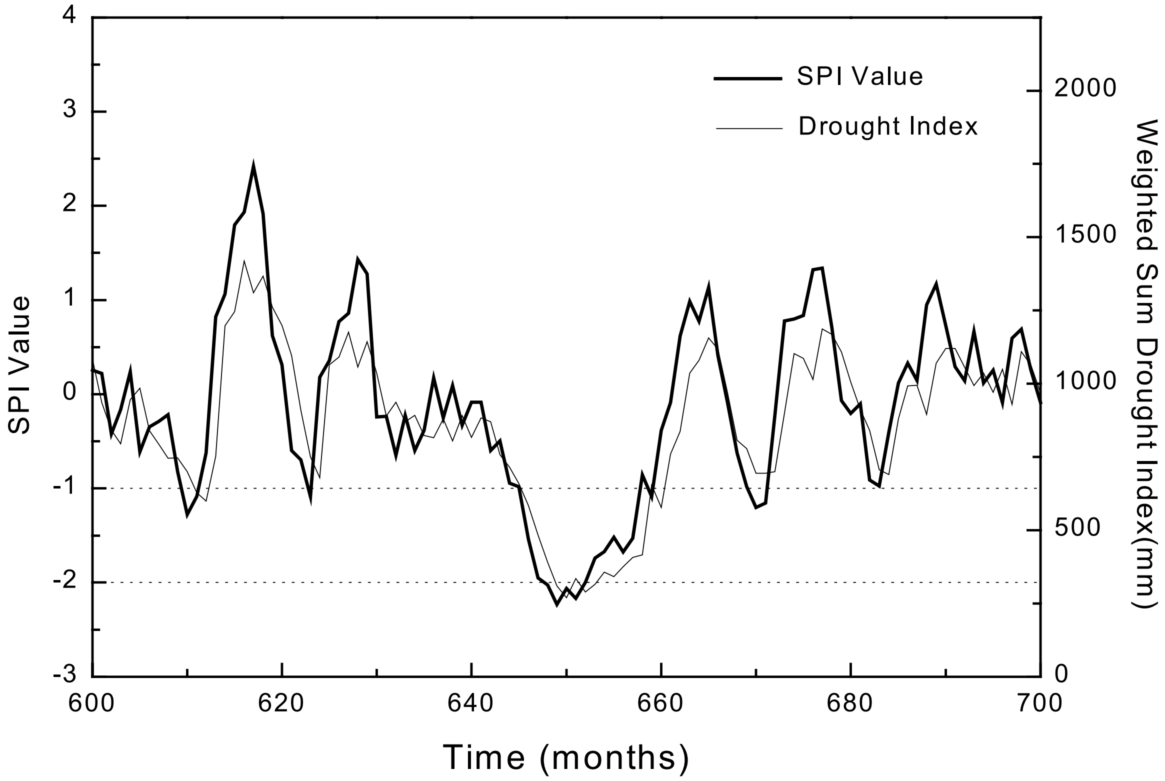

Figure 6: Standardised Precipitation Index and Weighted Sum Drought Index

The Weighted Sum Drought Index is plotted for the entire 69 years in Figure 7. Periods when the index fell below 600 (approximately equivalent to the SPI Moderate Drought rating) are marked. The 1982 drought stands out as the most severe for the 69 years of record. Details of the methods for calculating both the SPI and the Weighted Sum Drought Index are provided in Appendix 2.

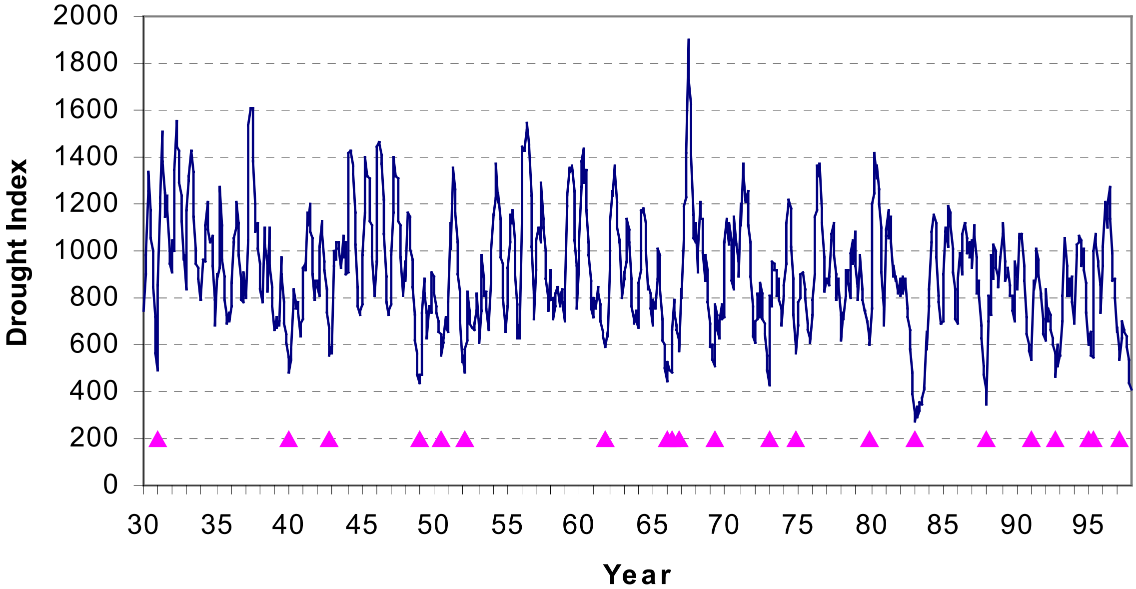

Figure 7: Weighted Sum Drought Index for 1929 to 1997
(periods where the index fell below 600 are indicated)

Groundwater availability

Beach Ridges (Aroa Sands)

The resistivity soundings clearly show that the carbonate sand and gravel deposit (Aroa Sands) contains freshwater. The water table ranges from less than one to two metres above mean sea level (m.s.l.), depending on the distance from the shore. Saltwater interface ranges from three to fourteen metres below m.s.l. Hydrogeological properties in these deposits appear to be quite homogeneous, influenced only by different matrix composition.

Basically, the groundwater potential is related to the width of sandy outcrops and the extent of the likely reservoir. Sounding RARO10 near the Rarotongan Hotel is placed on the widest Aroa Sands outcrop and shows a freshwater saturated layer with a thickness of 14 metres. The second key factor is the amount of recharge from direct infiltration of local precipitation and from sub-surface flow from inland. Rarotonga's rainfall distribution suggests that conditions would be more favourable for direct recharge in the south-east and interior of the island. The extent and efficiency of river catchments will determine, to some extent, the amount of water that can infiltrate the sands though the main sediment bodies. In addition, the degree of capture by surface water intakes will exert some influence on groundwater availability.

In some areas of the island the resistivity survey has indicated the presence of shallow volcanic basement under the sandy deposit. This shallow basement is found on the west and south-east of the island and restricts aquifer thickness thus limiting its potential. The results show, in these areas, that freshwater saturated layer ranges from a minimum of five to twelve metres (soundings RARO5 and RARO12w). The consequent reduction of aquifer thickness poses a risk of relatively rapid saltwater intrusion if the abstraction rate exceeds a delimited portion of the recharge input. This phenomenon has been observed in the airport well where the concentration of saltwater in the well has increased rapidly in extended dry periods.

Coastal Terraces (Nikao Gravels) and Swamp Area

These deposits show different results reflecting the heterogeneity of these sediments. The resistivity soundings indicate the local occurrence of an aquifer under the upper clayey layer of coastal terraces, formed by Nikao Gravels. Generalizations about the potential and occurrence of this aquifer cannot be made because there are insufficient data: only four soundings were carried out on these deposits. To gain a more detailed picture of the extent and nature of these aquifers it would be necessary to carry out investigation drilling, possibly supported by more resistivity soundings.

In the east side of the island groundwater occurs under a clayey layer. The aquifer is locally formed by a gravel occurrence in the fans of coastal terraces. In this situation recharge comes only from the rainfall that infiltrates at higher altitude and flows upon the impermeable volcanic basement. Though this will limit the potential for local recharge from precipitation it may also provide a measure of protection from contamination from the land surface.

Groundwater zonation

Based on the interpretation of the survey results, the coastal plain of Rarotonga has been divided into different sectors (zones) depending on their likely groundwater potential. The sandy lithology (identified as Beach Ridges/Aroa Sands) is the most reliable and exploitable aquifer because of its hydrogeological uniformity and ease with which water can be found. Further inland the coastal terraces (Nikao gravels and locally reworked fan sediments) could give good groundwater potential but water occurrence is not as widely available as in the sands.

The following zones have been shown in Figure 8 along with the boundaries of the existing water supply catchments (NB: The sector between the airport and Tupapa Stream has not been included in this investigation).

Zone 1. Sands with good potential because of width. Shallow volcanic basement (depth ranges from 5 to 15 metres below mean sea level) limits aquifer reservoir. Risks of relatively rapid onset of saltwater intrusion during drought time.

Zone 2. Sands with good potential. Further inland, groundwater potential in fans located in coincidence with streams outlet. The zone is located in the "wet" part of the island and receives an input of recharge not only from direct precipitation but also from lateral flow through stream alluvium sediment bodies.

Zone 3. The width of the biggest sand outcrop provides a good groundwater potential. Volcanic basement only marginally affects the northern border.

Zone 4. Medium groundwater potential from the sands, due to limited width of Aroa Sands outcrop

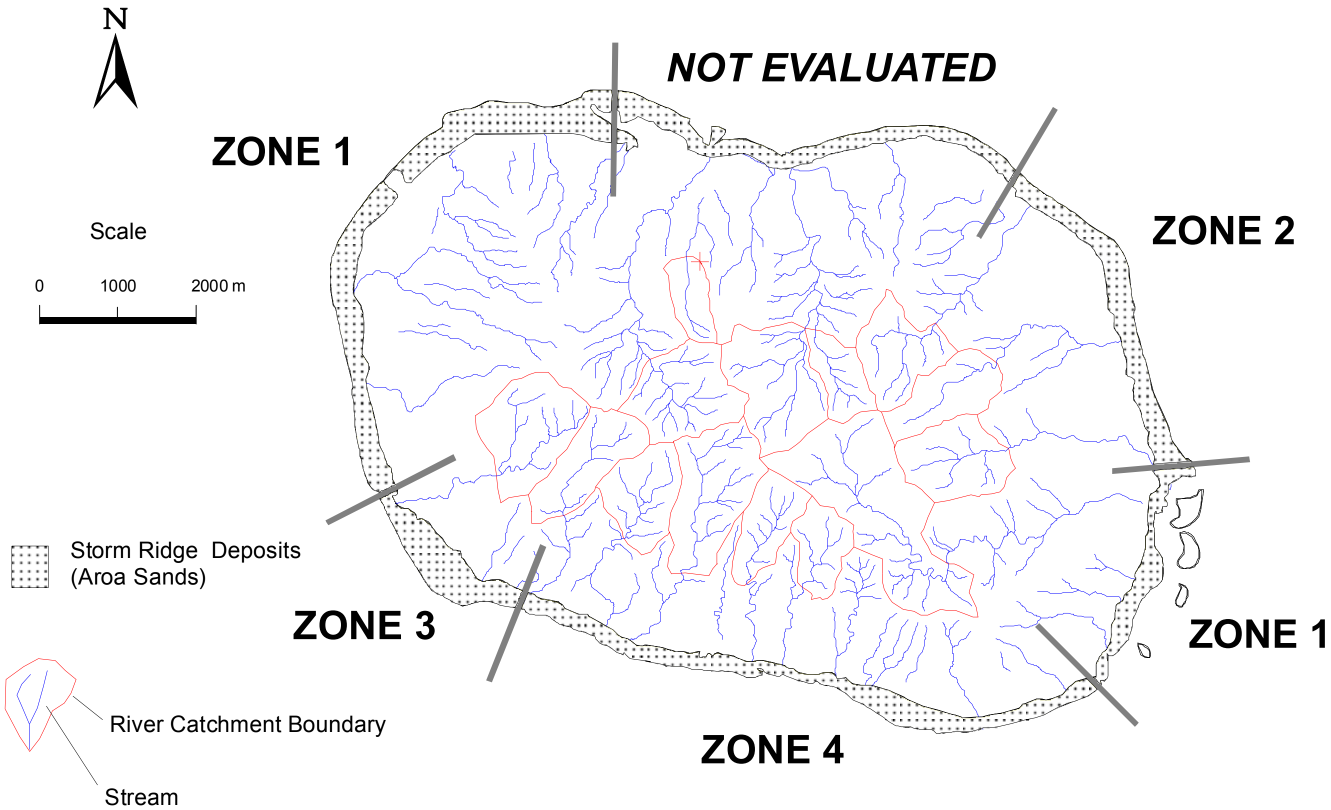

Figure 8: Groundwater zones and existing water supply catchments

Groundwater development

The geophysical survey suggests that the sand of the Beach Ridges Deposit contain the most reliable aquifer, with some differences from zone to zone. However, because of the proximity of the seashore the exploitation of this aquifer requires careful management. It is important in planning future use of the Aroa Sands aquifer to find sites where both the thickness and distance from the sea are a maximum, so that there is the least risk of saline intrusion and loss of yield in drought periods. Sites on the seaward side of swamp areas are most likely to meet that requirement.

Coastal aquifer exploitation increases the risk of saline intrusion. Conventional wells tend to produce a localised water table drawdown resulting in the upconing of saltwater from below. However, if water abstraction is distributed over a wider area, the water table drawdown and the consequent uprising of the mixing zone can be reduced. Horizontal infiltration galleries effectively skim freshwater from the surface of the aquifer, thus distributing the pumping over a wide area. There are likely to be significant advantages in using that technology for the development of groundwater on the Rarotonga coastal plain sandy deposits, especially where the depth to the water table is relatively low.

The horizontal infiltration gallery, because of its structure, will have a higher cost compared to a conventional vertical well. Nevertheless, when exploiting a coastal aquifer with saline intrusion risk, the higher initial cost may be justified in the long-term period by the higher reliability and longer life of the horizontal well.

Groundwater development options

The coastal aquifer is the natural site where all possible pollutants infiltrated from inland are accumulated. Piggeries distributed around the terrace at the foot of the volcanic hills and various human activities (for instance widespread use of fertiliser, herbicides, septic tank discharges and uncontrolled waste landfills, etc.) have very likely already polluted the coastal plain aquifer. In addition to these actual or potential risks of water contamination, the coastal aquifer, if overexploited, can be contaminated by saltwater intrusion.

One development option would be to take groundwater from the coastal plain aquifers and use it to directly augment the present reticulation system. However this option would require extensive land-use controls or require treatment to remove pollutants such as nitrates or fertilisers. That treatment could make this option quite expensive. In addition this option would expose the reticulated water supply to a serious threat of contamination from saltwater occurrence in the wells.

The first and immediate development option for the groundwater extracted from the plain is irrigation. Water that does not meet drinking water standards of high content of faecal bacteria or high nitrate content may still be suitable for irrigation without any treatment. However, because many irrigation water users do not have permanent tenure on the land they are farming there is likely to be some reluctance to investment in developments having long-term benefits over a local area. Groundwater development for irrigation could occur in a number of different contexts and require different strategies. Landowners may develop groundwater for their own use or to increase the potential rental value of their land. Other farmers may prefer to use low cost development options which may be more likely to result in contamination (e.g. the use of temporary dug pits). It may be possible to promote the development of communal systems to serve several small farmers in return for some payment. However, as long as water users are able to take their requirements from the reticulated system there will be little incentive to develop other sources. Perhaps the largest incentive to development would be user charges and controls on use for the reticulated system.

Drought management

The ability to quantify the severity of a drought makes it feasible to consider a number of management responses. The weighted sum drought index presented in this report can be simply calculated from monthly rainfall records (see Appendix 2). It could be used initially as a basis for public information; when the index falls below 750 (say) the Water Supply Department could issue monthly reports which advise the public about the state of the water supply system and place the current situation in context with previous droughts. This could be a useful aid in promoting water conservation efforts and raising the level of understanding about the nature of Rarotonga's water resources.

Where conditions required some rationing of supplies a drought index could be used as an objective basis for introducing constraints. For instance, it might be considered appropriate to limit the use of reticulated water for irrigation to the period 6pm to 6am in order to minimise evaporation losses and reduce pressure on the system. The implementation of that constraint could be based on a pre-determined drought index value so that controls were exercised in a progressive way. Again, if it was envisaged that a total ban on certain classes of water use could be required this could be linked to a particular drought index value. These particular uses of a drought index would require some detailed study to establish appropriate decision point values and consultation with the affected parties.

CONCLUSIONS

Groundwater development policies

Because of the high risk of saltwater intrusion coastal aquifer groundwater development should be carried out with care. The horizontal infiltration gallery technology is well suited to the conditions and should be demonstrated and evaluated and demonstrated in a follow-up project.

From the indications about coastal plain groundwater potential in different zones, particular care should be taken where the shallow volcanic basement limits the thickness of the aquifer. Because of the potential for rapid development of saltwater intrusion, groundwater conductivity should be monitored routinely for a few selected wells. Once brackish water is detected in a well, conductivity monitoring should be carried out on a monthly basis and pumping activity decreased or stopped if a limit of 2000 μS*cm is reached.

Demonstration project

A demonstration horizontal gallery well should be built with the objective of encouraging farmers to exploit the groundwater potential of the coastal plain. A technical sketch of a horizontal infiltration gallery with indicative costs is attached in Appendix 5. Subject to the availability of project funds a site can be chosen bearing in mind the need to make productive use of the extracted groundwater, to monitor the effects of the abstraction and to place the gallery in an appropriate groundwater zone.

The expected outcomes of this project are:

- To refine construction details with a possible cost reduction
- to identify criteria to define the sustainable yield
- to promote horizontal gallery use sharing between farmers
- to identify criteria and set up methodology for future monitoring of the coastal plain aquifer.

Gallery well technical features as well as construction details would be published in a report.

Drought management strategies

It would be possible to introduce a number of measures designed to improve the drought tolerance of the existing system. The drought index introduced in this report could be used to provide some objective measurement of the severity of a drought with the following possible management interventions in mind:

- Initially, the use of public information to increase public and political awareness of the nature of Rarotonga's water supply and to promote conservation efforts
- Control of irrigation watering from the reticulated supply during droughts of specified intensity and duration
- Bans on specified classes of water use during severe or extreme droughts.

Apart from the public information option these measures would require further analysis and public consultation. A starting point in the development of these strategies could be for the Cook Islands' Meteorological Service to report on drought condition using the Weighted Sum Drought Index or an appropriate alternative measure.

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APPENDICES

1 Resistivity data and details of interpreted models
2 Drought Index calculations
3 Dairy of visit
4 Groundwater levels
5 Design and estimate for a horizontal gallery well

APPENDIX 1

RESISTIVITY SOUNDINGS

This appendix presents the detailed field observations and interpretation for each sounding. Location information is provided in Table A1-1 and a brief commentary on the interpretation is recorded in Table A1-2. The field data and sounding curve plots are presented for all soundings. Details of interpreted models are presented for those soundings which were used in the analysis (Figures A1-1 to A1-19).

Table A1-1: Resistivity sounding locations

Sounding	Location	Altitude (m)	Depth to WL (m)	Lithology
RARO1	Titikaveka, Botanic Garden	4		Contact coastal terraces/sand Clay top soil
RARO2	Airport, alongside airstrip	3.6	2 (?)	Sand Top soil 0.5 m as stabilizer
RARO3	P.W. Dept, close to beach	2.5		Unconsolidated carbonate sand and gravel
RARO4	Golf Course	5.5		Dry sand. Towards the quarry more clay mixed with sand
RARO5	Sunset Motel, 40m from main rd	5.5		Unconsolidated carbonate sand and gravel
RARO6	Matavera (back rd)	9.3		Coastal terraces
RARO7	Matavera, between main & back	6.5 - 7.5		Swamp area
RARO8	Matavera (main rd)	5.5		Dry sand without clay
RARO9	Rarotongan Hotel, swamp area 45m inland	2.8 – 3.2		Contact swamp/sand
RARO10	Rarotongan Hotel (main rd)	2.8		Unconsolidated carbonate sand and gravel
RARO11w	Titikaveka, S.D.A.	4.4		Carbonate sand and gravel
RARO11s	Titikaveka, S.D.A.	4.4		Carbonate sand and gravel
RARO12w	Muri Beach (main rd)	3.7	3.3	Carbonate sand and gravel
RARO12s	Muri Beach (main rd)	3.7	3.3	Carbonate sand and gravel
RARO13	Ngatangiia (back rd)	7.6		Flood plain
RARO14	Ngatangiia (main rd)	6.8		Carbonate sand and gravel
RARO15	Titikaveka, up from Botanic Garden	9		Coastal terraces
RARO16	Takitumu (back rd)	10		Coastal terraces

Sounding	Location	Altitude (m)	Depth to WL (m)	Lithology
RARO17	Takitumu (main rd)	2.8		Unconsolidated carbonate sand and gravel
RARO18	Arorangi (main rd)	5.4		Carbonate sand and gravel

Table A1-2: Commentary on resistivity sounding interpretations

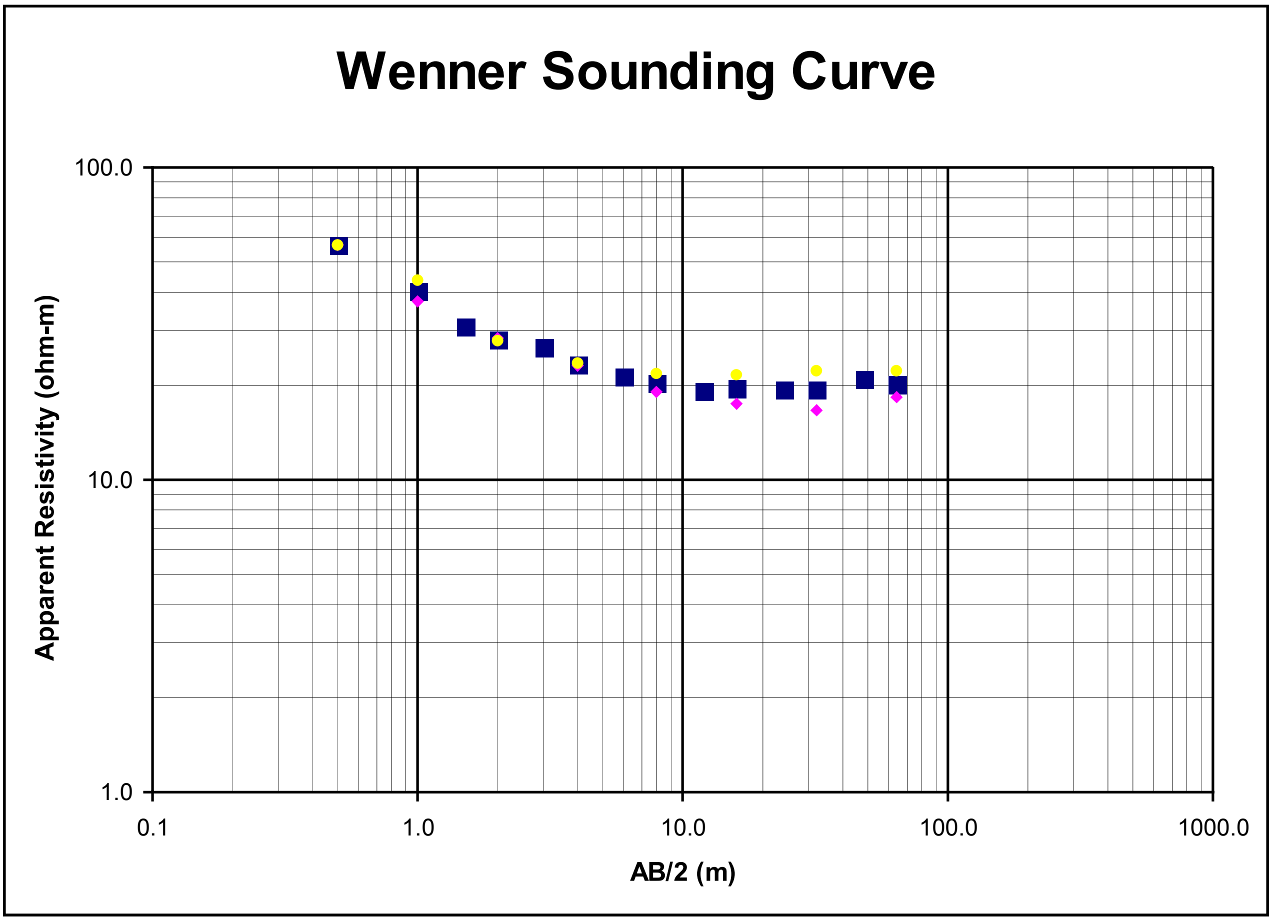
No	Site	Comment
RARO1 256 m	Botanic Garden	Low value for unsaturated zone (27.6 ohm*m related to sand + clay), but presence of clay could lower resistivity value. It is not possible to insert a layer with resistivity more than 20-25 ohm*m, even if water conductivity (563 μS) indicates freshwater. Depth to WT in accord with field observation
RARO2 512 m	Airport	Freshwater saturated sand has same value as RARO1. Close geological contact with coastal terraces (NK) could explain presence of clay in the sand. Something wrong with dry volcanic basement value – too high. Depth to WT (2 m) measured on the field is different from modelled result. May be problems related to methodology itself due to the steep fall of resistivity (?)
RARO3 256 m	P.W. Dept.	High value of freshwater saturated sand dues to very clean beach deposit (carbonate sand, gravel and debris coral rock)
RARO4 256 m	Golf Course	Good correspondence with RARO3
RARO5 256 m	Sunset Motel	Good correspondence with RARO3 and 4
RARO6 512 m	Matavera back rd	Second layer cannot be water saturated because of its altitude and location on flood plain. More likely it is fine sediment (clay, silt with few gravel). The lowest inflection reflects a thin pure clay layer. Last layer, since equivalence analysis ranges from 140 to 170 ohm*m, indicates presence of sand and gravel (likely) in saturated condition. During Don Dorrel well boring, at higher elevation, the presence of gravel was noted.
RARO7 256 m	Matavera	Penetration of current doesn't go enough deep to identify gravel layer (if existing…)
RARO8 256 m	Matavera main rd	Usual values for top soil and freshwater saturated sand. The last point of the curve (average of RD1-RD2) presents big offset errors (80%) indicating lateral variation (geological, hydrogeological). The last layer resistivity value (likely saltwater sand saturated) more reflects the RD1 value.
RARO9 512 m	Rarotongan swamp area	Low value of resistivity for the freshwater saturated layer (compared to other results). Maybe matrix composition.
RARO10 256 m	Rarotongan main rd	Good result. Third freshwater saturated layer with usual resistivity value.
RARO11 w 256 m	Titikaveka SDA	W.T. too high. Eventually, freshwater saturated layer can be suppressed without any variation to RMS.
RARO12 w 512 m	Muri Beach main rd	Some problems. Third layer (freshwater pointed out) with low resistivity; could be matrix composition. Volcanic basement likely to be more or less where it is (-13.65 from soil level). W.T. may be little deeper (something like –1.8 from soil level).
RARO13 200 m	Ngatangiia back rd	Equivalence analysis shows many possible different solutions. According to the fact that RARO13 & RARO14 are located on stream alluvium deposit, quite heterogeneous lithology. Big problem is the presence of clay (coming from weathering of volcanic rock) that is present more or less in every deposit. The clay presence (in different percentage) lowers the value of resistivity and makes the recognition of water saturated layers more difficult.
RARO14 294 m	Ngatangiia main rd	Anomalous second unsaturated layer with low resistivity. Cannot be saturated because of altitude. Is this altitude (6.8 m) correct?

No	Site	Comment
RARO15 256 m	Titikaveka bot. garden	Third layer unlikely to be saturated because of its depth. If a water table occurs it should have been detected. Sounding with 256 m of array, then more or less 40/50 m of soil penetration.
RARO16 256 m	Takitumu back rd	Equivalence analysis shows many possible different solutions. It could be as in RARO6, where gravel aquifer is located under clayey layers.
RARO17 256 m	Takitumu main rd	Similar value to RARO11 (quite close) but good accord between estimated W.T. and sounding level.
RARO18 512 m	Arorangi main rd	But for the second layer (low resistivity) good accordance with results obtained on the west coast (presence of volcanic basement)

Site:	Akapuao Botanical Garden	Ref No:	**RARO1**	Weather:	Hot, Overcast
Observers:	David, Giovanni, Ben, Adrian	Bearing:		Topography:	Flat
Date:	16/01/98	Soil:		Geology:	boundary swamp/Aroa sands

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	21	19.33	17.99	18.05	1.393	1.33	-0.33		0.5	56.61
2	8.78	8.44	5.94	6.91	0.358	-0.20	-15.10	55.23	1.0	40.37
									1.5	31.01
3	2.9	2.73	2.27	2.22	0.1775	-0.26	2.23	-78.74	2.0	28.21
									3.0	26.56
4	1.212	1.137	0.926	0.942	0.0771	-0.17	-1.71	-3.10	4.0	23.47
									6.0	21.53
5	0.531	0.503	0.381	0.436	0.0304	-0.45	-13.46	1.09	8.0	20.53
									12.0	19.24
6	0.273	0.262	0.1745	0.216	0.01381	-1.02	-21.25	4.36	16.0	19.63
									24.0	19.56
7	0.1421	0.1272	0.0832	0.1114	0.0095	3.88	-28.98	-34.45	32.0	19.56
									48.0	21.08
8	0.0675	0.0628	0.0459	0.0553	0.0034	1.94	-18.58	-27.92	64.0	20.35
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	1.66	16.02	37.49	*192.0*	
									256.0	

Comments: Botanic Garden water well conductivity was 563 µS/cm @ 25 C degrees



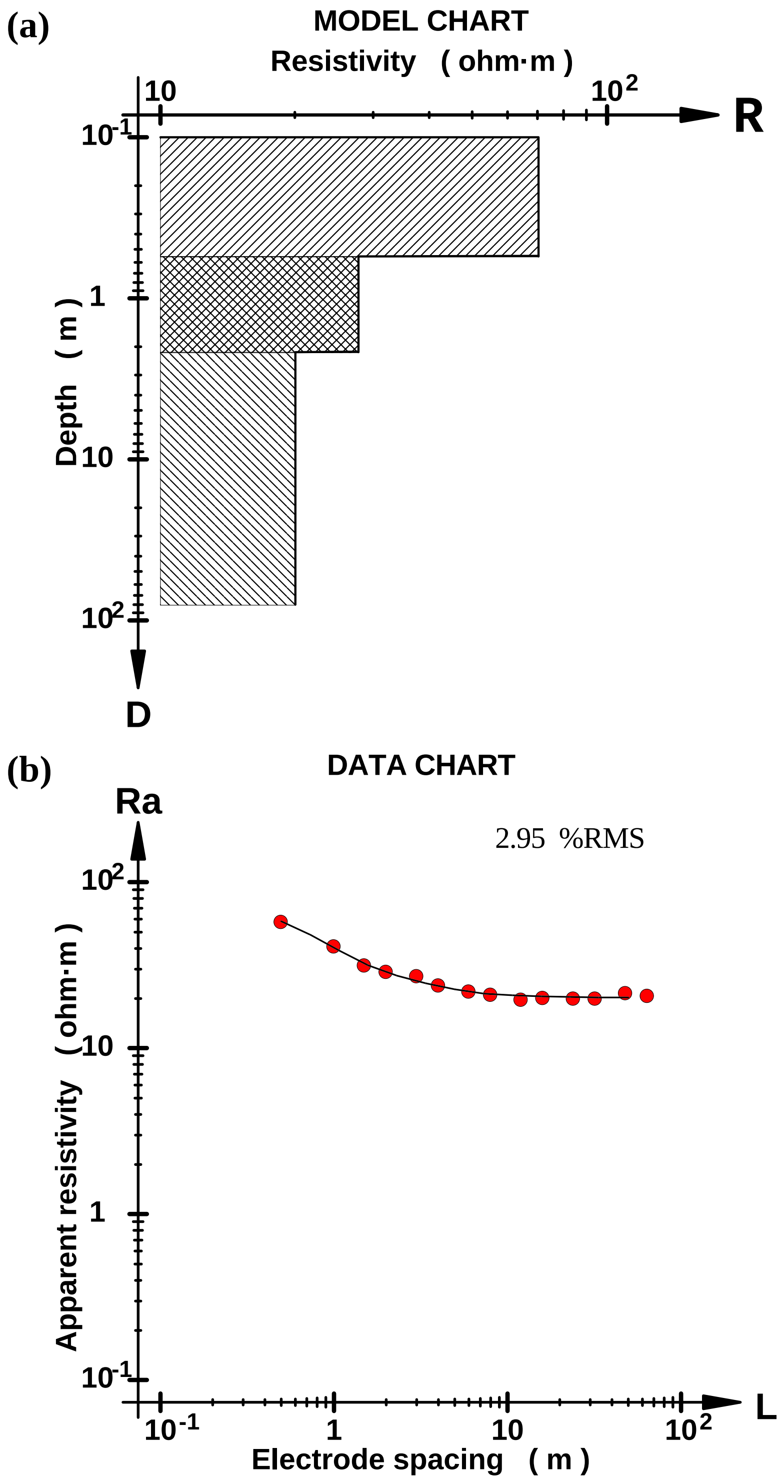
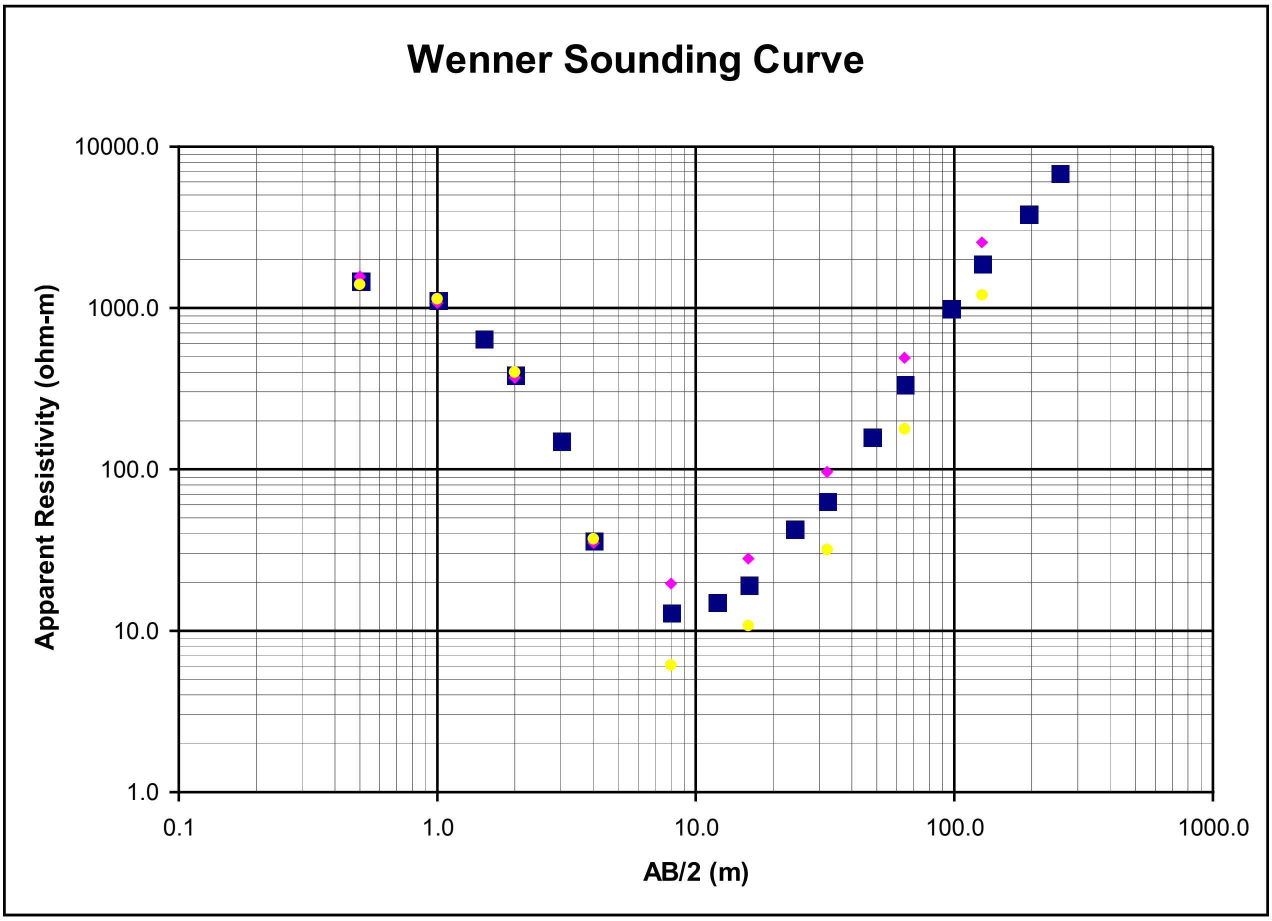


Figure A1-1: Interpreted model for RARO1

Site:	Rarotonga International Airport			Ref No:	**RARO2**		Weather:	Hot, overcast		
Observers:	David, Giovanni, Ben, Adrian			Bearing:	D2 towards east		Topography:	Flat		
Date:	16/01/98			Soil:			Geology:	Aroa sands		
SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	551	507	495	443	43.9	0.02	11.09		0.5	1473.41
2	222	212	170.2	183	9	0.45	-7.25	56.91	1.0	1109.61
									1.5	647.40
3	26.4	25.4	29.5	31.6	1.0185	-0.07	-6.87	-134.88	2.0	383.90
									3.0	150.68
4	1.286	1.267	1.397	1.486	0.0497	-2.36	-6.17	815.77	4.0	36.23
									6.0	-4.51
5	0.485	0.461	0.391	0.1234	0.0228	0.25	104.04	247.31	8.0	12.93
									12.0	14.98
6	0.374	0.35	0.278	0.1073	0.0527	-7.40	88.61	-112.17	16.0	19.37
									24.0	42.86
7	0.537	0.588	0.481	0.1589	0.00575	-10.06	100.67	9.73	32.0	64.33
									48.0	160.96
8	2.2	1.983	1.229	0.447	0.0881	6.04	93.32	43.07	64.0	336.98
									96.0	1006.37
9	4.74	4.45	3.17	1.4865	-0.01483	6.65	72.31	-3.50	128.0	1872.49
					RMS Error:	5.19	69.13	291.09	*192.0*	*3836.01*
									256.0	*6825.64*

Comments: No direct conductivity measurement carried out in Airport water well.
Conductivity was reported to be around 800 µS/cm @ 25 C degrees.



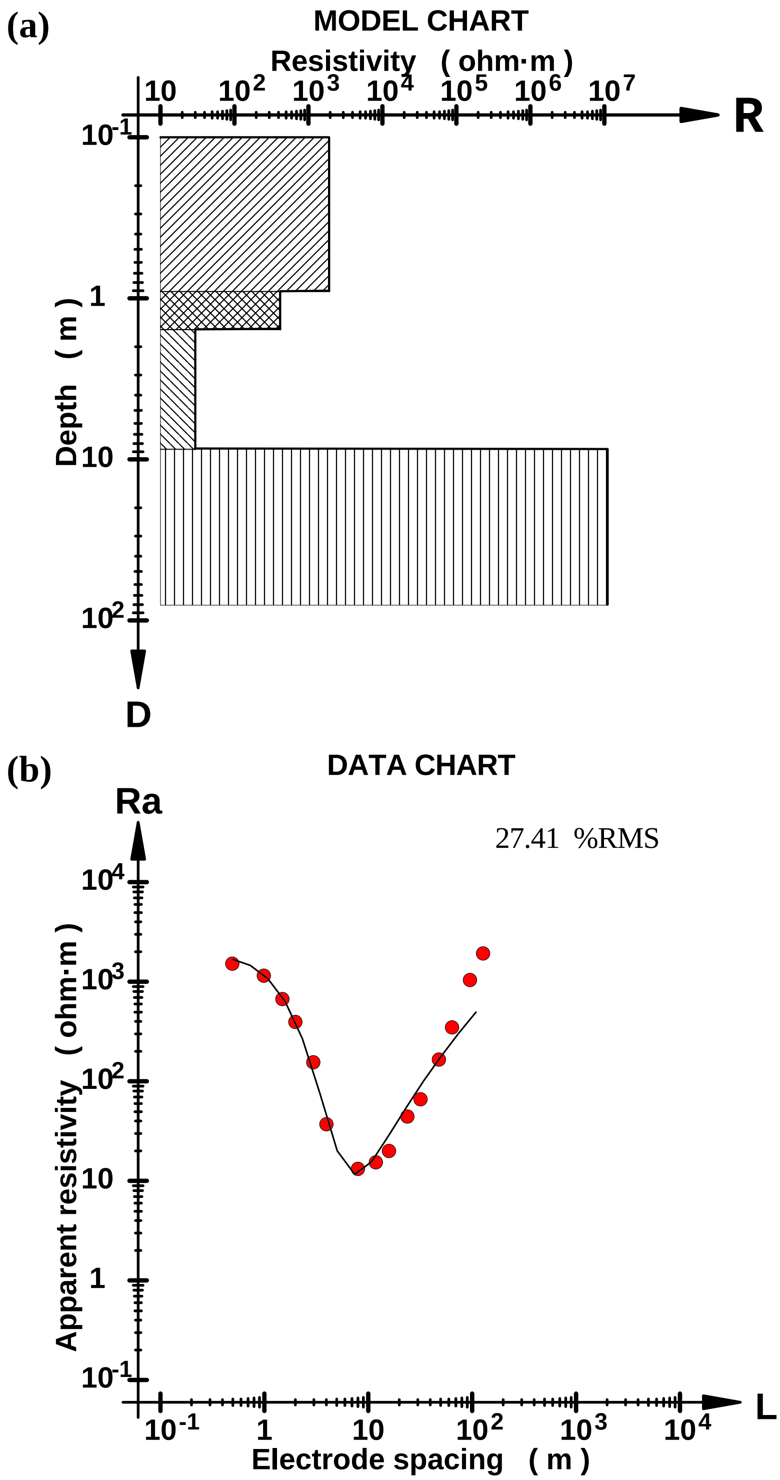
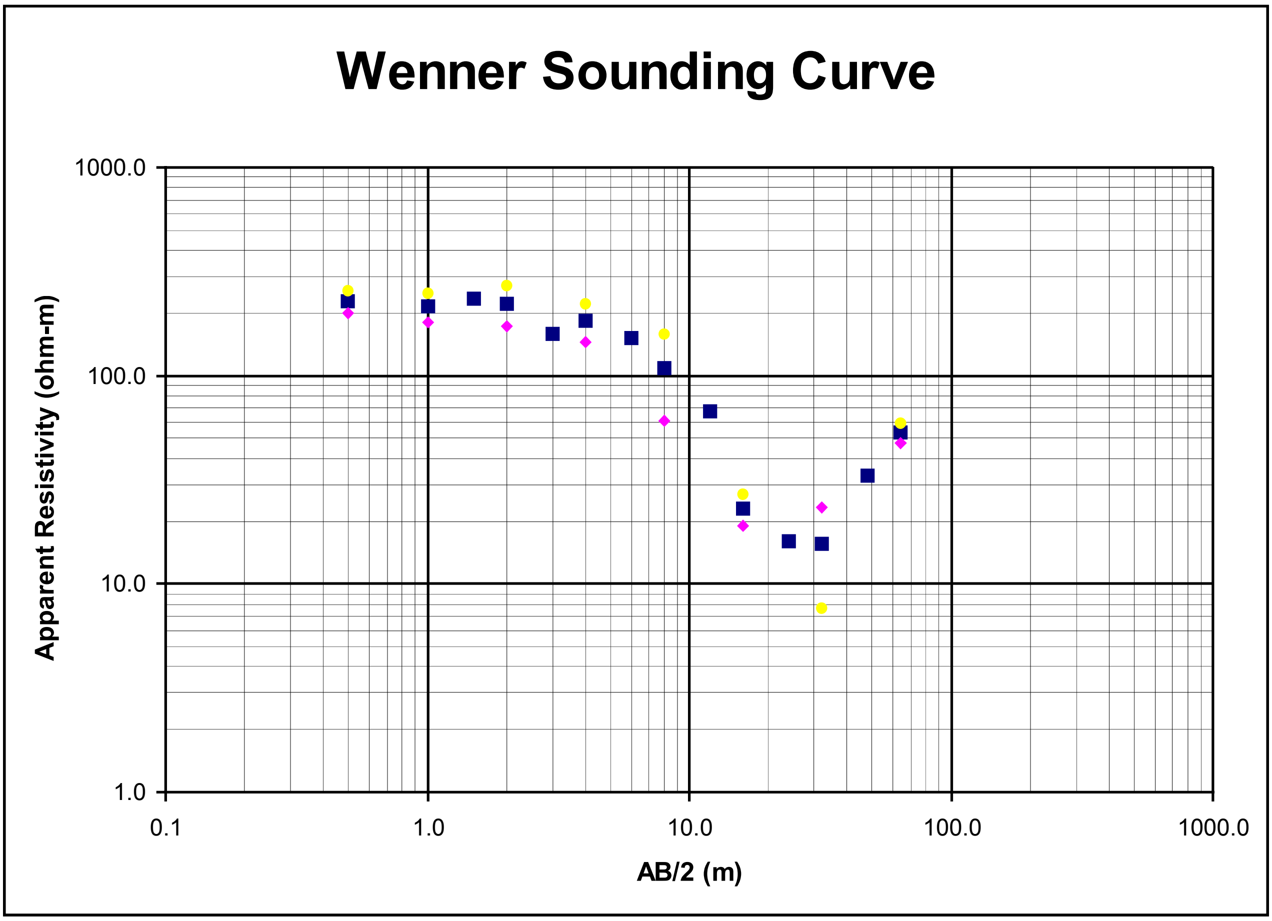


Figure A1-2: Interpreted model for RARO2

Site:	Shoreline behind Water Supply Dpt	Ref No:	RARO3	Weather:	Fine, falling coconuts
Observers:	Giovanni, Terence, David	Bearing:	D1 Counterclockwise	Topography:	Flat
Date:	19/01/98	Soil:	Dry	Geology:	Aroa sand

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	98.3	92.1	64	81.3	6.26	-0.06	-23.81		0.5	228.24
2	40.3	35	28.8	39.3	5.11	0.47	-30.84	-14.08	1.0	213.94
									1.5	232.78
3	23.3	22.2	13.74	21.5	1.084	0.07	-44.04	88.28	2.0	221.42
									3.0	158.76
4	8.54	8.18	5.77	8.83	0.367	-0.08	-41.92	-25.69	4.0	183.47
									6.0	151.49
5	2.74	2.67	1.204	3.14	0.0583	0.43	-89.13	19.28	8.0	109.18
									12.0	67.25
6	0.296	0.284	0.1885	0.269	0.011	0.34	-35.19	-340.40	16.0	23.00
									24.0	15.90
7	0.117	0.1165	0.116	0.038	0.01778	-13.82	101.30	-44.75	32.0	15.48
									48.0	33.19
8	0.261	0.263	0.1173	0.1467	0.0055	-2.83	-22.27	52.29	64.0	53.08
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	4.99	56.08	127.30	*192.0*	
									256.0	

Comments:



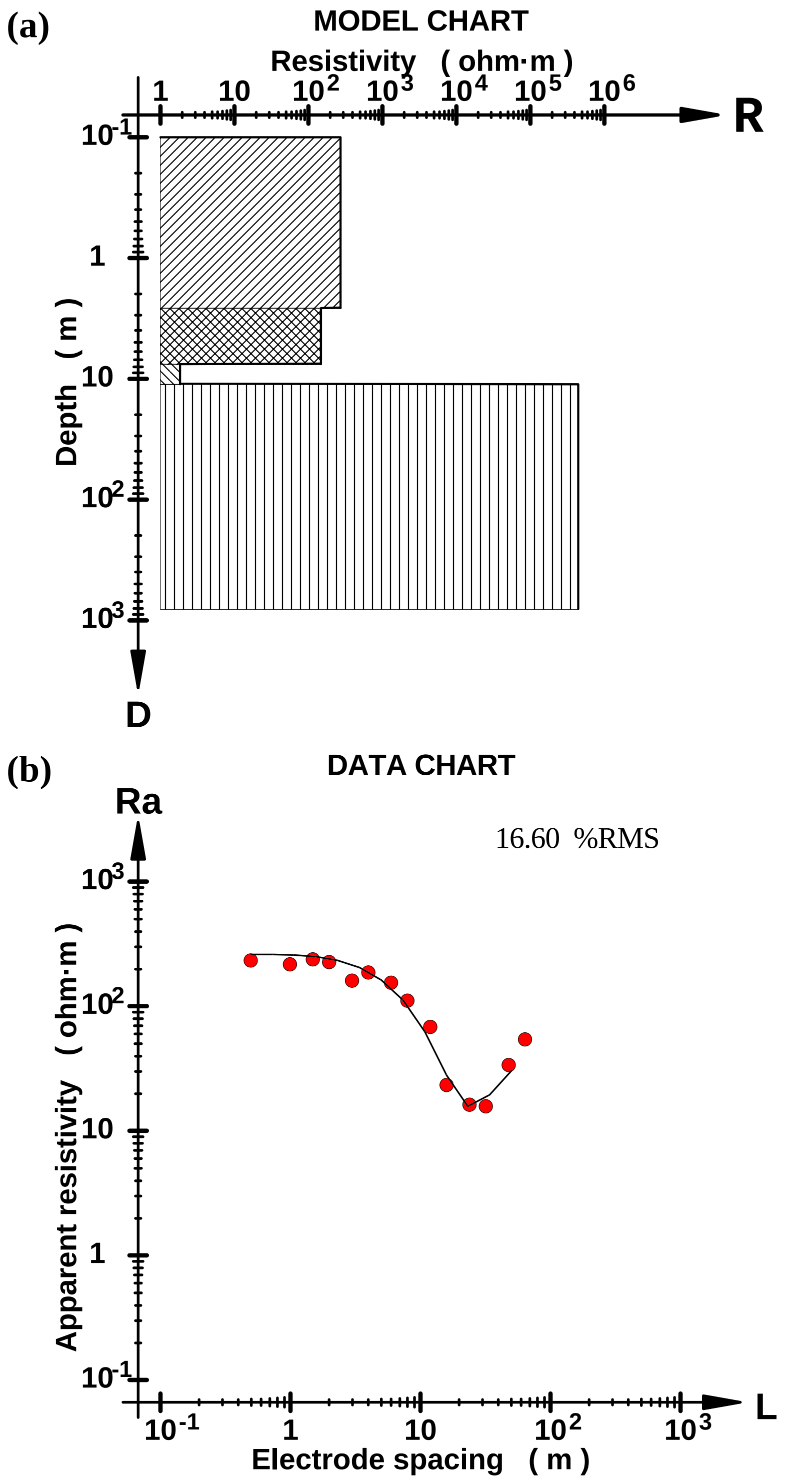
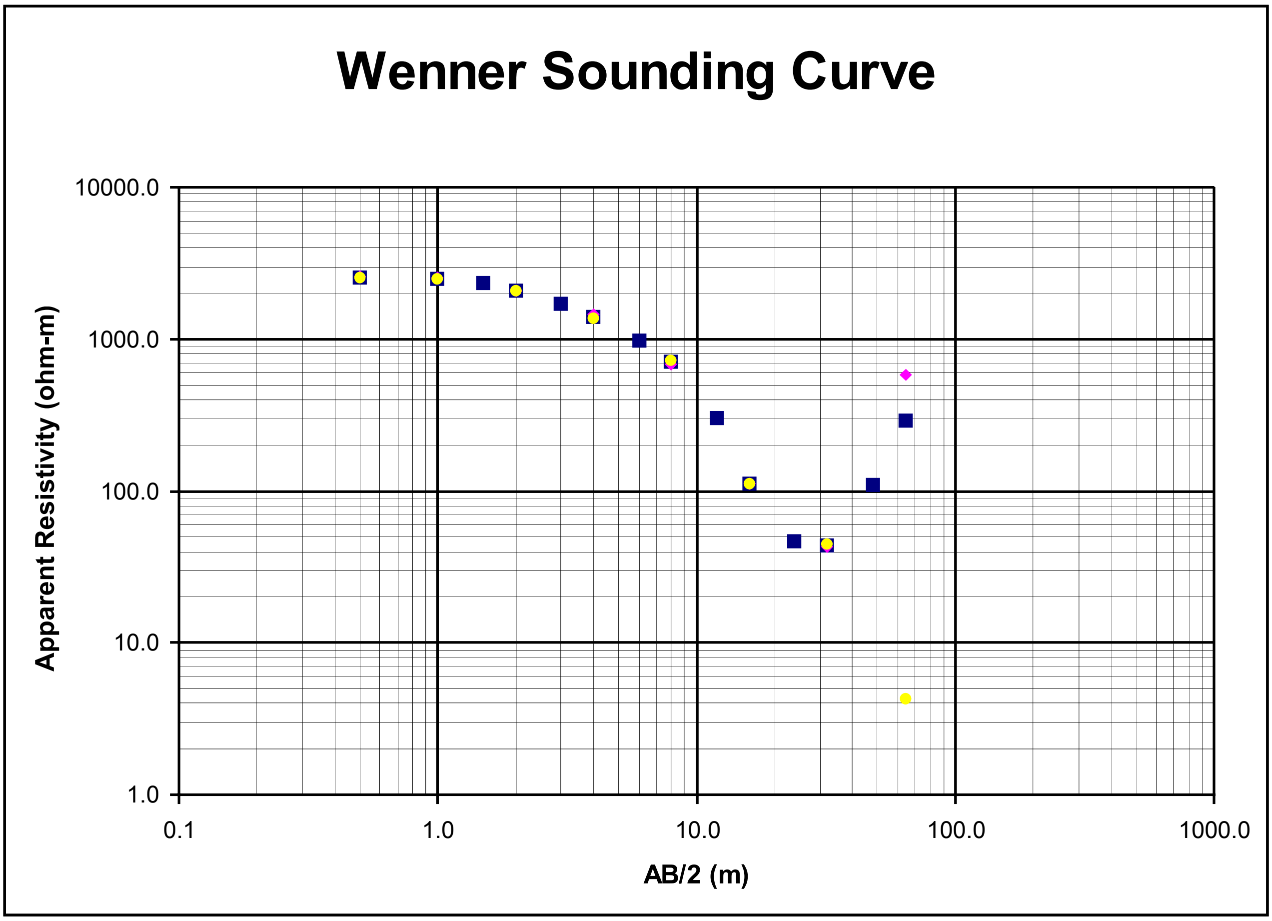


Figure A1-3: Interpreted model for RARO3

Site:	Golf Course	Ref No:	**RARO4**	Weather:	Dry
Observers:	Giovanni, Terence, David	Bearing:	D1 Clockwise	Topography:	
Date:	19/01/98	Soil:	Dry	Geology:	Aroa sands

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	1115	1050	823	800	66.2	-0.11	2.83		0.5	2549.40
2	490	455	402	393	33.3	0.35	2.26	-19.72	1.0	2497.56
									1.5	2343.88
3	209	194.3	165.4	165.6	13	0.82	-0.12	29.56	2.0	2079.73
									3.0	1705.32
4	67.1	63	57.3	54.8	4.08	0.03	4.46	-5.60	4.0	1408.69
									6.0	982.25
5	15.25	14.7	13.69	14.32	0.499	0.33	-4.50	0.62	8.0	703.97
									12.0	299.69
6	1.168	1.043	1.104	1.108	0.1463	-1.81	-0.36	-30.13	16.0	111.19
									24.0	46.35
7	0.474	0.43	0.215	0.222	0.0331	2.33	-3.20	166.29	32.0	43.93
									48.0	108.47
8	1.568	1.469	1.437	0.01064	0.0716	1.76	197.06	40.18	64.0	291.07
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	1.26	69.73	62.72	*192.0*	
									256.0	

Comments:



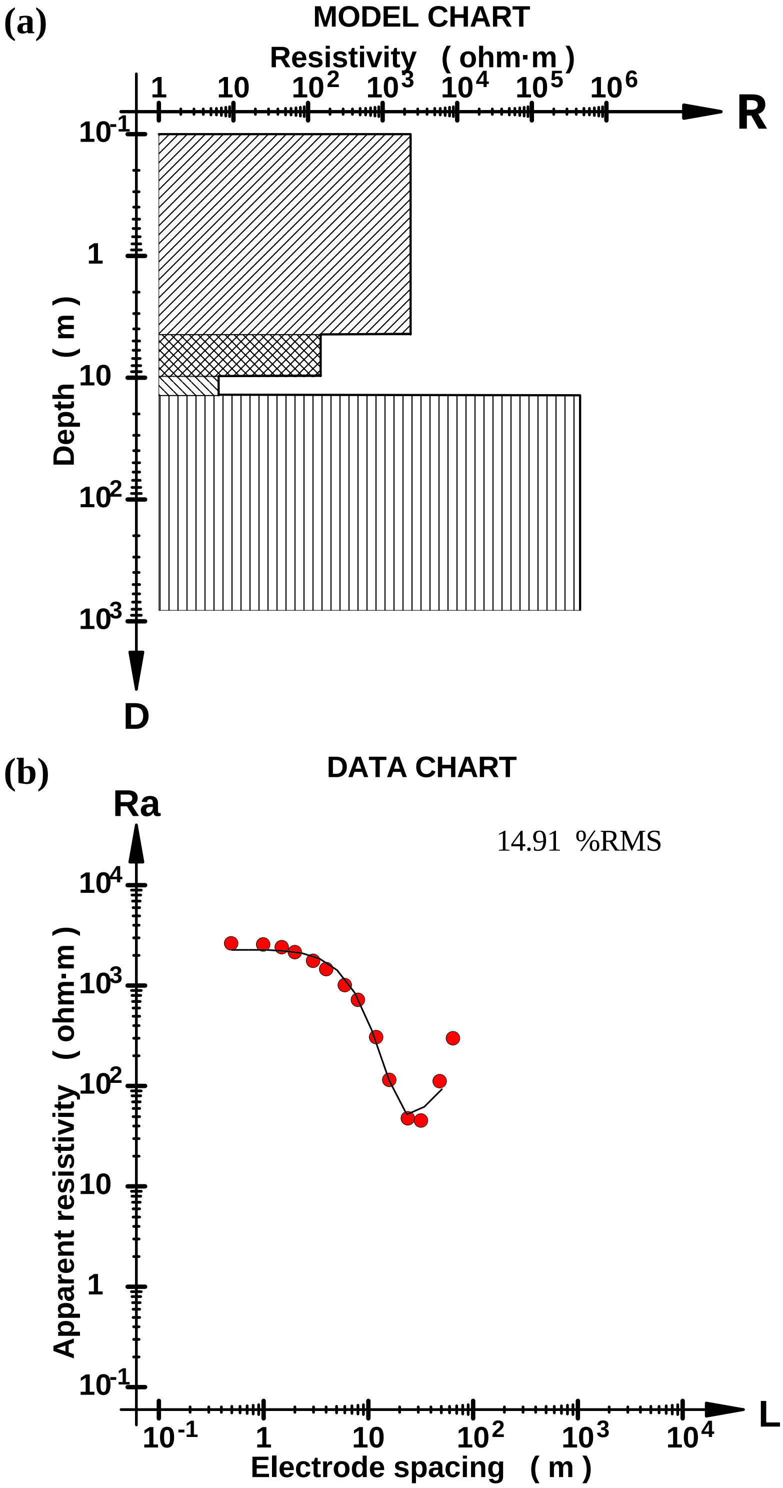
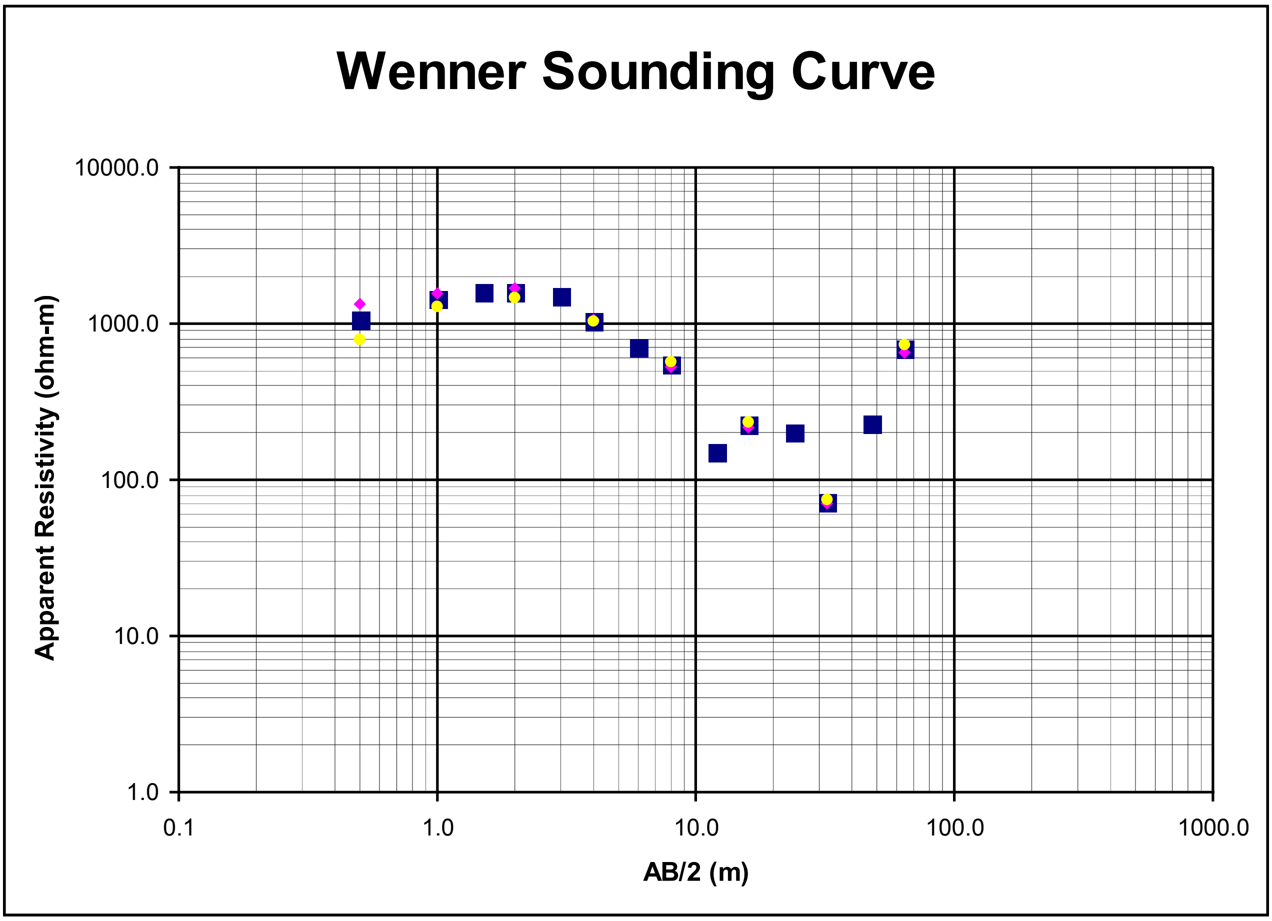

(a)
MODEL CHART
Resistivity (ohm·m)
1
10
10^2
10^3
10^4
10^5
10^6
R
10^-1
1
10
10^2
10^3
Depth (m)
D
(b)
DATA CHART
Ra
14.91 %RMS
10^4
10^3
10^2
10
1
10^-1
Apparent resistivity (ohm·m)
10^-1
1
10
10^2
10^3
10^4
L
Electrode spacing (m)

Figure A1-4: Interpreted model for RARO4

Site:	Outside Rarotonga Sunset Motel	Ref No:	**RARO5**	Weather:	Dry
Observers:	Giovanni, Terence, David	Bearing:	D1 Counter-clockwise	Topography:	
Date:	19/01/98	Soil:		Geology:	Aroa sands

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	507	482	426	252	25.6	-0.12	51.33		0.5	1065.00
2	338	321	250	206	17.03	-0.01	19.30	-25.19	1.0	1432.57
									1.5	1587.08
3	164.6	152	134.7	117.1	12.52	0.05	13.98	-47.71	2.0	1582.10
									3.0	1493.24
4	40.3	35.4	42.1	41	4.88	0.05	2.65	-25.81	4.0	1044.26
									6.0	701.42
5	13.01	12.81	10.51	11.38	0.268	-0.52	-7.95	212.22	8.0	550.16
									12.0	149.37
6	2.52	2.35	2.14	2.35	0.295	-4.84	-9.35	-63.17	16.0	225.69
									24.0	199.47
7	0.655	0.575	0.349	0.37	0.00295	12.55	-5.84	73.23	32.0	72.28
									48.0	227.94
8	1		1.614	1.829		#DIV/0!	-12.49	70.79	64.0	692.26
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	#DIV/0!	21.07	88.73	*192.0*	
									256.0	

Comments:



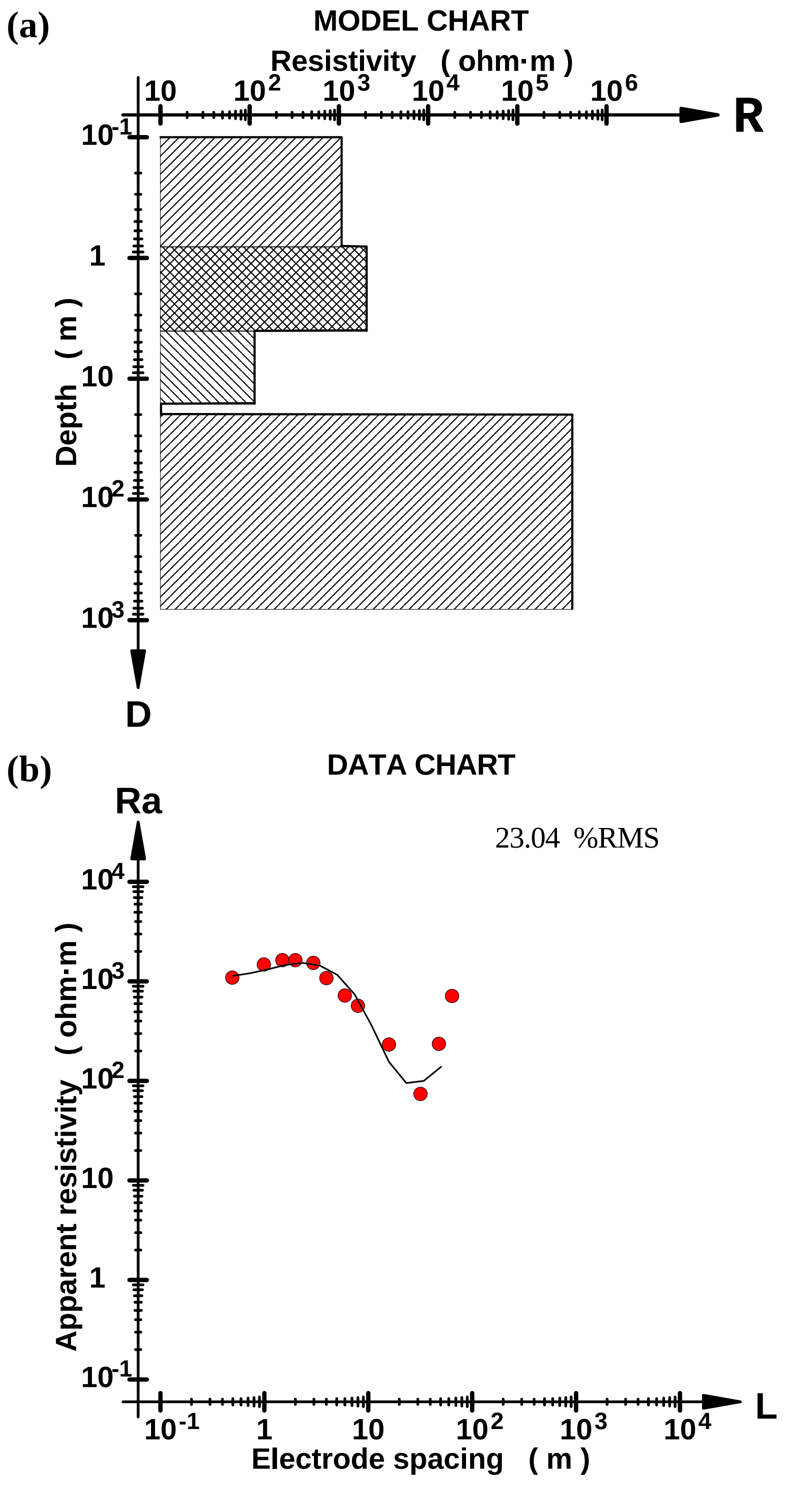
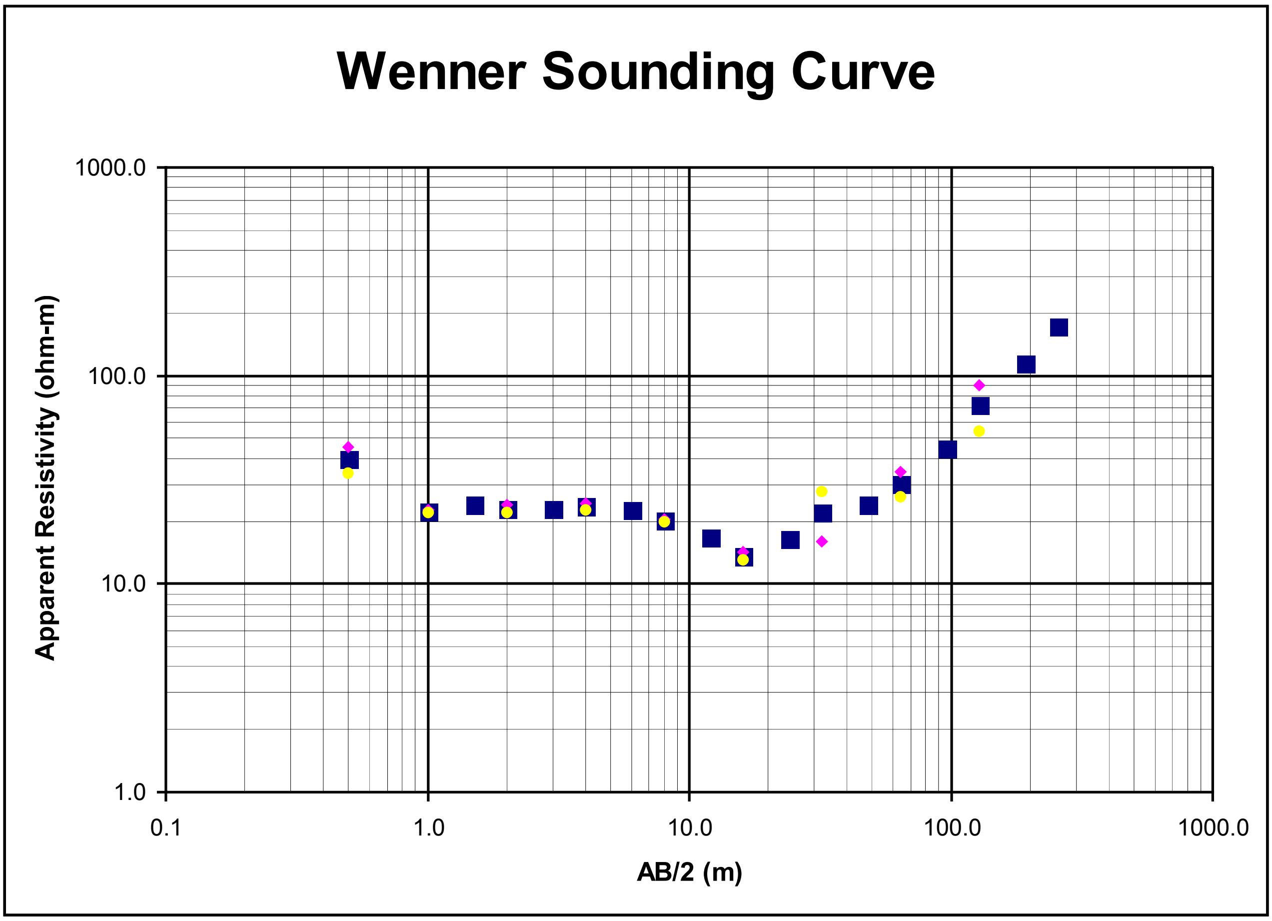


Figure A1-5: Interpreted model for RARO5

Site:	Back Rd beyond Tupapa Stream	Ref No:	**RARO6**	Weather:	Fine (rain previous night)
Observers:	Giovanni, Terence, David	Bearing:	D1 Counterclockwise	Topography:	
Date:	20/01/98	Soil:		Geology:	Coastal terraces sediments

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	17.36	16.97	14.45	10.87	0.452	-0.36	28.28		0.5	39.77
2	4.78	4.48	3.59	3.49	0.314	-0.29	2.82	-141.79	1.0	22.24
									1.5	24.00
3	2.5	2.34	1.915	1.743	0.1517	0.33	9.40	-2.07	2.0	22.98
									3.0	23.04
4	1.256	1.174	0.976	0.9025	0.08645	-0.35	7.83	-9.64	4.0	23.61
									6.0	22.81
5	0.492	0.448	0.41	0.394	0.0399	0.84	3.98	-15.76	8.0	20.21
									12.0	16.77
6	0.233	0.204	0.1408	0.1298	0.0275	0.65	8.13	29.23	16.0	13.60
									24.0	16.53
7	0.1423	0.1256	0.0798	0.138	0.01456	1.52	-53.44	-27.38	32.0	21.90
									48.0	23.88
8	0.1247	0.1186	0.0859	0.0647	0.00693	-0.66	28.15	53.12	64.0	30.28
									96.0	45.10
9	0.1499	0.1432	0.1118	0.0677	0.00456	1.44	49.14	4.39	128.0	72.18
					RMS Error:	0.84	28.09	52.59	*192.0*	*115.82*
									256.0	*171.95*

Comments:



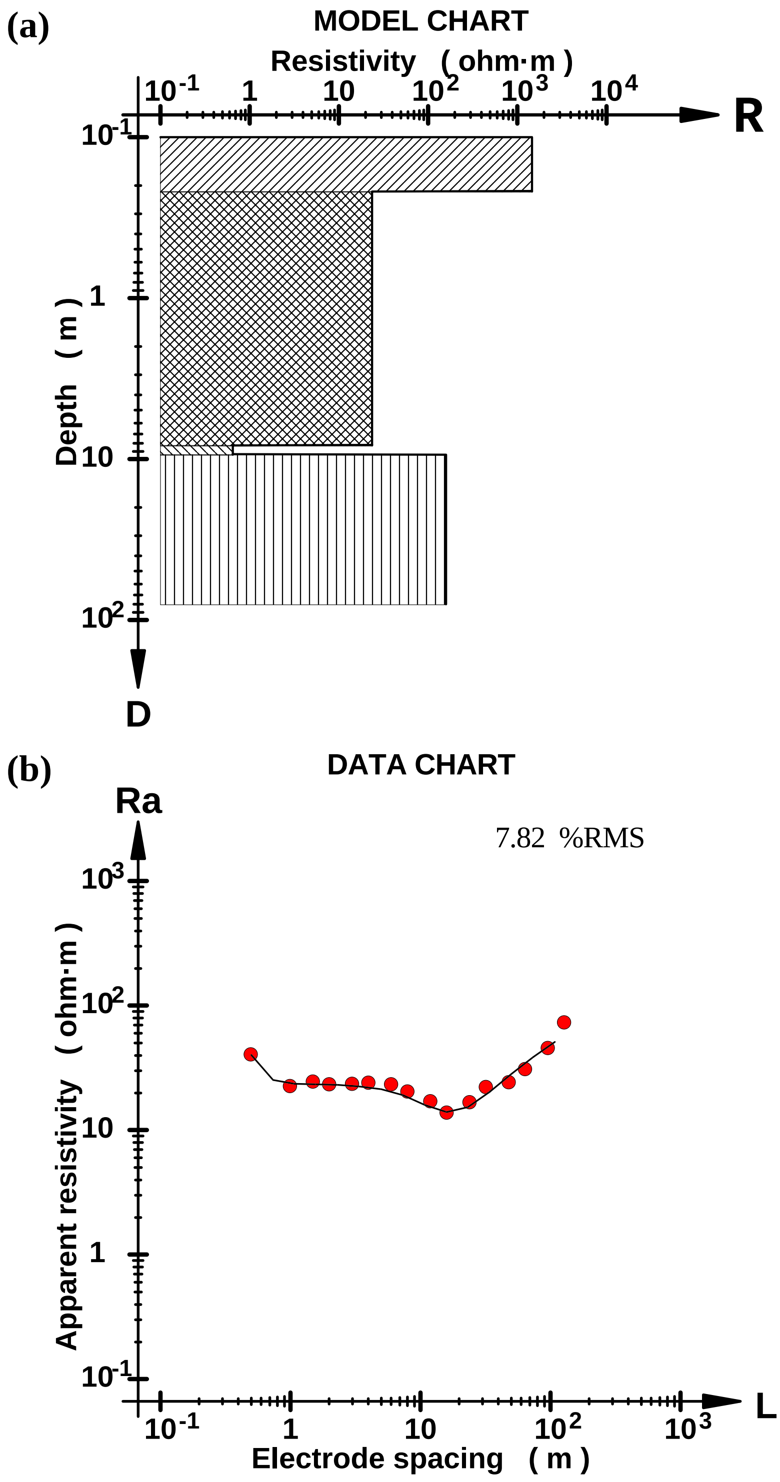
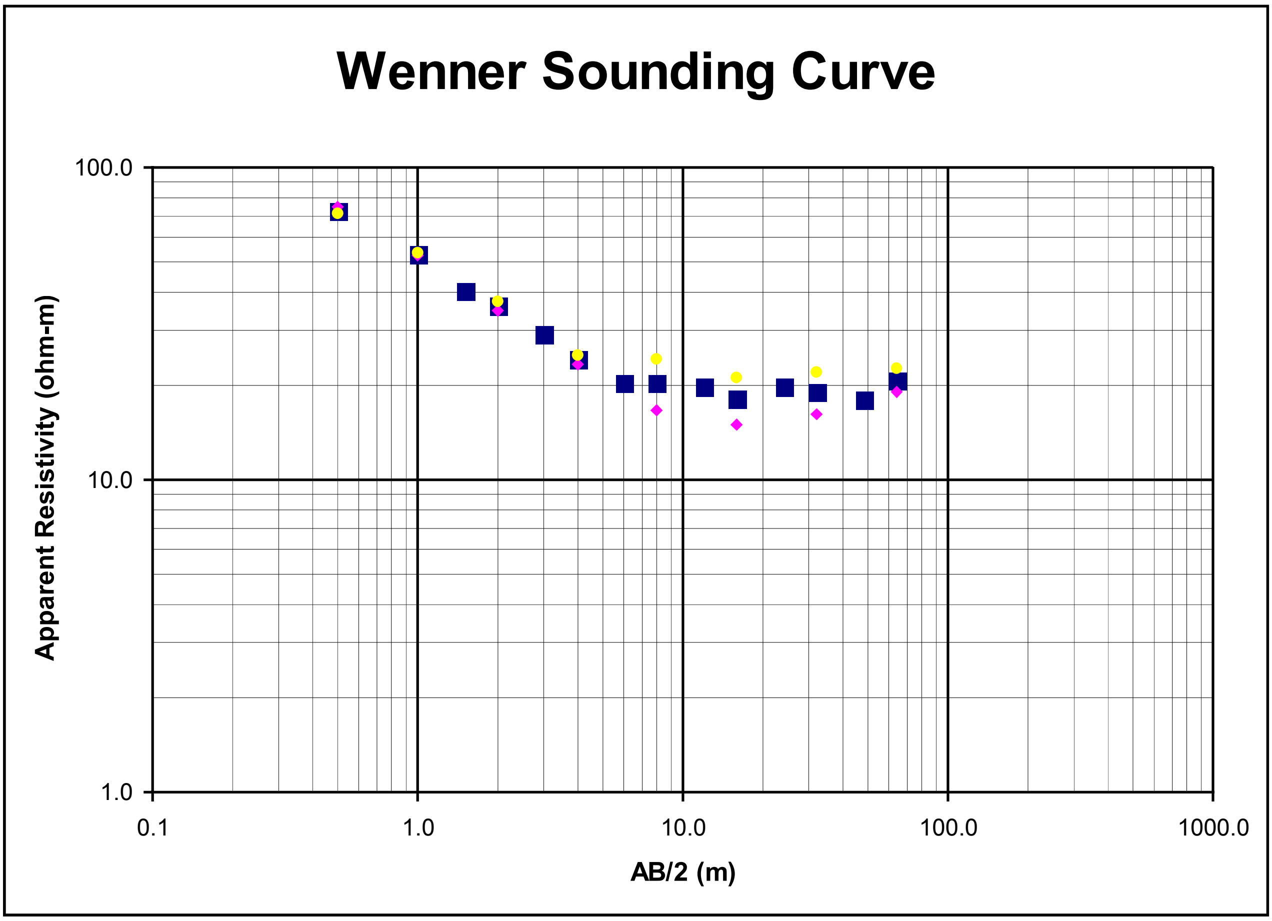


Figure A1-6: Interpreted model for RARO6

Site:	Half-way between back & main road	Ref No:	**RARO7**	Weather:	
Observers:	Giovanni, Terence, David	Bearing:	D1 Counterclockwise	Topography:	
Date:	20/01/98	Soil:	Tending swampy	Geology:	swamp area

SETTING	OBSERVED MEASUREMENTS					ERRORS			SPACING	WENNER
(n)	RA	RC	RD1	RD2	RB	OBS	OFFSET	LATERAL	(metres)	RESISTIVITY
1	25.4	23.4	23.7	22.6	1.959	0.16	4.75		0.5	72.73
2	10.57	9.99	8.36	8.51	0.577	0.03	-1.78	93.62	1.0	53.00
									1.5	40.23
3	3.46	3.26	2.76	2.98	0.205	-0.14	-7.67	-8.46	2.0	36.07
									3.0	29.13
4	1.236	1.183	0.935	0.995	0.0596	-0.53	-6.22	19.66	4.0	24.25
									6.0	20.42
5	0.574	0.55	0.333	0.485	0.0275	-0.61	-37.16	-5.06	8.0	20.56
									12.0	19.81
6	0.242	0.225	0.1491	0.212	0.0212	-1.72	-34.84	-54.34	16.0	18.15
									24.0	19.84
7	0.1403	0.1301	0.0807	0.11	0.0073	2.09	-30.73	10.82	32.0	19.17
									48.0	18.12
8	0.0709	0.0648	0.0477	0.0565	0.00744	-1.87	-16.89	-38.61	64.0	20.95
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	1.20	22.21	41.55	*192.0*	
									256.0	

Comments:



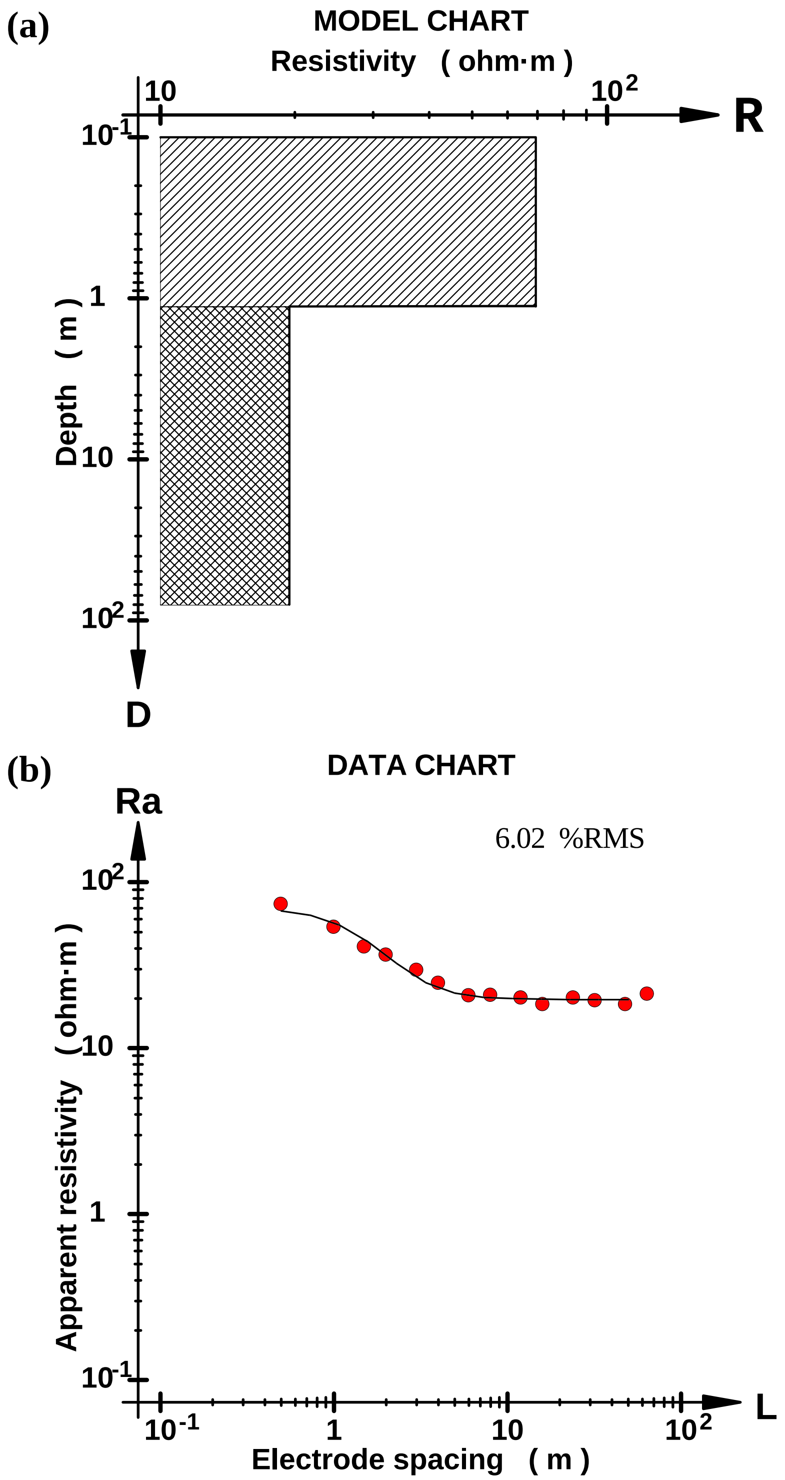
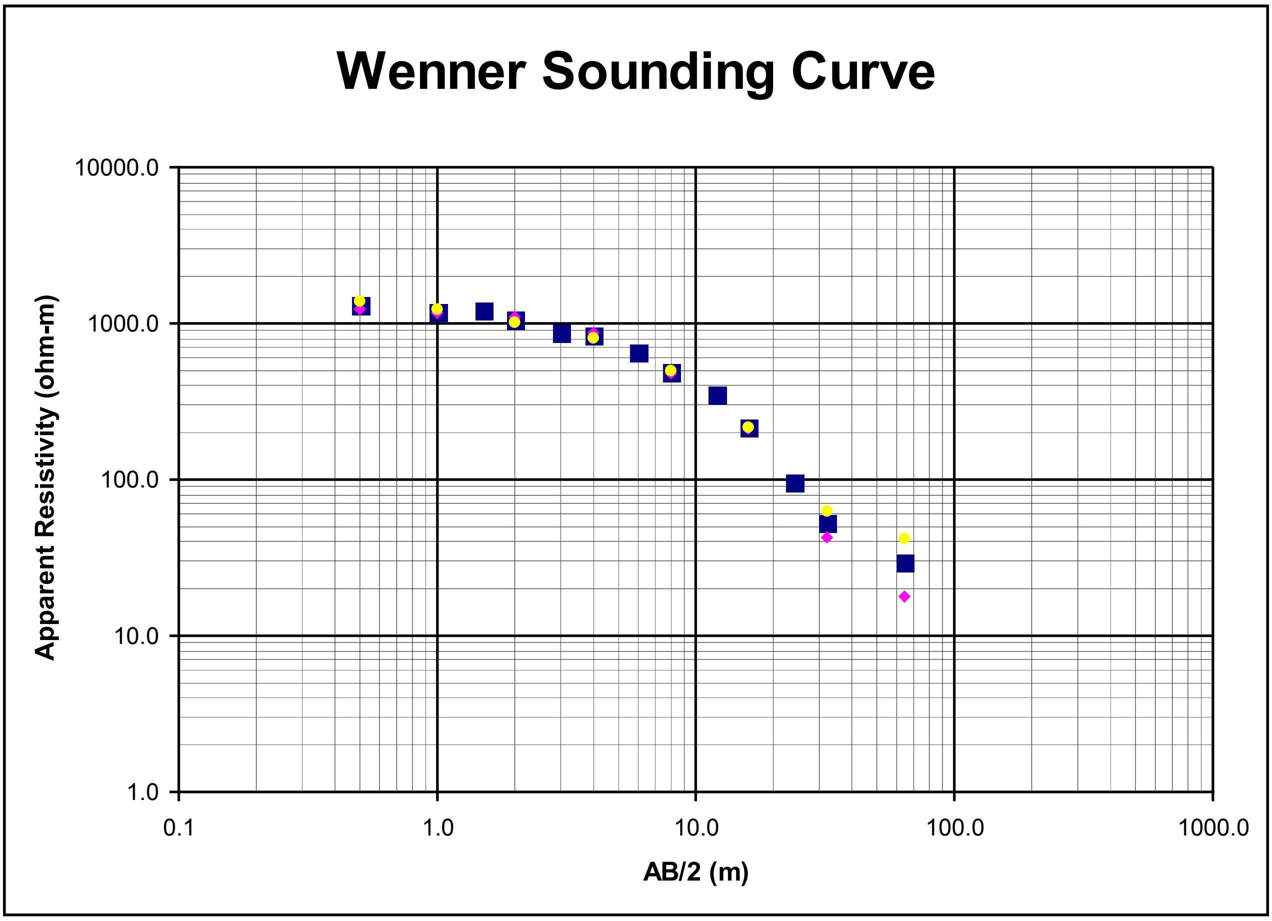


Figure A1-7: Interpreted model for RARO7

Site:	Main Road adjacent to RARO7	Ref No:	RARO8	Weather:	
Observers:	Giovanni, Terence, David	Bearing:		Topography:	
Date:	20/01/98	Soil:		Geology:	Aroa sands

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	549	521	397	444	27.8	0.04	-11.18		0.5	1321.04
2	236	217	184.5	195.1	18.49	0.22	-5.58	-6.00	1.0	1192.55
									1.5	1202.41
3	106.8	100.5	87.5	80.4	6.21	0.08	8.46	34.64	2.0	1054.95
									3.0	872.31
4	42.3	40.2	34.5	31.9	2.03	0.17	7.83	0.05	4.0	834.41
									6.0	651.88
5	12.2	11.54	9.55	9.94	0.721	-0.50	-4.00	-44.35	8.0	489.84
									12.0	349.10
6	2.37	2.25	2.13	2.15	0.1643	-1.85	-0.93	-65.07	16.0	215.14
									24.0	97.12
7	0.335	0.353	0.212	0.31	-0.0494	9.86	-37.55	31.67	32.0	52.48
									48.0	-14.18
8	0.1895	0.1788	0.0442	0.1041	0.01092	-0.12	-80.78	-194.96	64.0	29.82
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	3.55	32.10	76.20	*192.0*	
									256.0	

Comments:



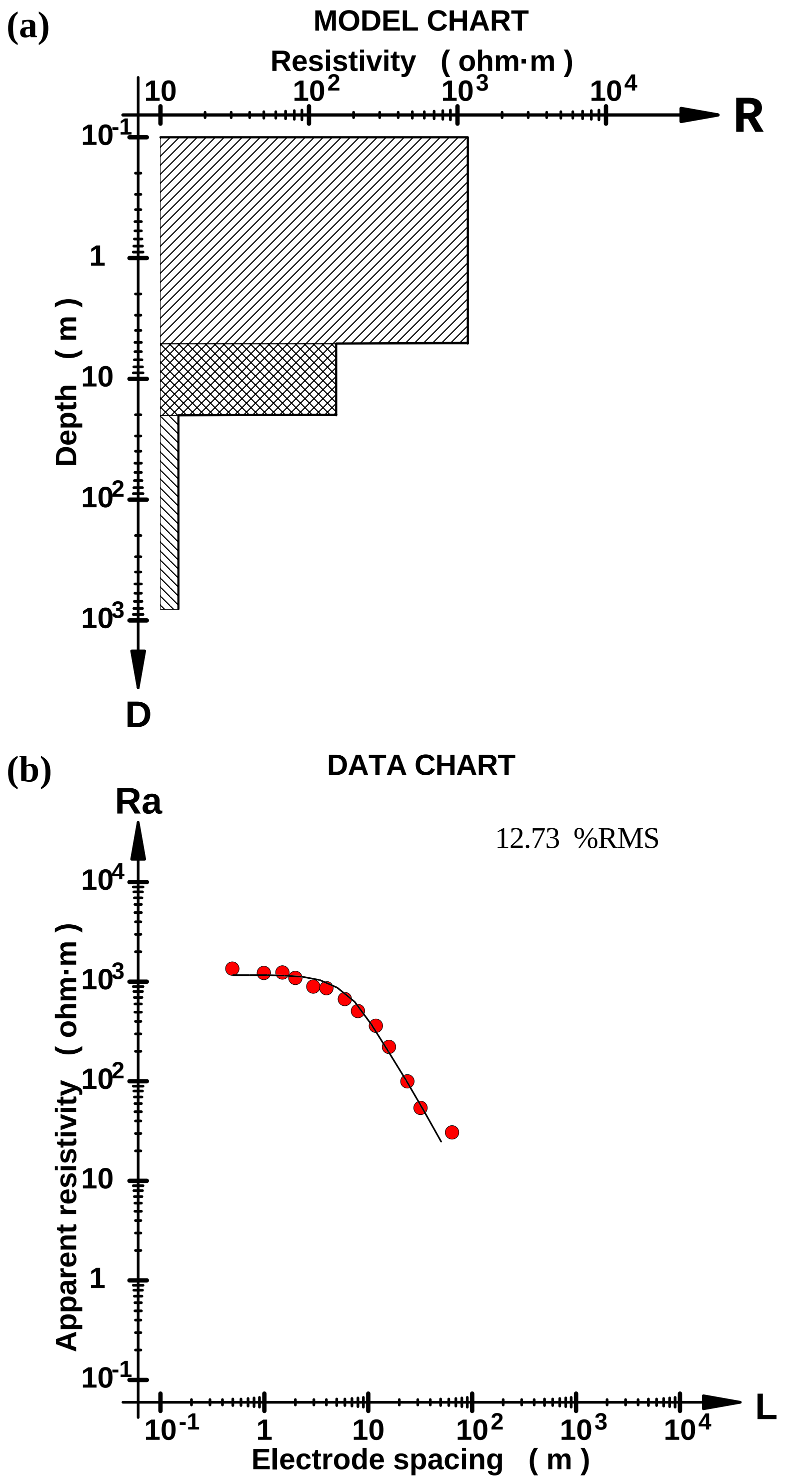
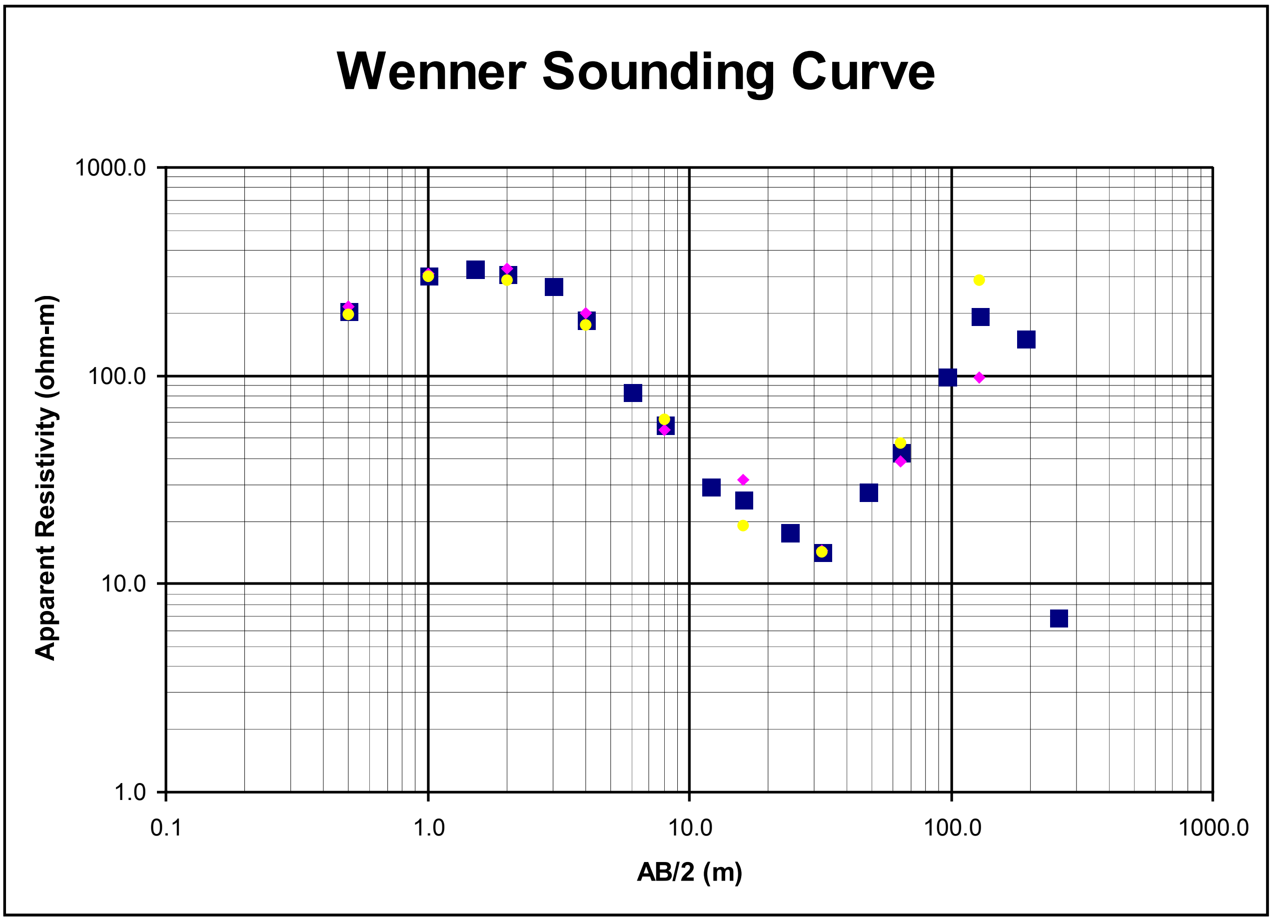


Figure A1-8: Interpreted model for RARO8

Site:	Swamp area close to the Rarotonga	Ref No:	RARO9	Weather:	Fine
Observers:	Giovanni, Adrian, David	Bearing:	D1 Clockwise	Topography:	
Date:	21/01/98	Soil:		Geology:	swamp area

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	OBS	ERRORS OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	99.8	94.2	68.1	62.9	5.4	0.20	7.94		0.5	205.77
2	70.5	66.5	48.8	48	3.89	0.16	1.65	-18.99	1.0	304.11
									1.5	328.81
3	29.3	26.8	26	22.8	2.45	0.17	13.11	-48.79	2.0	306.62
									3.0	272.78
4	8.54	8.15	7.9	6.95	0.373	0.20	12.79	34.74	4.0	186.61
									6.0	83.48
5	1.195	1.141	1.094	1.228	0.0543	-0.03	-11.54	-26.29	8.0	58.36
									12.0	29.24
6	0.259	0.251	0.315	0.1906	0.0092	-0.46	49.21	115.94	16.0	25.41
									24.0	17.63
7	0.085	0.0814	0.0717	0.0707	0.01199	-9.43	1.40	106.69	32.0	14.32
									48.0	27.57
8	0.0699	0.0657	0.0962	0.1181	0.00207	3.10	-20.44	88.11	64.0	43.09
									96.0	99.33
9	0.218	0.243	0.1227	0.359	0.00591	-13.30	-98.11	133.58	128.0	193.70
					RMS Error:	5.53	38.01	78.22	*192.0*	*151.99*
									256.0	*6.92*

Comments: D1 direction cable detoured around house for outer electrode.



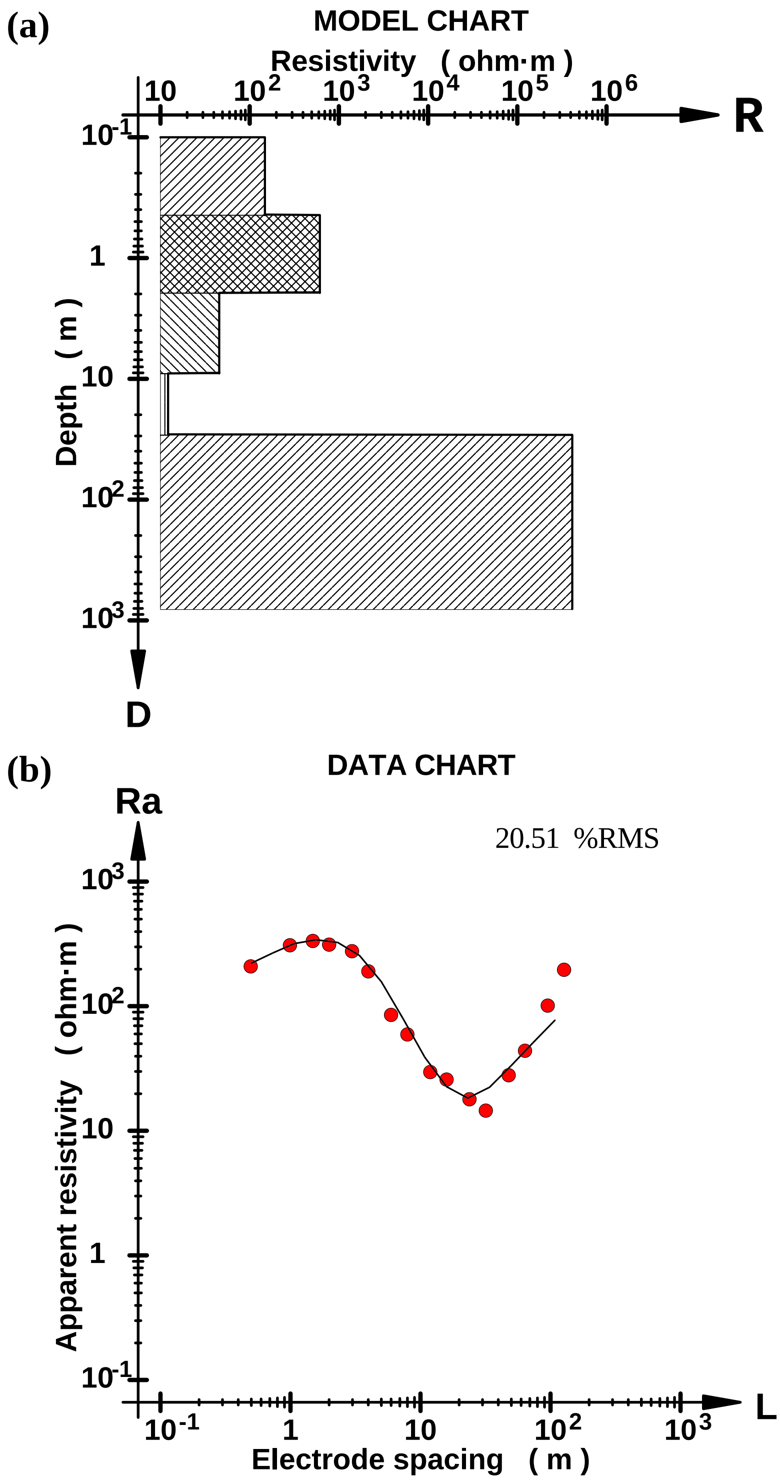
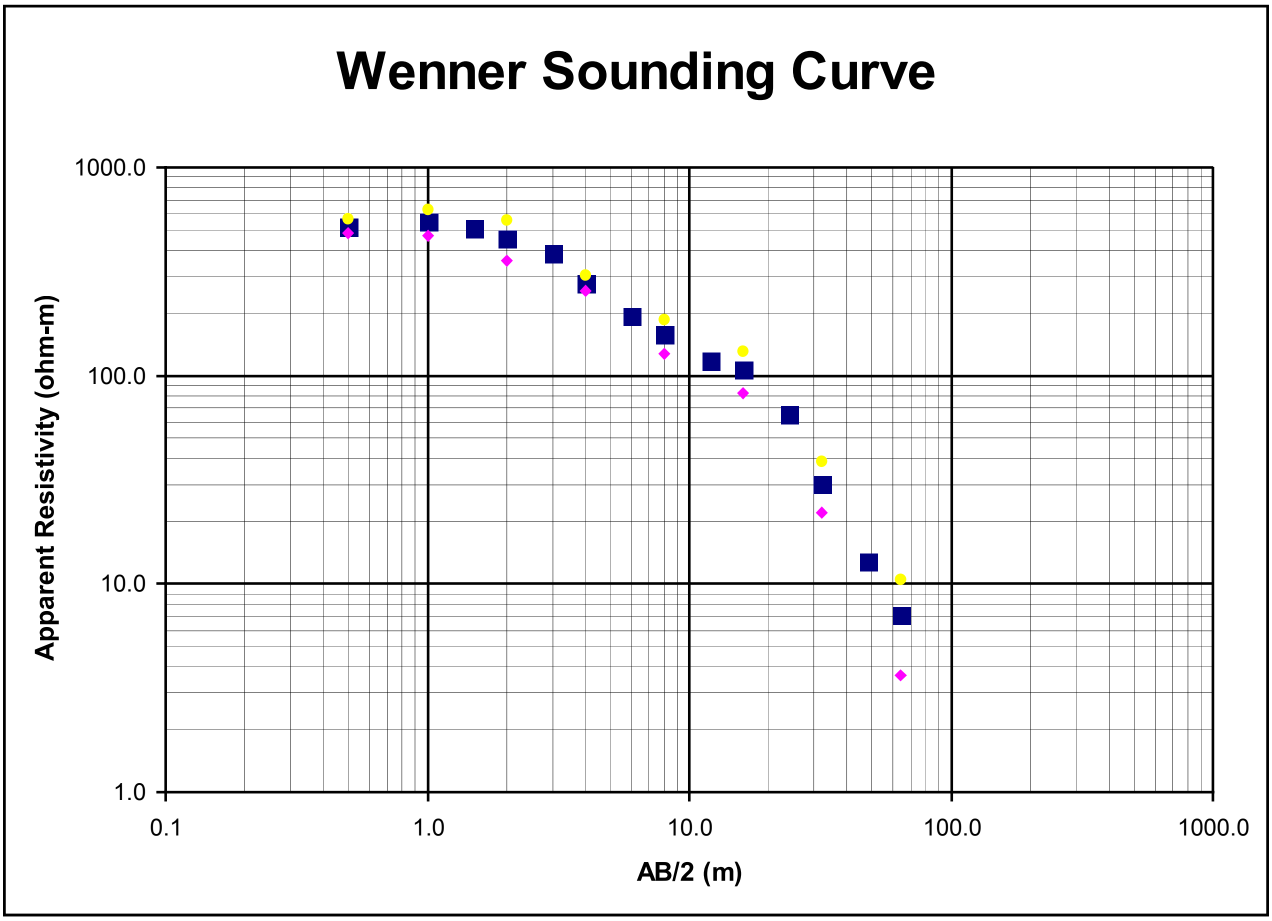


Figure A1-9: Interpreted model for RARO9

Site:	Close to beach adjacent to RARO9	Ref No:	**RARO10**	Weather:	
Observers:	Giovanni, Adrian, David	Bearing:	D1 Clockwise	Topography:	
Date:	21/01/98	Soil:		Geology:	Aroa sands

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	230	216	153	180.3	13.78	0.10	-16.38		0.5	523.55
2	115.6	109.6	74.8	100.1	6.03	-0.03	-28.93	-13.10	1.0	549.46
									1.5	511.22
3	46.1	43.3	28.5	44.6	2.73	0.15	-44.05	-21.13	2.0	459.30
									3.0	387.22
4	12.76	12	10.17	12.09	0.755	0.04	-17.25	-21.88	4.0	279.73
									6.0	194.27
5	3.92	3.7	2.55	3.71	0.219	0.03	-37.06	44.26	8.0	157.33
									12.0	117.59
6	1.298	1.272	0.825	1.298	0.0448	-1.44	-44.56	-7.48	16.0	106.71
									24.0	65.08
7	0.1724	0.1699	0.1089	0.1926	0.00293	-0.25	-55.52	-167.14	32.0	30.31
									48.0	12.85
8	0.0283	0.0299	0.009	0.0261	0.00247	-13.48	-97.44	-115.82	64.0	7.06
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	4.79	49.09	74.55	*192.0*	
									256.0	

Comments: Estimated GL to be 2.7 m above sea level (high tide). Attempted to use ABEM Booster unit but obtained highly suspect values.



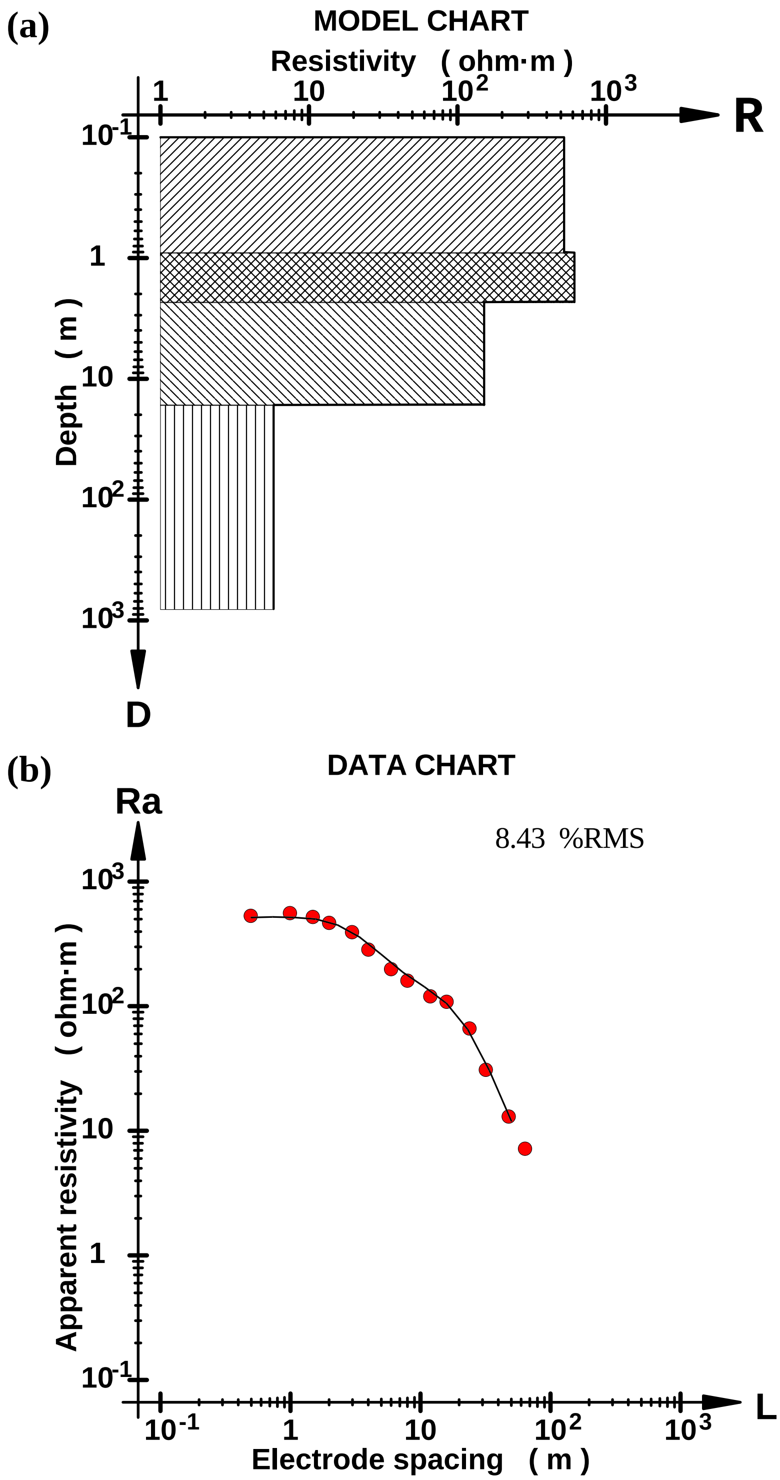
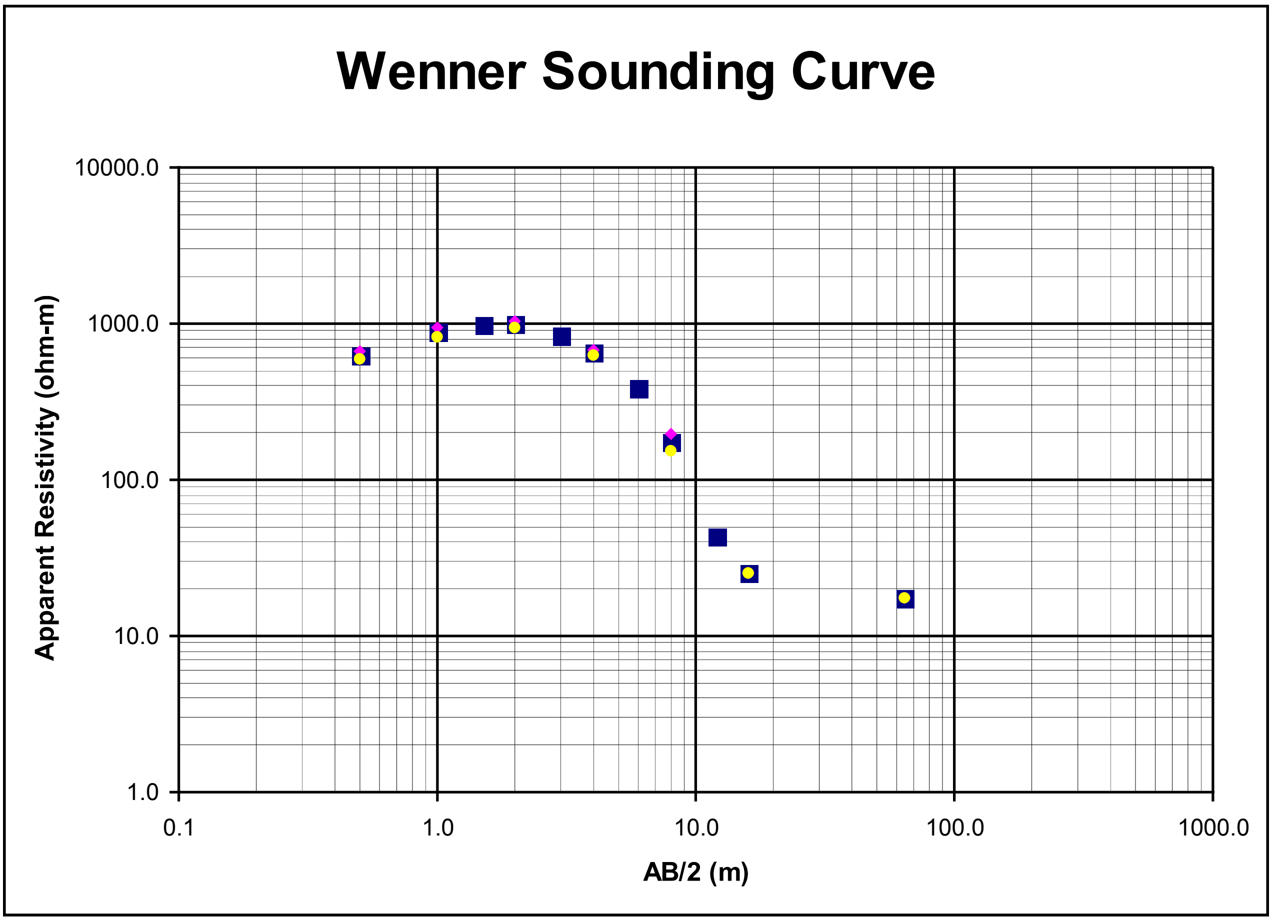


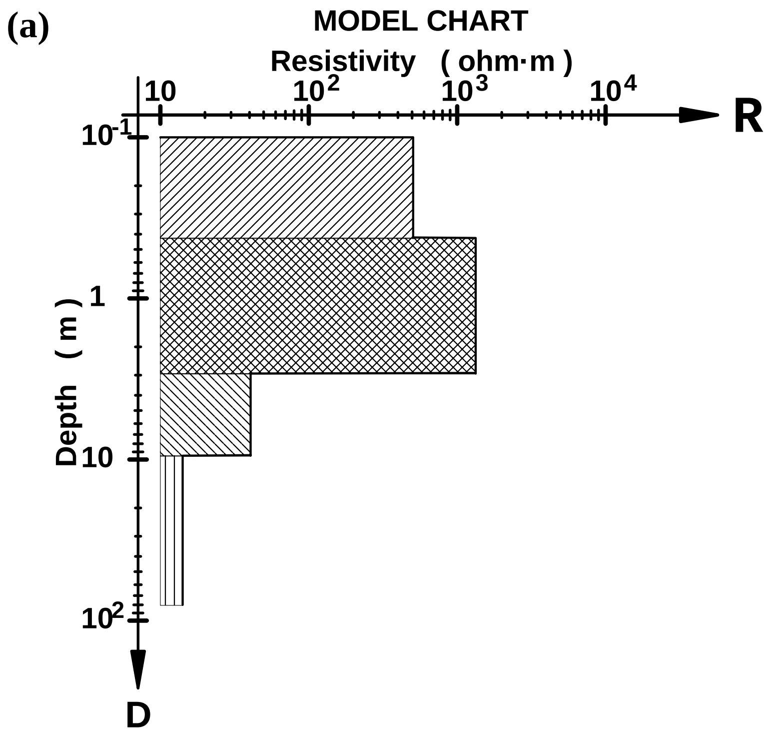
Figure A1-10: Interpreted model for RARO10

Site:	SDA School	Ref No:	**RARO11w**	Weather:	Heavy rain overnight
Observers:	Giovanni, Adrian, David	Bearing:		Topography:	
Date:	22/01/98	Soil:	Damp	Geology:	Aroa sands

SETTING	OBSERVED MEASUREMENTS					ERRORS			SPACING	WENNER
(n)	RA	RC	RD1	RD2	RB	OBS	OFFSET	LATERAL	(metres)	RESISTIVITY
1	283	262	212	188.7	20.8	0.07	11.63		0.5	629.42
2	189.3	175.1	149.1	131.6	14.12	0.04	12.47	12.02	1.0	881.84
									1.5	971.61
3	103.8	98	83.1	75.3	5.84	-0.04	9.85	12.15	2.0	995.26
									3.0	836.75
4	28.5	27.1	27.1	25.2	1.375	0.09	7.27	-43.64	4.0	657.22
									6.0	390.44
5	3.65	3.55	3.91	3.07	0.0835	0.45	24.07	44.88	8.0	175.43
									12.0	43.66
6	1		0.252	0.252		#DIV/0!	0.00	46.00	16.0	25.33
									24.0	
7						N/A	N/A	N/A	32.0	
									48.0	#DIV/0!
8	1		0.0435	0.0435		#DIV/0!	0.00	#DIV/0!	64.0	17.49
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	#DIV/0!	12.07	#DIV/0!	*192.0*	
									256.0	

Comments: Sounding abandoned after persistent reports of poor contact and suspected cable faults. Schlumberger sounding (RARO11s) completed in its place.





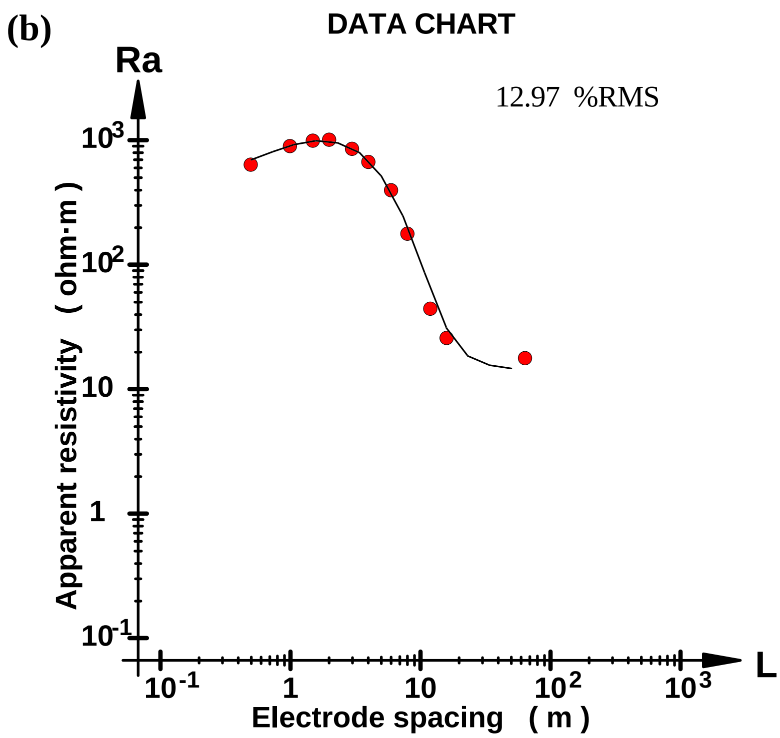
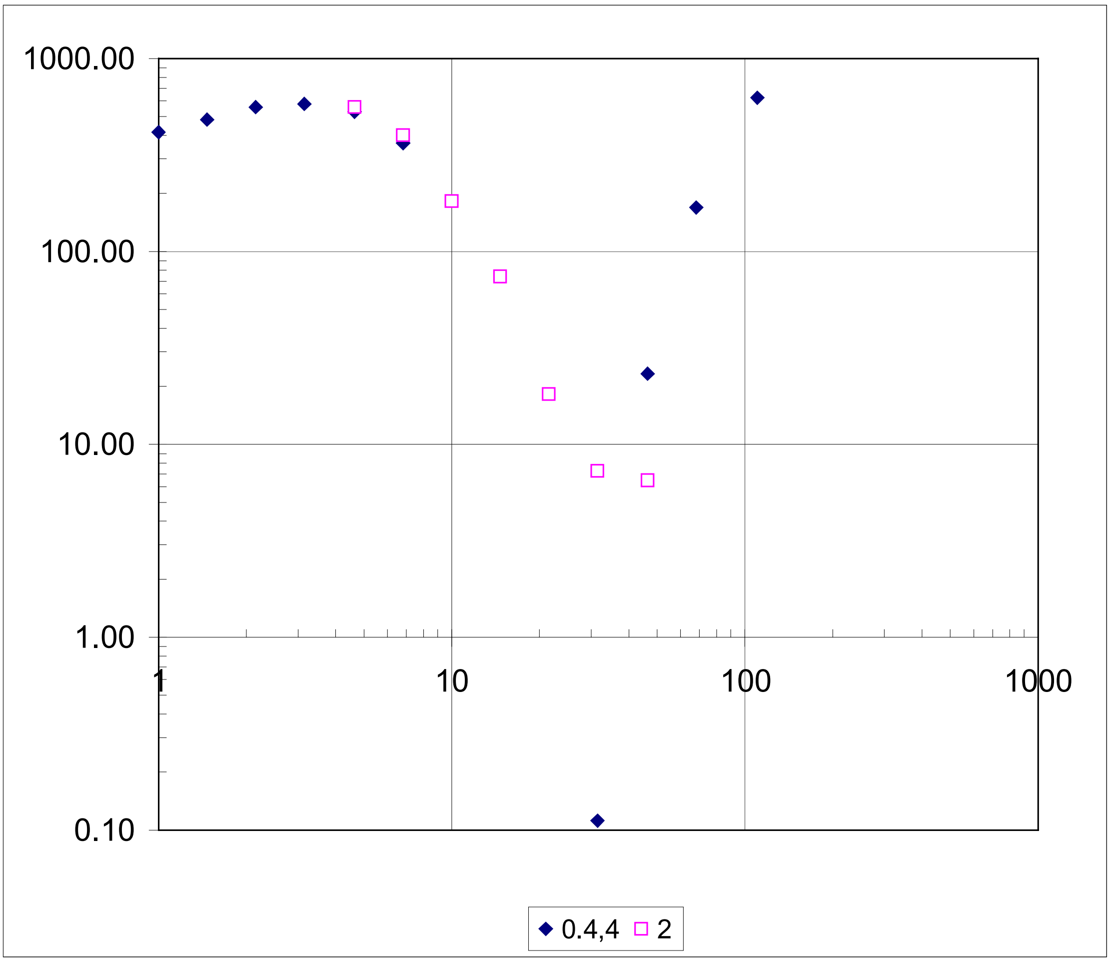


Figure A1-11: Interpreted figure for RARO11w

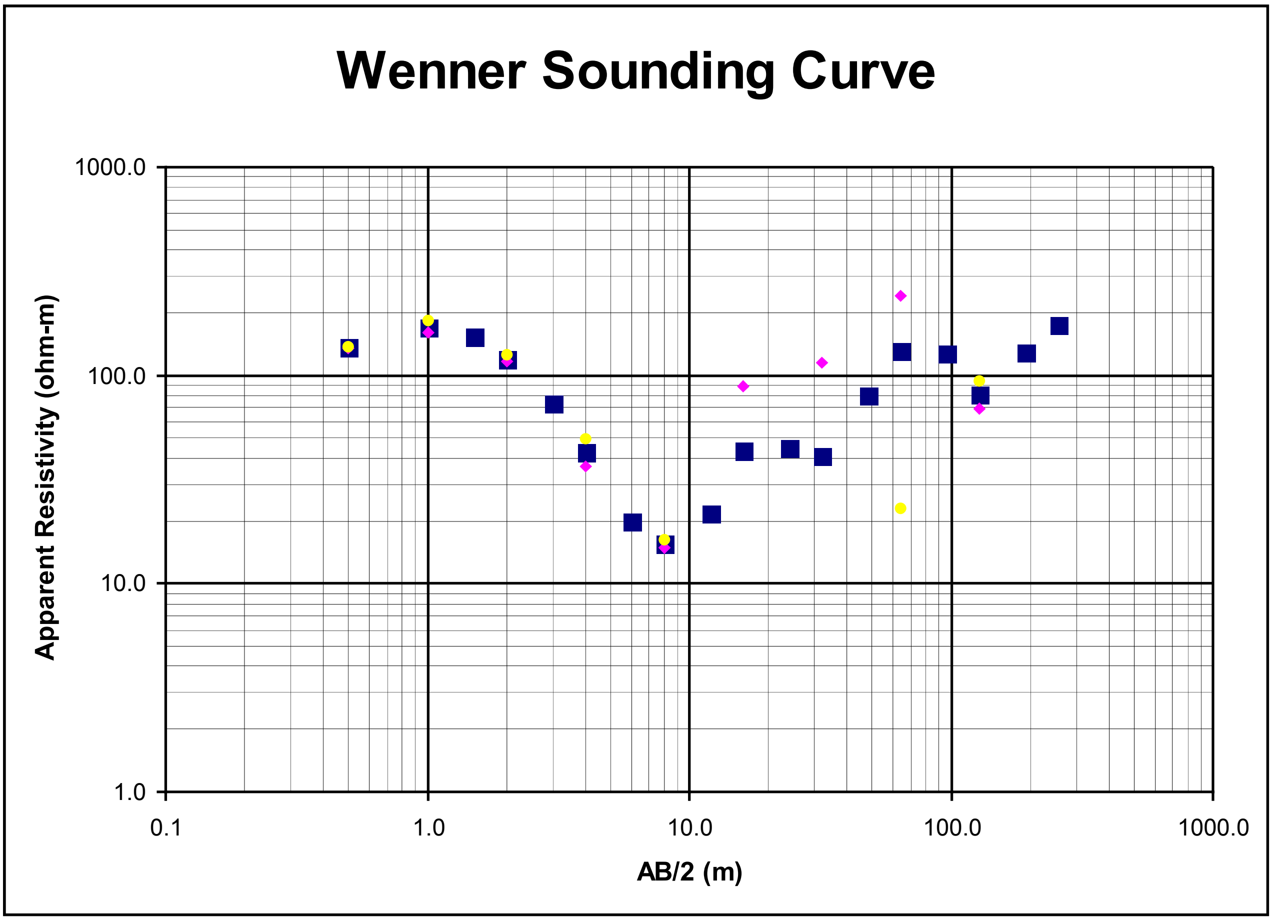
No.	RARO11s			Date:	22/01/98
Location:	*Tikaveka*			*Coordinates:*	
Elevation:				*Bearings:*	
AB/2	**MN/2**	**Resistivity**	**k**	**Apparent Res.**	**Apparent Res.**
(m)	(m)	(ohm*m)		(ohm*m)	(ohm*m)
1	0.4	125.2	3.297	412.78	
1.47	0.4	61.6	7.853533	483.78	
2.15	0.4	31.8	17.51531	556.99	
3.16	0.4	14.93	38.56548	575.78	
4.64	0.4	6.25	83.87568	524.22	
6.81	0.4	2	181.3982	362.80	
4.64	2	40.4	13.76074		555.93
6.81	2	12	33.26524		399.18
10	2	2.4	75.36		180.86
14.7	2	0.443	166.4907		73.76
21.5	2	0.0504	359.7263		18.13
31.6	2	0.00935	780.7296		7.30
46.4	2	0.00384	1686.934		6.48
31.6	4	0.000288	385.6548	0.11	
46.4	4	0.0278	838.7568	23.32	
68.1	4	0.0936	1813.982	169.79	
110	4	0.1329	4742.97	630.34	
147	4	0.664	8475.253	5627.57	



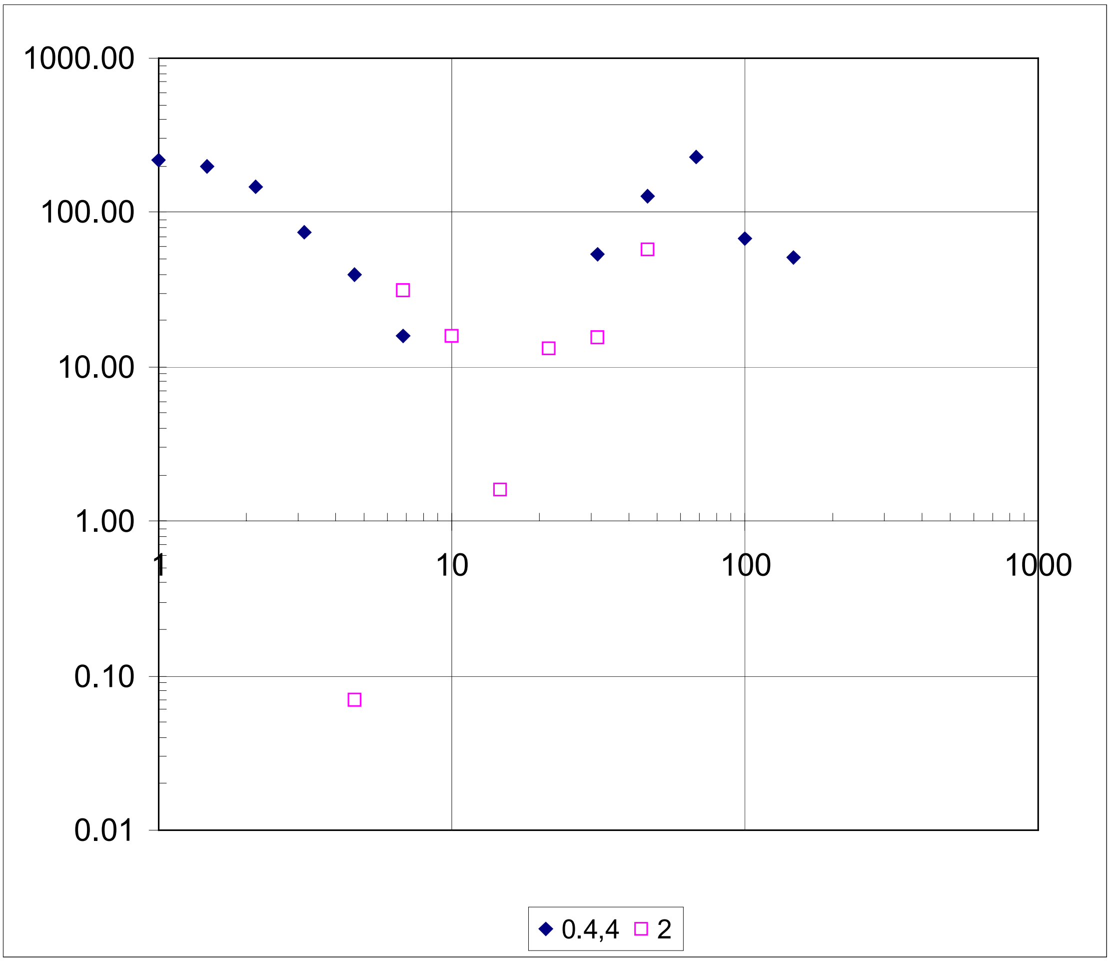
Site:	Main Rd outside Muri Beachcombe	Ref No:	**RARO12w**	Weather:	Fine
Observers:	Giovanni, Adrian, David	Bearing:	D1 Counterclockwise	Topography:	Flat
Date:	26/01/98	Soil:		Geology:	Aroa sands

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	61.3	56.7	43	43.9	4.51	0.15	-2.07		0.5	136.50
2	35.1	32.7	25.5	29	2.36	0.11	-12.84	2.45	1.0	171.22
									1.5	153.51
3	10.3	9.69	9.3	9.96	0.6	0.10	-6.85	-13.58	2.0	121.01
									3.0	73.75
4	1.963	1.806	1.45	1.984	0.112	2.32	-31.10	92.46	4.0	43.15
									6.0	19.84
5	0.409	0.284	0.294	0.325	0.0255	28.24	-10.02	28.96	8.0	15.56
									12.0	21.61
6	0.73	0.73	0.885	-0.0207	0.0068	-0.93	209.58	93.60	16.0	43.44
									24.0	44.73
7	0.489	0.485	0.573	-0.1618	0.0081	-0.83	357.39	-186.45	32.0	41.34
									48.0	80.62
8	0.1225	0.1196	0.596	0.0568	0.0056	-2.18	165.20	-69.96	64.0	131.25
									96.0	127.54
9	0.1612	0.156	0.0863	0.1168	0.0081	-1.78	-30.03	509.85	128.0	81.67
					RMS Error:	9.50	149.49	187.96	*192.0*	*129.94*
									256.0	*175.17*

Comments: Water well conductivity (Muri Beach Villas) was 376 µS/cm @ 25 C degrees



No.	RARO12s			Date:	22/01/1998
Location:	*Muri Beach*			*Coordinates:*	
Elevation:				*Bearings:*	
AB/2	**MN/2**	**Resistivity**	**k**	**Apparent Res.**	**Apparent Res.**
(m)	(m)	(ohm*m)		(ohm*m)	(ohm*m)
1	0.4	65.8	3.297	216.94	
1.47	0.4	25.2	7.853533	197.91	
2.15	0.4	8.44	17.51531	147.83	
3.16	0.4	1.941	38.56548	74.86	
4.64	0.4	0.468	83.87568	39.25	
6.81	0.4	0.0871	181.3982	15.80	
4.64	2	0.00505	13.76074		0.07
6.81	2	0.944	33.26524		31.40
10	2	0.21	75.36		15.83
14.7	2	0.00966	166.4907		1.61
21.5	2	0.0364	359.7263		13.09
31.6	2	0.01983	780.7296		15.48
46.4	2	0.0341	1686.934		57.52
31.6	4	0.138	385.6548	53.22	
46.4	4	0.1526	838.7568	127.99	
68.1	4	0.1251	1813.982	226.93	
100	4	0.01745	3918.72	68.38	
147	4	0.00599	8475.253	50.77	



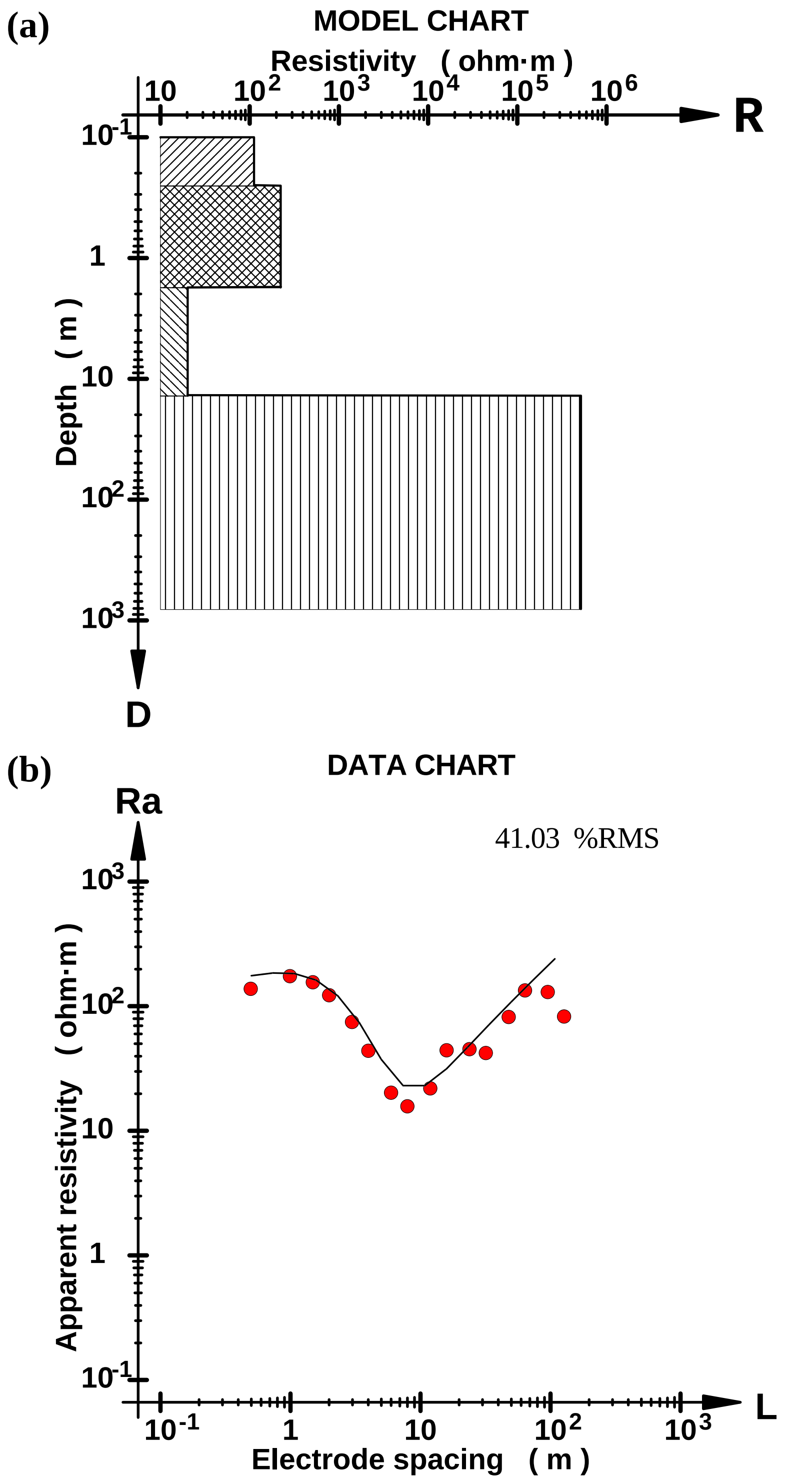
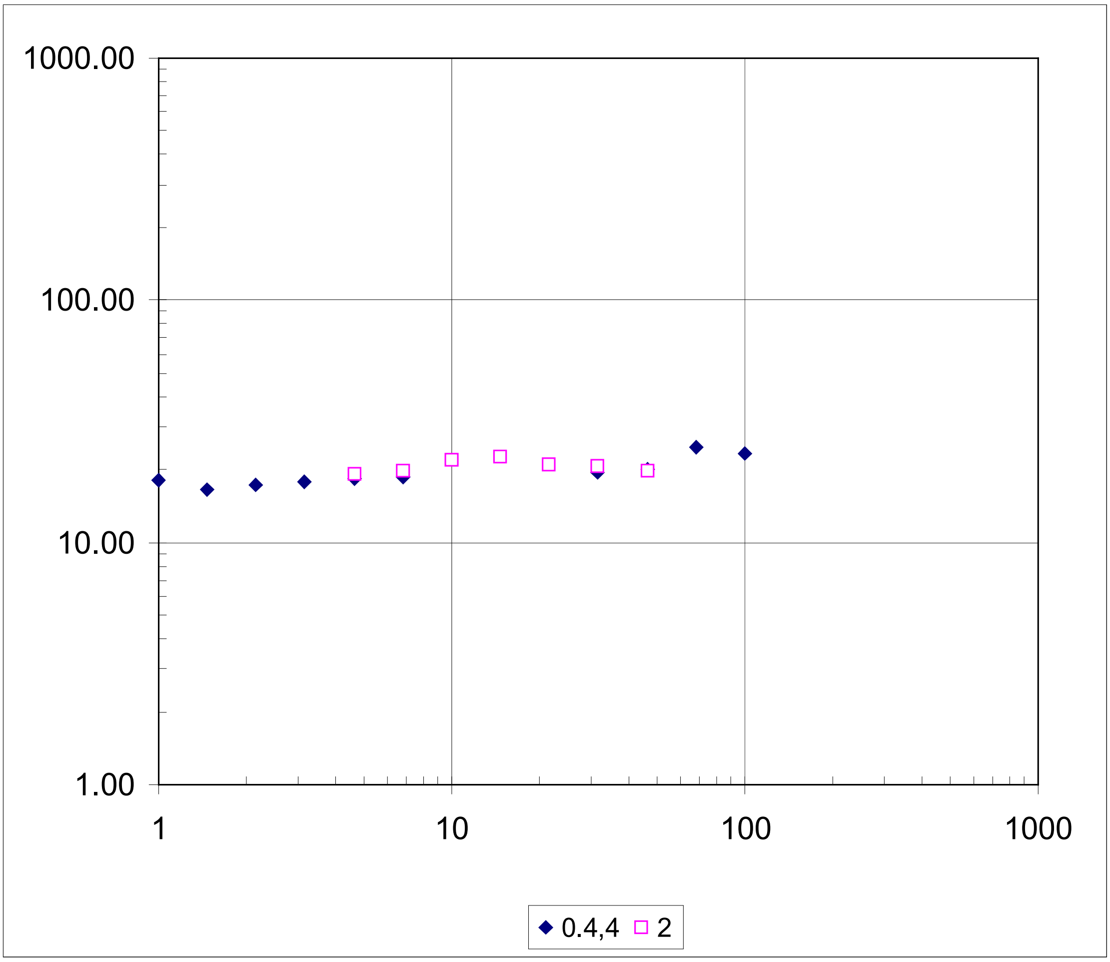


Figure A1-12: Interpreted figure for RARO12w

No.	raro 13			Date:	23/01/1998
Location:	*back road*			*Coordinates:*	
Elevation:				*Bearings:*	
AB/2	**MN/2**	**Resistivity**	**k**	**Apparent Res.**	**Apparent Res.**
(m)	(m)	(ohm*m)		(ohm*m)	(ohm*m)
1	0.4	5.5	3.297	18.13	
1.47	0.4	2.1	7.853533	16.49	
2.15	0.4	0.989	17.51531	17.32	
3.16	0.4	0.461	38.56548	17.78	
4.64	0.4	0.218	83.87568	18.28	
6.81	0.4	0.1032	181.3982	18.72	
4.64	2	1.393	13.76074		19.17
6.81	2	0.597	33.26524		19.86
10	2	0.29	75.36		21.85
14.7	2	0.1349	166.4907		22.46
21.5	2	0.0582	359.7263		20.94
31.6	2	0.0265	780.7296		20.69
46.4	2	0.01173	1686.934		19.79
31.6	4	0.0503	385.6548	19.40	
46.4	4	0.024	838.7568	20.13	
68.1	4	0.0137	1813.982	24.85	
100	4	0.0059	3918.72	23.12	
147	4		8475.253	0.00	



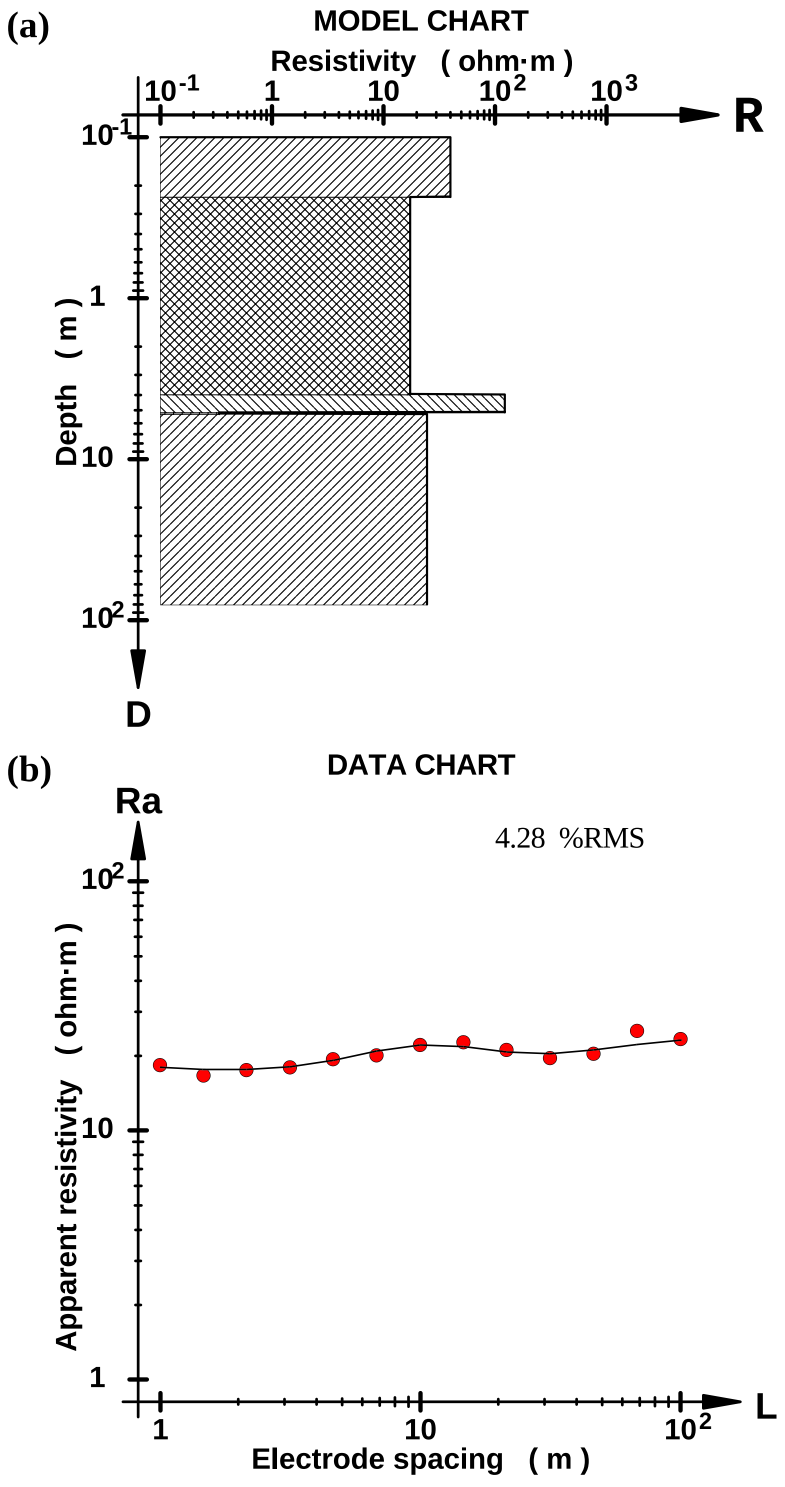
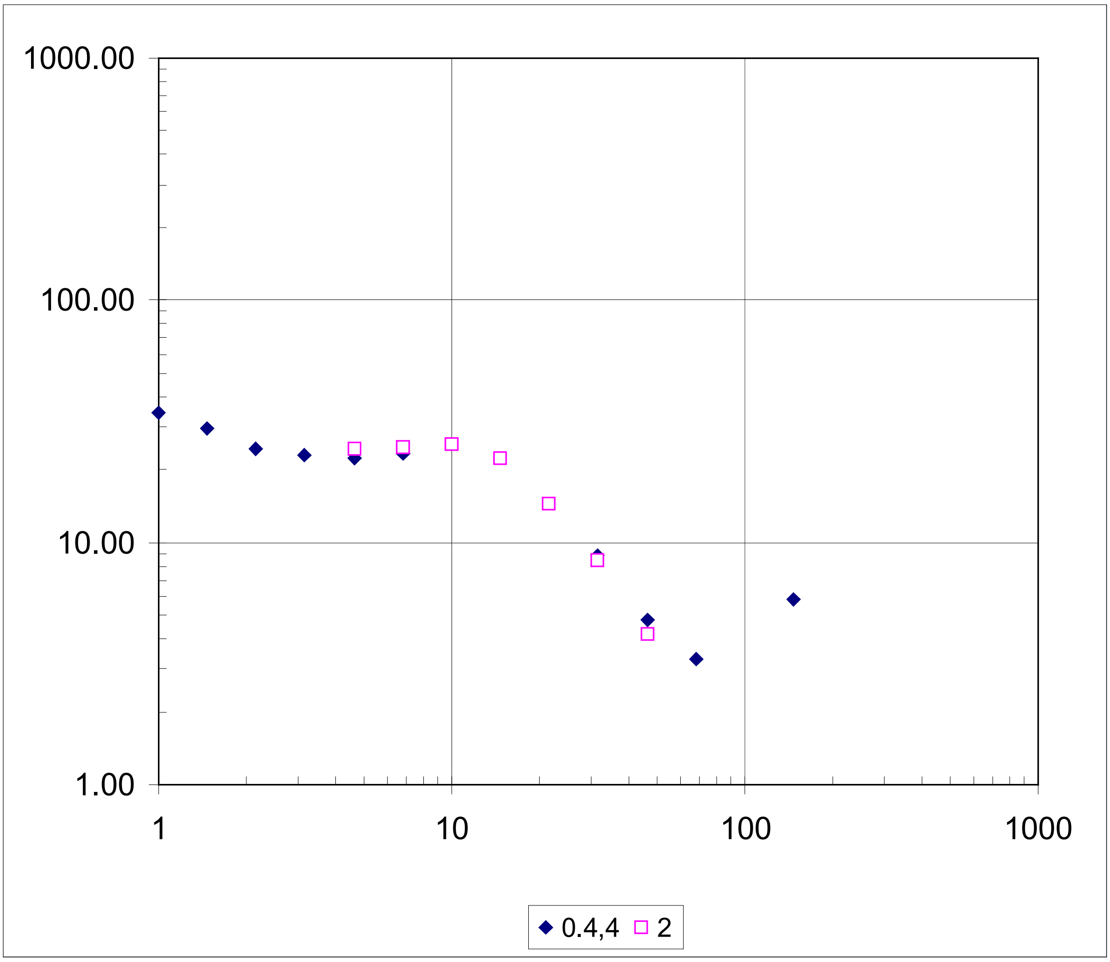


Figure A1-13: Interpreted model for RARO13

No.	RARO14	Turangi		Date:	23/01/1998
Location:	*main road*			*Coordinates:*	
Elevation:				*Bearings:*	
AB/2	MN/2	Resistivity	k	Apparent Res.	Apparent Res.
(m)	(m)	(ohm*m)		(ohm*m)	(ohm*m)
1	0.4	10.43	3.297	34.39	
1.47	0.4	3.74	7.853533	29.37	
2.15	0.4	1.391	17.51531	24.36	
3.16	0.4	0.595	38.56548	22.95	
4.64	0.4	0.267	83.87568	22.39	
6.81	0.4	0.129	181.3982	23.40	
4.64	2	1.781	13.76074		24.51
6.81	2	0.745	33.26524		24.78
10	2	0.337	75.36		25.40
14.7	2	0.1337	166.4907		22.26
21.5	2	0.0404	359.7263		14.53
31.6	2	0.01074	780.7296		8.39
46.4	2	0.0025	1686.934		4.22
31.6	4	0.023	385.6548	8.87	
46.4	4	0.00568	838.7568	4.76	
68.1	4	0.001817	1813.982	3.30	
100	4		3918.72	0.00	
147	4	0.000684	8475.253	5.80	



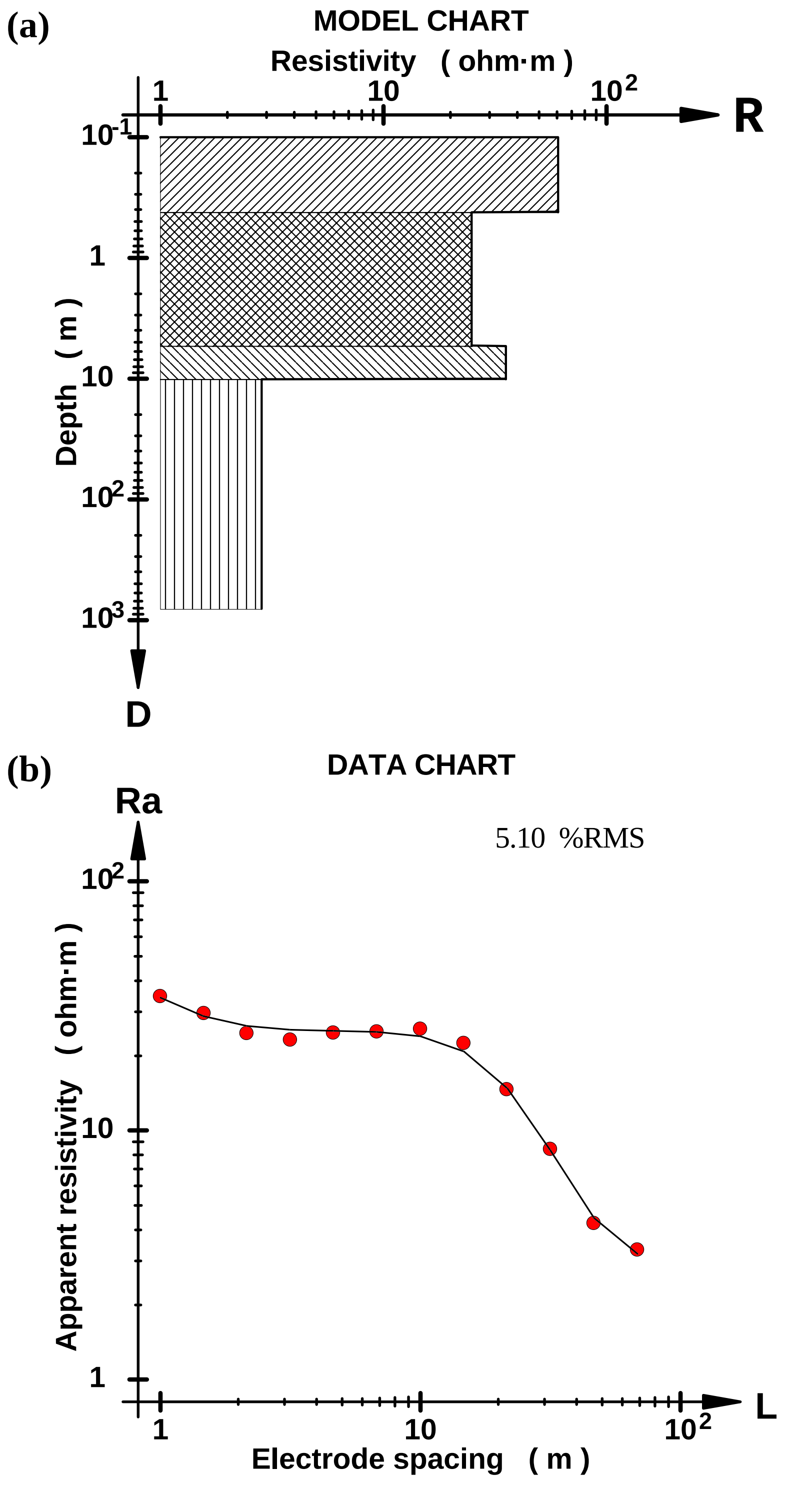
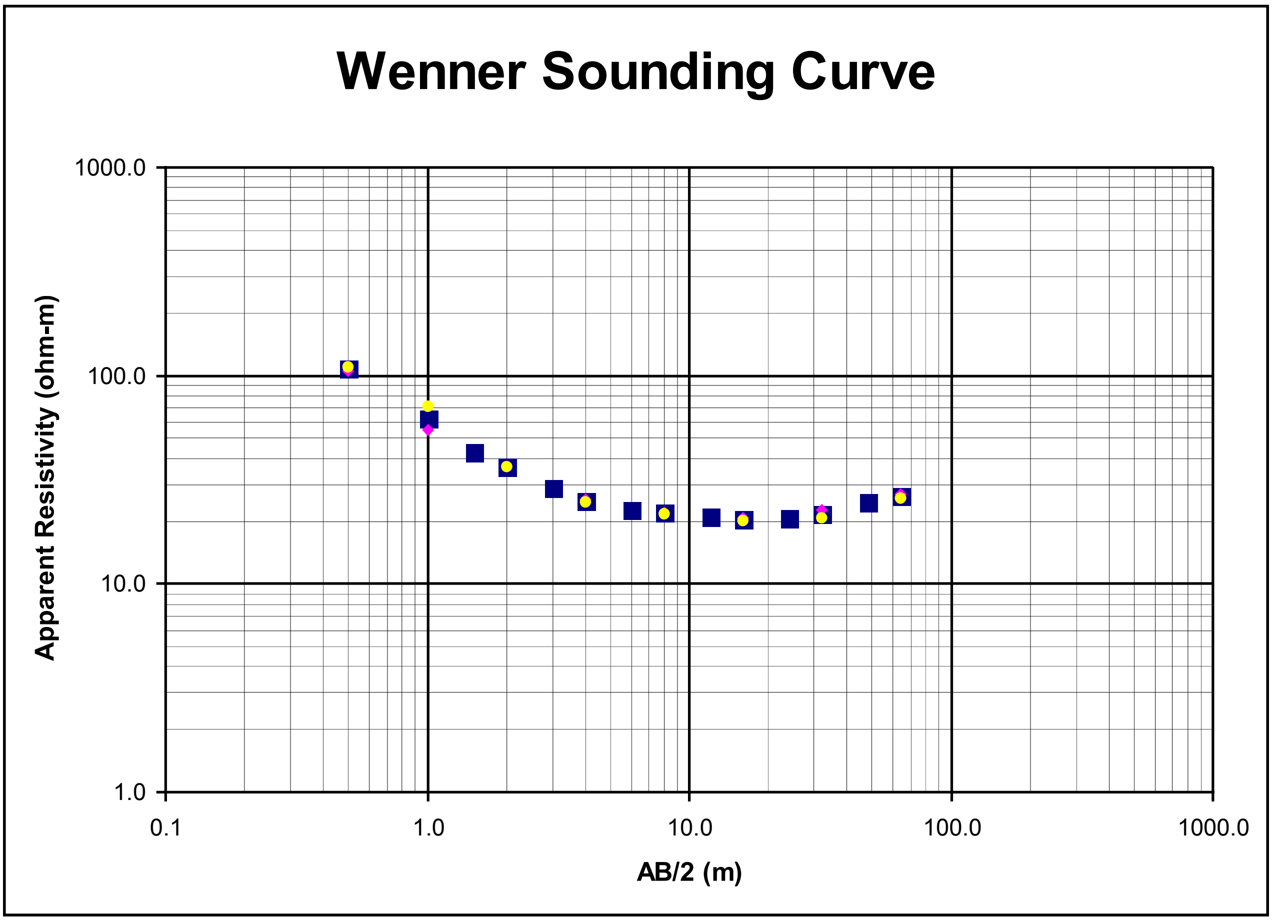


Figure A1-14: Interpreted model for RARO14

Site:	Botanic Garden, back road	Ref No:	**RARO15**	Weather:	Cloudy, hot
Observers:	Giovanni, Adrian, David	Bearing:	D1 Counterclockwise	Topography:	
Date:	23/01/98	Soil:		Geology:	Coastal terraces sediments

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	41.4	38.9	33.7	35.1	2.54	-0.10	-4.07		0.5	108.07
2	11.96	11.35	8.73	11.29	0.609	0.01	-25.57	10.47	1.0	62.89
									1.5	42.67
3	3.63	3.44	2.92	2.89	0.1908	-0.02	1.03	7.71	2.0	36.51
									3.0	28.92
4	1.268	1.191	1.01	0.99	0.0775	-0.04	2.00	-6.92	4.0	25.13
									6.0	22.78
5	0.58	0.548	0.436	0.434	0.0375	-0.94	0.46	12.29	8.0	21.87
									12.0	21.06
6	0.261	0.251	0.207	0.201	0.0193	-3.50	2.94	-8.25	16.0	20.51
									24.0	20.77
7	0.1443	0.14	0.1128	0.1037	0.01498	-7.15	8.41	21.28	32.0	21.76
									48.0	24.85
8	0.0942	0.0869	0.0667	0.0645	0.0051	2.36	3.35	18.43	64.0	26.38
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	2.95	9.79	12.39	*192.0*	
									256.0	

Comments:



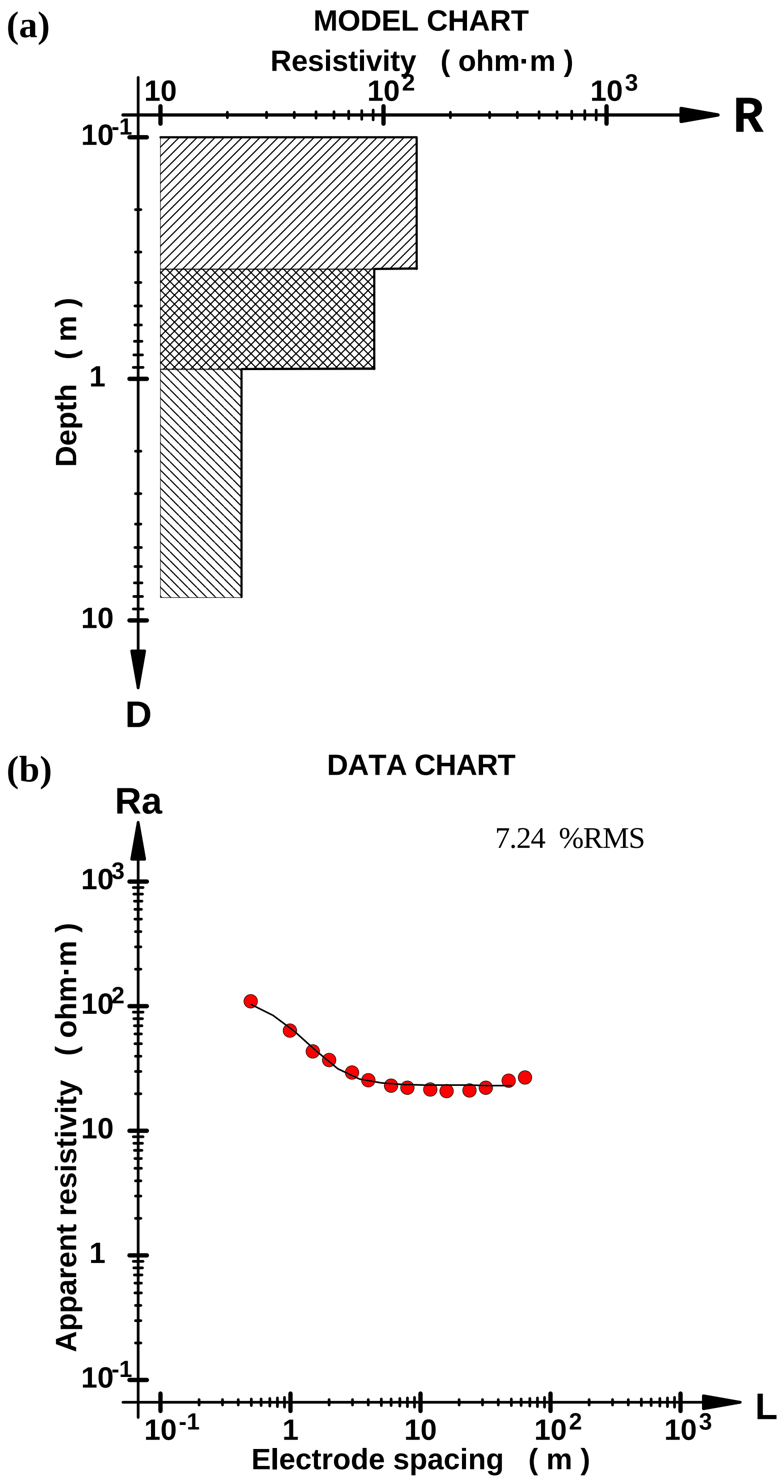
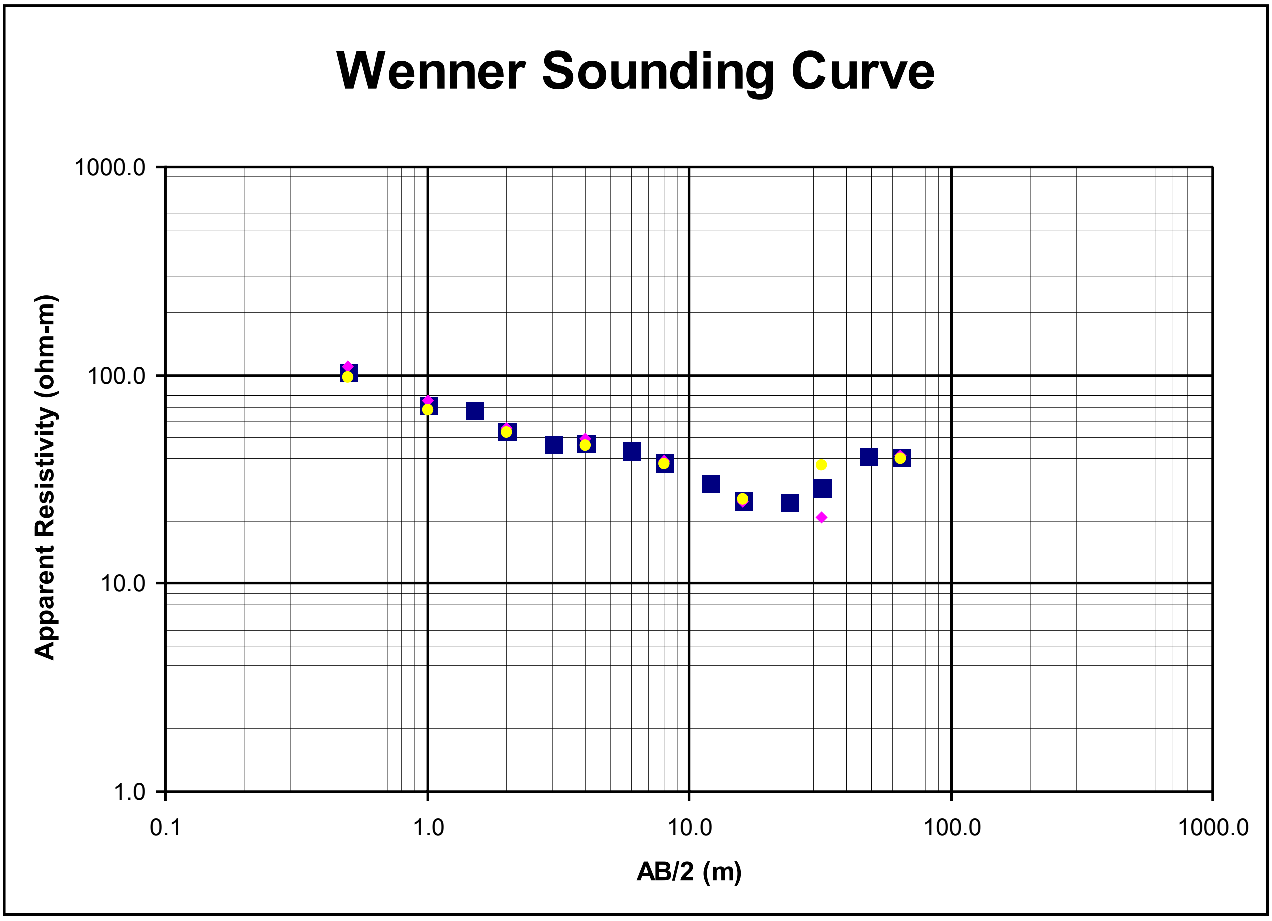


Figure A1-15: Interpreted model for RARO15

Site:	Takitumu on the back road	Ref No:	**RARO16**	Weather:	
Observers:	Giovanni, Adrian, David	Bearing:	D1 Counter-clockwise	Topography:	
Date:	23/01/98	Soil:		Geology:	Coastal terraces sediments

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	47	45.5	34.9	31.4	1.578	-0.17	10.56		0.5	104.14
2	13.77	12.82	12.06	10.88	0.951	-0.01	10.29	-114.69	1.0	72.07
									1.5	68.49
3	5.52	5.22	4.4	4.23	0.317	-0.31	3.94	37.45	2.0	54.22
									3.0	46.54
4	2.38	2.24	1.959	1.824	0.1419	-0.08	7.14	5.16	4.0	47.54
									6.0	43.39
5	0.994	0.952	0.771	0.749	0.0401	0.19	2.89	8.52	8.0	38.20
									12.0	30.37
6	0.337	0.334	0.245	0.253	0.00662	-1.07	-3.21	-54.95	16.0	25.03
									24.0	24.55
7	0.1823	0.1525	0.1039	0.1835	0.0201	5.47	-55.39	-15.82	32.0	28.89
									48.0	41.13
8	0.1472	0.135	0.1023	0.0996	0.01637	-2.79	2.67	74.31	64.0	40.59
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	2.21	20.55	54.14	*192.0*	
									256.0	

Comments:



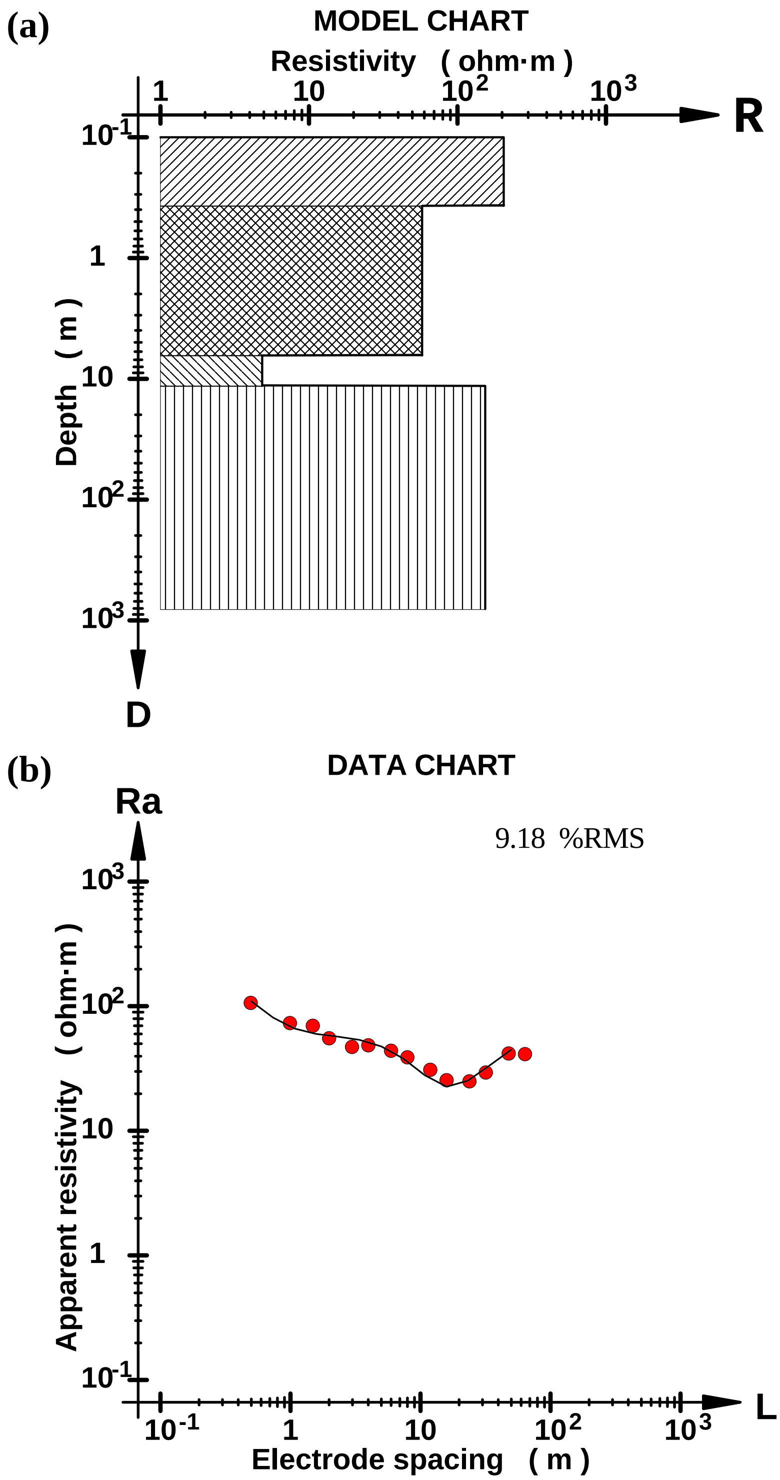
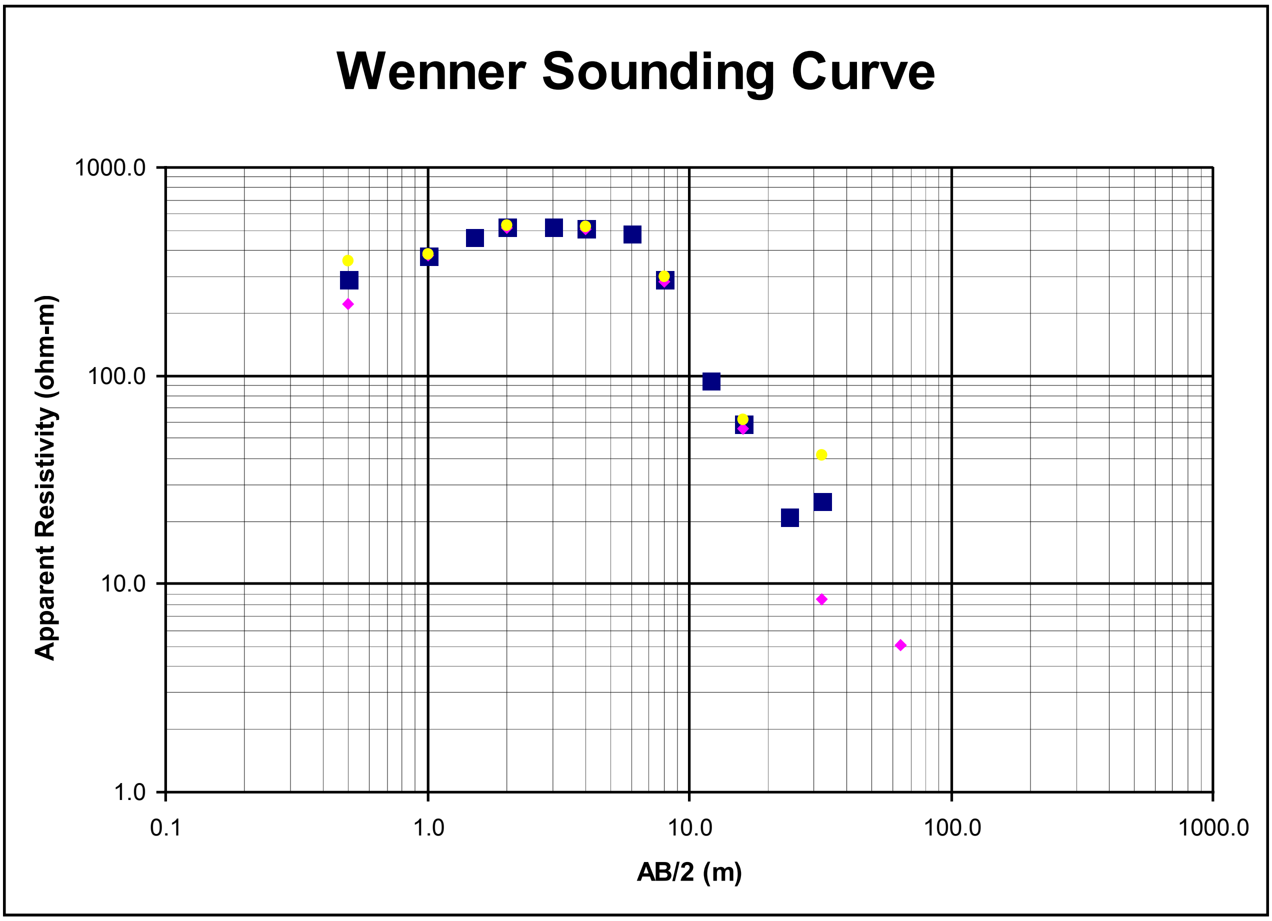


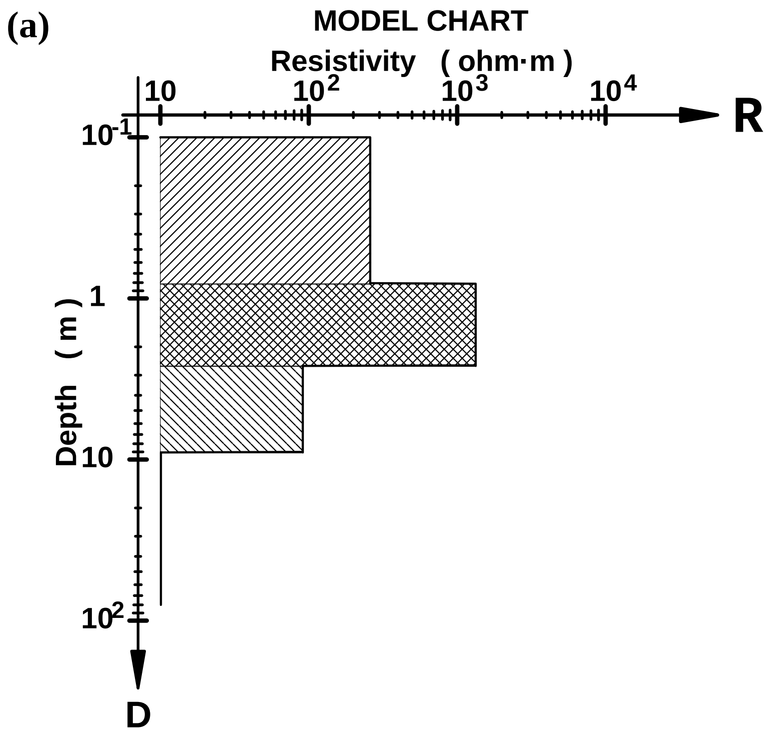
Figure A1-16: Interpreted model for RARO16

Site: Takitimu on the main road	Ref No: **RARO17**	Weather: Fine
Observers: Giovanni, Adrian, David	Bearing: D1 Clockwise	Topography:
Date: 26/01/98	Soil:	Geology: Aroa sands

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	143.7	136.7	69.9	114.2	7.81	-0.56	-48.13		0.5	289.18
2	86.1	79.4	59.9	60.9	5.94	0.89	-1.66	-46.58	1.0	379.50
									1.5	463.97
3	56.8	54.3	41.1	42.3	2.56	-0.11	-2.88	7.18	2.0	524.02
									3.0	521.04
4	22.7	20.6	20	20.8	2.28	-0.79	-3.92	-23.25	4.0	512.71
									6.0	483.30
5	5.3	4.95	5.64	5.99	0.33	0.38	-6.02	95.92	8.0	292.29
									12.0	95.01
6	0.46	0.457	0.556	0.616	0.1321	-24.99	-10.24	392.03	16.0	58.91
									24.0	21.14
7	0.0805	0.0766	0.0418	0.206	0.00781	-4.74	-132.53	399.01	32.0	24.91
									48.0	-14.96
8	0.0273	0.0264	0.01264	-0.026	-0.001412	8.86	-578.44	-1370.54	64.0	-2.69
									96.0	
9						N/A	N/A	N/A	128.0	
					RMS Error:	9.54	210.55	524.79	*192.0*	
									256.0	

Comments:





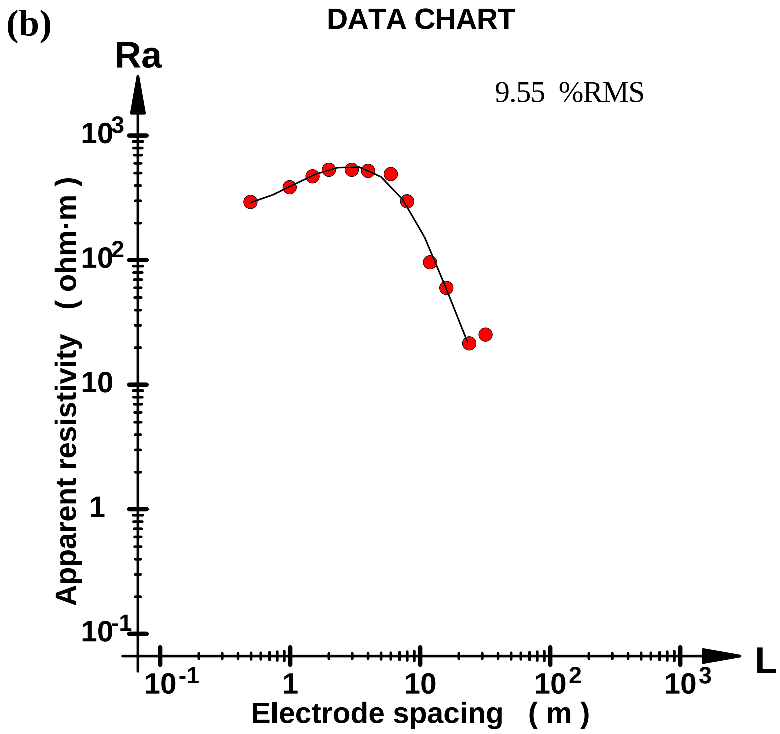
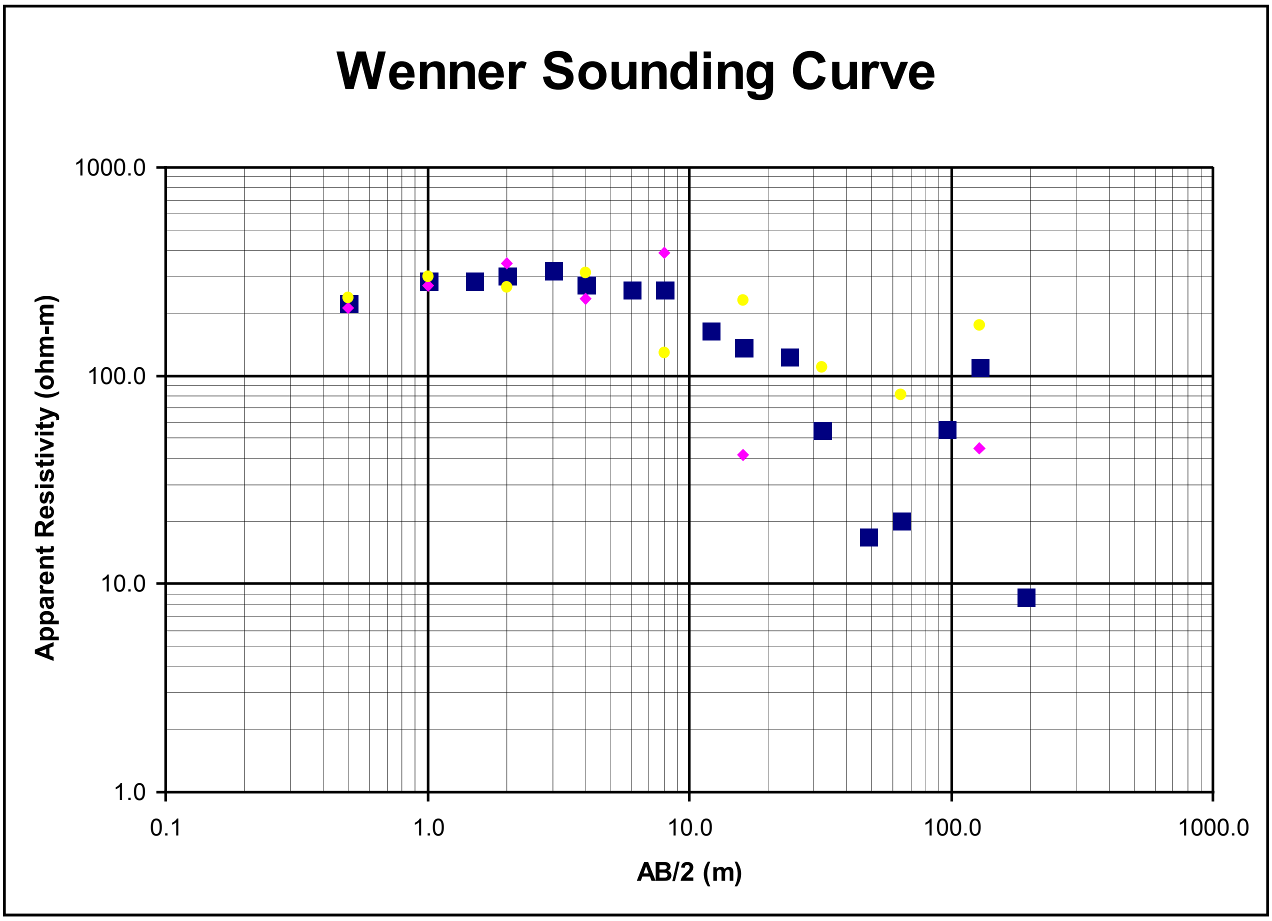


Figure A1-17: Interpreted model for RARO17

Site:	Arorangi on the main road	Ref No:	**RARO18**	Weather:	Fine
Observers:	Giovanni, Adrian, David	Bearing:	D1 Counter-clockwise	Topography:	
Date:	26/01/98	Soil:		Geology:	Aroa sands

SETTING (n)	OBSERVED MEASUREMENTS RA	RC	RD1	RD2	RB	ERRORS OBS	OFFSET	LATERAL	SPACING (metres)	WENNER RESISTIVITY
1	96.5	89.1	67.5	75.2	7.42	-0.02	-10.79		0.5	224.15
2	65.5	62.8	43.4	48	2.68	0.03	-10.07	22.36	1.0	287.14
									1.5	285.44
3	35.9	33.6	27.5	21.2	2.27	0.08	25.87	-40.53	2.0	305.99
									3.0	324.55
4	17.43	16.21	9.38	12.43	1.161	0.34	-27.97	-69.90	4.0	274.07
									6.0	261.05
5	6.64	6.56	7.74	2.58	0.0988	-0.28	100.00	-106.69	8.0	259.37
									12.0	165.46
6	1.054	0.953	0.415	2.3	0.1082	-0.68	-138.86	-104.90	16.0	136.47
									24.0	124.22
7	0.501	0.501	-0.00557	0.549	0.0032	-0.64	-204.10	400.13	32.0	54.63
									48.0	17.01
8	0.1537	0.1496	-0.1002	0.201	0.00224	1.22	-597.62	-803.53	64.0	20.27
									96.0	55.82
9	0.0832	0.0738	0.0561	0.217	0.00385	6.91	-117.83	-46.63	128.0	109.82
					RMS Error:	2.36	222.02	305.02	*192.0*	*8.75*
									256.0	*-201.87*

Comments:



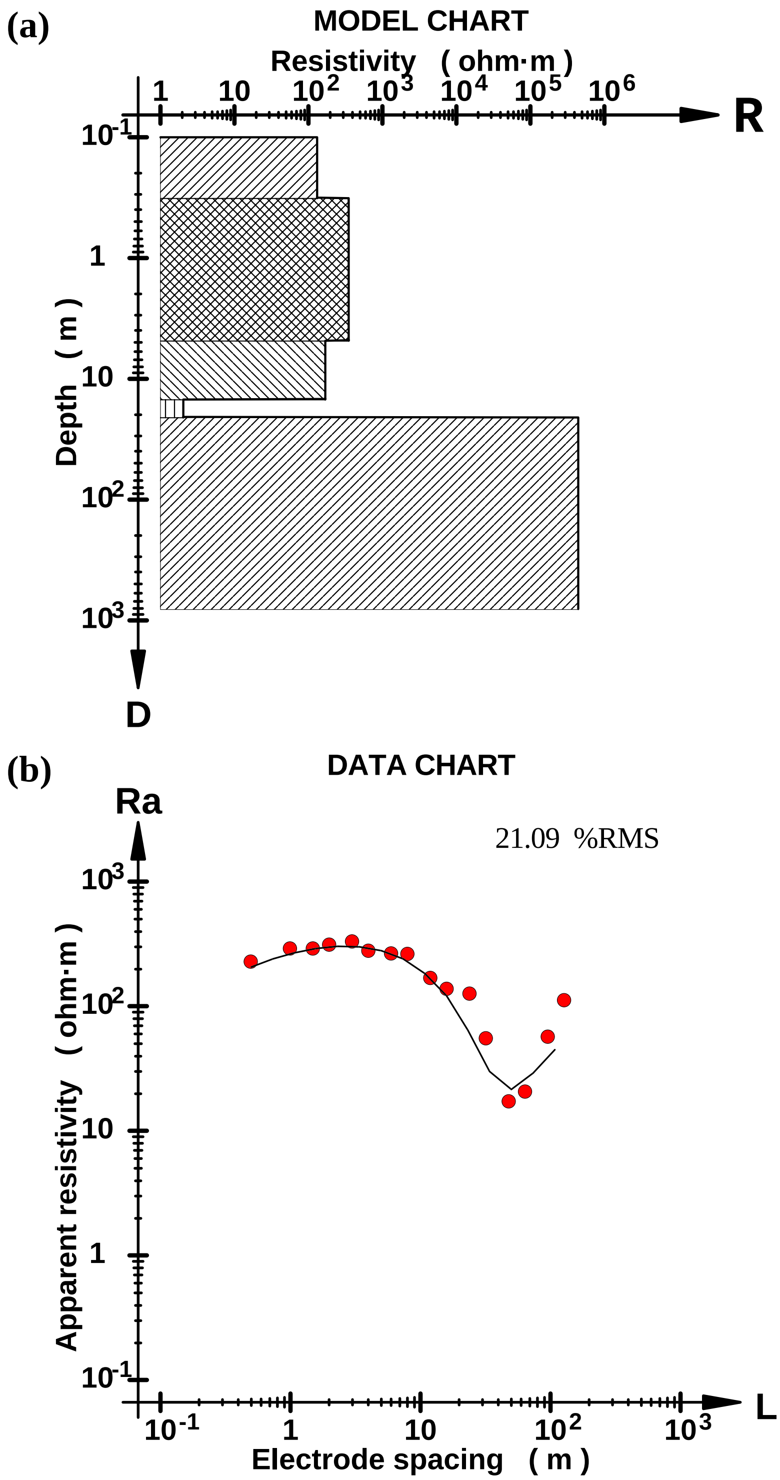


Figure A1-18: Interpreted model for RARO18

APPENDIX 2

DROUGHT INDEX CALCULATIONS

(a) Standardised Precipitation Index

The Standardised Precipitation Index (SPI) as defined by McKee et al (1993) is calculated by taking the difference of the precipitation from the mean for a particular time scale, and then dividing by the standard deviation. Because precipitation is not normally distributed for time scales shorter than 12 months the SPI is generally adjusted so that the mean for a particular location and time scale is zero and the standard deviation is one. For this particular study, in the interests of simplicity and because inter-site comparisons are not required, a non-normalised SPI has been calculated using the following FORTRAN program:

```
      DIMENSION RAIN(1000), PI(10,1000), INTERV(10)
      OPEN(10,'TSERIES.PRN')
      OPEN(11,'SPI.DAT')
      OPEN(12,'SPI.OUT')
      INTERV(1) = 1
      INTERV(2) = 3
      INTERV(3) = 6
      INTERV(4) = 12
      INTERV(5) = 24
      NINT      = 5
      DO 10 I = 1,1000
         READ(10,*,END=20) YYMM, RAIN(I)
   10 CONTINUE
   20 NUM = I - 1
C
      DO 50 K = 1,NINT
         J = INTERV(K)
C     Calculate mean and standard deviation
         RTOT  = 0.0
         DO 30 I = 1,J
            RTOT = RTOT + RAIN(I)
   30    CONTINUE
C
         SUM   = RTOT
         SUMSQ = RTOT*RTOT
         DO 35 I = J+1,NUM
            RTOT  = RTOT - RAIN(I-J) + RAIN(I)
            SUM   = SUM + RTOT
            SUMSQ = SUMSQ + RTOT*RTOT
   35    CONTINUE
         M   = NUM + 1 - J
         AVG = SUM/REAL(M)
         SD  = SQRT((REAL(M)*SUMSQ - SUM*SUM)/(REAL(M)*REAL(M-1)))
         WRITE(12,36) J, NUM, M, SUM, SUMSQ, AVG/REAL(J), SD
   36    FORMAT(3I5,4G10.3)
C........Calculate Precipitation Index
         RTOT = 0.0
         DO 40 I = 1,J
            RTOT    = RTOT + RAIN(I)
            PI(K,I) = 0.0
   40    CONTINUE
         PI(K,J) = (RTOT - AVG)/SD
         DO 45 I = J + 1,NUM
            RTOT    = RTOT - RAIN(I-J) + RAIN(I)
            PI(K,I) = (RTOT - AVG)/SD
   45    CONTINUE
   50 CONTINUE
C
      DO 60 I = 1,NUM
         WRITE(11,65) I, (PI(K,I),K=1,NINT)
   65    FORMAT(I3,2X,10F8.3)
```

```
60 CONTINUE
   STOP
   END
```

(b) Weighted Sum Drought Index

The Weighted Sum Drought Index as defined in equation 1 is simply calculated in an Excel spreadsheet. Figure A2-1 illustrates how this is done using the initial months from the Rarotonga Airfield rainfall record. The second column (Column B) contains the monthly rainfall. The calculated index is derived by inserting the following formula in row 12, and then copying it to the remainder of the column.

=B11 + 0.9*B10 + 0.8*B9 + 0.7*B8 + 0.6*B7 + 0.5*B6 + 0.4*B5 + 0.3*B4 + 0.2*B3 + 0.1*B2

Obviously alternative indices can be determined by modifying the above formula: to give different weights to different months or to change the length of record involved. Once some experience has been gained with the use of a particular index it would be desirable to reassess its suitability for the particular purpose.

YYMM	Rain (mm)	Index
2901	121	
2902	281	
2903	165	
2904	99	
2905	44	
2906	159	
2907	20	
2908	69	
2909	33	
2910	86	
2911	128	459.7
2912	373	480
3001	277	744.6
3002	203	904
3003	417	978.2
3004	253	1256
3005	29	1332.5
3006	68	1175.6
3007	133	1056.8
3008	35	1003.1
3009	66	841.4
3010	35	715.8
3011	73	565.4
3012	501	486.8

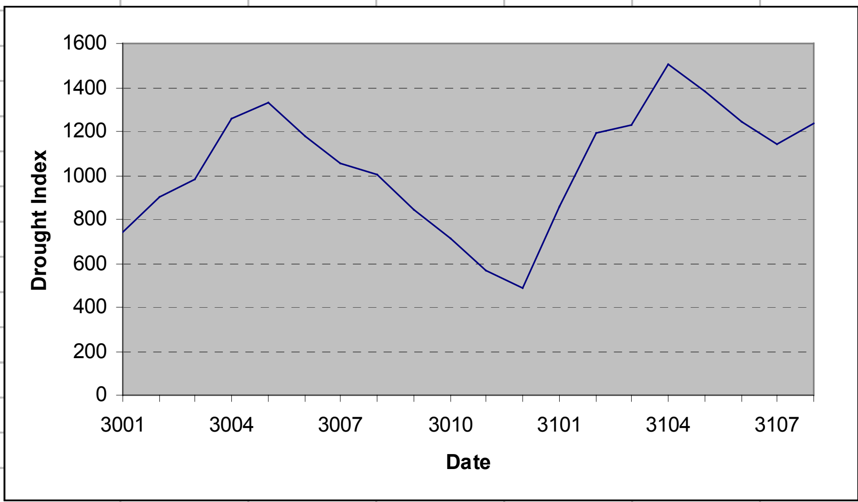


Figure A2-1: Section of Excel spreadsheet to calculate Standardised Precipitation Index

APPENDIX 3

DAIRY

Wednesday 14 Jan (Fiji)
Suva – Nadi - Rarotonga.

Wednesday 14 Jan (Cook Is)
Met by Ben Parakoti, visited some sites where leaks were reported or inspected and witnessed the use compressed air to pinpoint a buried leak. Orientation tour of the island with a visit to one of the intakes (new gravel filter). Met with Don Durrell (spoke about coastal protection). Visit to Keu Mataroa (Acting Secretary of MOWEP).

Thursday 15 Jan
Field trip with Keu Mataroa and Terii Tipokoroa to visit sites where groundwater is already being exploited in one way or another. Undertook a preliminary analysis of monthly rainfall data to illustrate the concept of a drought index.

Friday 16 Jan
Resistivity surveys at Botanical Garden (RARO1) and Rarotonga Airport (RARO2). Office to complete initial interpretation. Return to Botanical Garden site to do some levelling and make some observations about the well. Inspected an additional ‘gallery’ site and discussed the alternatives.

Saturday 17 Jan
Reconnaissance trip with Ben Parakoti to select resistivity survey sites for Monday & Tuesday

Sunday 18 Jan
Rest Day

Monday 19 Jan
Resistivity surveys alongside beach behind Water Supply Department (RARO3), at Golf Course (RARO4) and adjacent to Rarotonga Sunset Motel (RARO5). Office to process and interpret results. Obtained copy of intake flow records for some additional analysis.

Tuesday 20 Jan
Visit to Raymond Newnham (SOPAC National Representative). Resistivity surveys (RARO6 to 8) in parallel beyond Tupapa Stream. Return to office to process and interpret. Preliminary processing of intake flow records to show longer term series.

Wednesday 21 Jan
Resistivity surveys (RARO9 & 10). Booster used for final setting of RARO10 with apparently erroneous results. Rain affected observations. Terence carried on with the presentation of the intake flow records. PC with modem returned to WSD & attempt made to contact SOPAC. Cook Island newspaper and radio carried a news item about the visit.

Thursday 22 Jan
Resistivity surveys at SDA site. Offset Wenner equipment appeared to be faulty so abandoned that in favour of Schlumberger and completed RARO11 & 12 with mixed results - lots of negative values. Visited Don Durrell with Ben Parakoti to ask about his well and hear about his coastal protection work. Field testing of Offset Wenner equipment which appeared to confirm suspicion that one cable had developed a fault. Subsequent bench testing demonstrated that there was no fault in the suspect cable.

Friday 23 Jan
Visit with Don Durrell to his former well. Collected video of coastal protection measures. Two Schlumberger soundings (RARO13 & 14) and two Offset Wenner soundings (RARO15&16) which were completed without any further problems.

Saturday 24 Jan
Office. Data processing and interpretation. Analysis of additional data requirements. Some more work on the drought index concept.

Sunday 25 Jan
Rest day.

Monday 26 Jan
Resistivity surveys in morning (RARO17, 18 & 19). Data processing and collection of background information on survey sites. Packed equipment and delivered to Air New Zealand cargo.

Tuesday 27 Jan
Meeting with MOWPP, Agriculture & growers with the following participants:

Mataio Aperau	Assistant Minister	MOWPP
Tepai Tepai	Assistant Minister	MOWPP
Keu Mataroa	Acting Secretary	MOWPP
Nooroa Ben Parakoti	Director Water Works	MOWPP
Terii Tipokoroa	Overseer Road Works	MOWPP
George Cowan	Consultant	MOWPP
Patrick Tangapiri	Eng. Supervisor	MOWPP
Gerome Johnson	UNV	MOWPP
Ngatokorua Mataio	Secretary	Ministry of Agriculture
Anau Manarangi	Director Research/Extension	Ministry of Agriculture
Robert Wigmore	Farmer/Developer	

Follow up discussion with Robert Wigmore and subsequent visit to Muri Beachcomber where Peter Kemp has maintained records of groundwater level at a gallery well. Wrap up meeting with Ben Parakoti. Entered Muri Beachcomber groundwater level data.

Wednesday 28 Jan/Thursday 29 Jan
Return to Suva.

APPENDIX 4

GROUNDWATER LEVELS

Date	WL (m)
970226	-4.5
970227	-3.7
970228	-3.4
970301	-3.38
970302	-3.34
970303	-3.4
970304	-3.4
970305	-3.45
970306	-3.4
970307	-3.5
970308	-3.5
970309	
970310	-3.46
970311	-3.45
970312	-3.44
970313	-3.43
970314	-3.32
970315	-3.34
970316	
970317	-3.31
970318	-3.34
970319	-3.36
970320	-3.26
970321	-3.3
970322	-3
970323	
970324	-3
970325	-3
970326	-3.1
970327	-3
970328	-3.04
970329	-3.04
970330	-3.01
970331	-3
970401	-3.1
970402	-3.1
970403	-3.01
970404	-3.1
970405	-3.1
970406	-3.106
970407	-3.108
970408	-3.1
970409	-3.1
970410	-3.1
970411	-3.1
970412	-3.2
Date	**WL (m)**
970413	-3.2
970414	-3.2
970415	-3.2
970416	-3.2
970417	-3.2
970418	-3.107
970419	-3.2
970420	
970421	-3.2
970422	-3.2
970423	-3.5
970424	-3.04
970425	-2.84
970426	-3.7
970427	
970428	-3.5
970429	-2.7
970430	-3.07
970501	-3.5
970502	-3.503
970503	-2.7
970504	
970505	-3.5
970506	-3.5
970507	-3.5
970508	-3.603
970509	-3.604
970510	-3.4
970511	-3.6
970512	-3.504
970513	-3.503
970514	-3.603
970515	-3.5
970516	-3.404
970517	-3.4
970518	
970519	-3.5
970520	-3.5
970521	-3.6
970522	-3.6
970523	-3.7
970524	-3.7
970525	-3.6
970526	-3.4
970527	-3.6
970528	-3.7
Date	**WL (m)**
970529	-3.6
970530	-3.6
970531	-3.4
970601	
970602	-3.3
970603	-3.3
970604	-3.7
970605	-3.7
970606	-3.7
970607	-3.6
970608	
970609	-3.6
970610	-3.6
970611	-3.5
970612	-3.5
970613	-3.45
970614	-3.5
970615	
970616	-3.2
970617	-3.2
970618	-3.2
970619	-3.17
970620	-3.1
970621	-2.64
970622	
970623	-2.6
970624	-2.63
970625	-2.84
970626	-2.92
970627	-2.75
970628	-2.9
970629	-2.9
970630	-2.74
970701	-2.9
970702	-2.94
970703	-2.96
970704	-3
970705	-3
970706	-3.05
970707	-3.05
970708	-2.9
970709	-3.02
970710	-3.05
970711	-3.1
970712	-3.1
970713	-3
Date	**WL (m)**
970714	-3
970715	-3.05
970716	-2.5
970717	
970718	
970719	
970720	
970721	
970722	
970723	
970724	
970725	
970726	
970727	
970728	
970729	
970730	-1.95

(Observations supplied by Peter Kemp of the Muri Beachcomber Motel)

Date	Comment
1/03/97	water run out 4.220
8/03/97	empty 11:45
9/03/97	rain started
12/03/97	1:30 empty
25/03/97	2:45 half pump
23/04/97	added hose from old main
24/04/97	10pm rain v.heavy WL 2.60
26/04/97	ran all night
27/04/97	pumped all night
28/04/97	rain all night
29/04/97	not pumped last night. On 9am - off 3pm, highest level yet
30/04/97	pumped all day off 6pm - to 2:0pm
1/05/97	pump all night
3/05/97	Villas start building
24/05/97	half throttle
25/05/97	heavy rain last night, 6.00pm WL 3.5
29/05/97	heavy rain last night
30/05/97	rain last night
31/05/97	rain last night
14/06/97	heavy rain last night
21/06/97	12:25 WL 2.900
3/07/97	pipe off main pipe
4/07/97	timer 2hrs off
5/07/97	wire been cut
9/07/97	back hose off main pipe
16/07/97	pump off all night till 1:20am, put on full tjrottle till 6pm
17/07/97	rain heavy morning. I didn't measure because pump not working
23/07/97	pump off
29/07/97	no pump
30/07/97	pump on again 10:50am full throttle
1/08/97	one quarter throttle
15/08/97	off 8:15
7/12/97	hurricane warning
8/12/97	cyclone pam
9/12/97	very busy
27/01/98	376 microS/cm, 187 ppm TDS

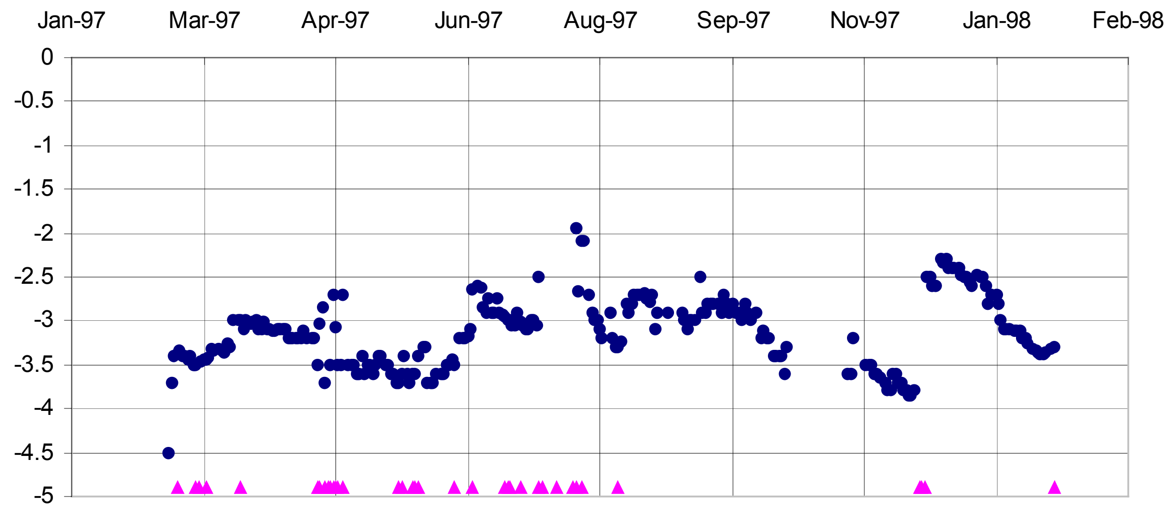
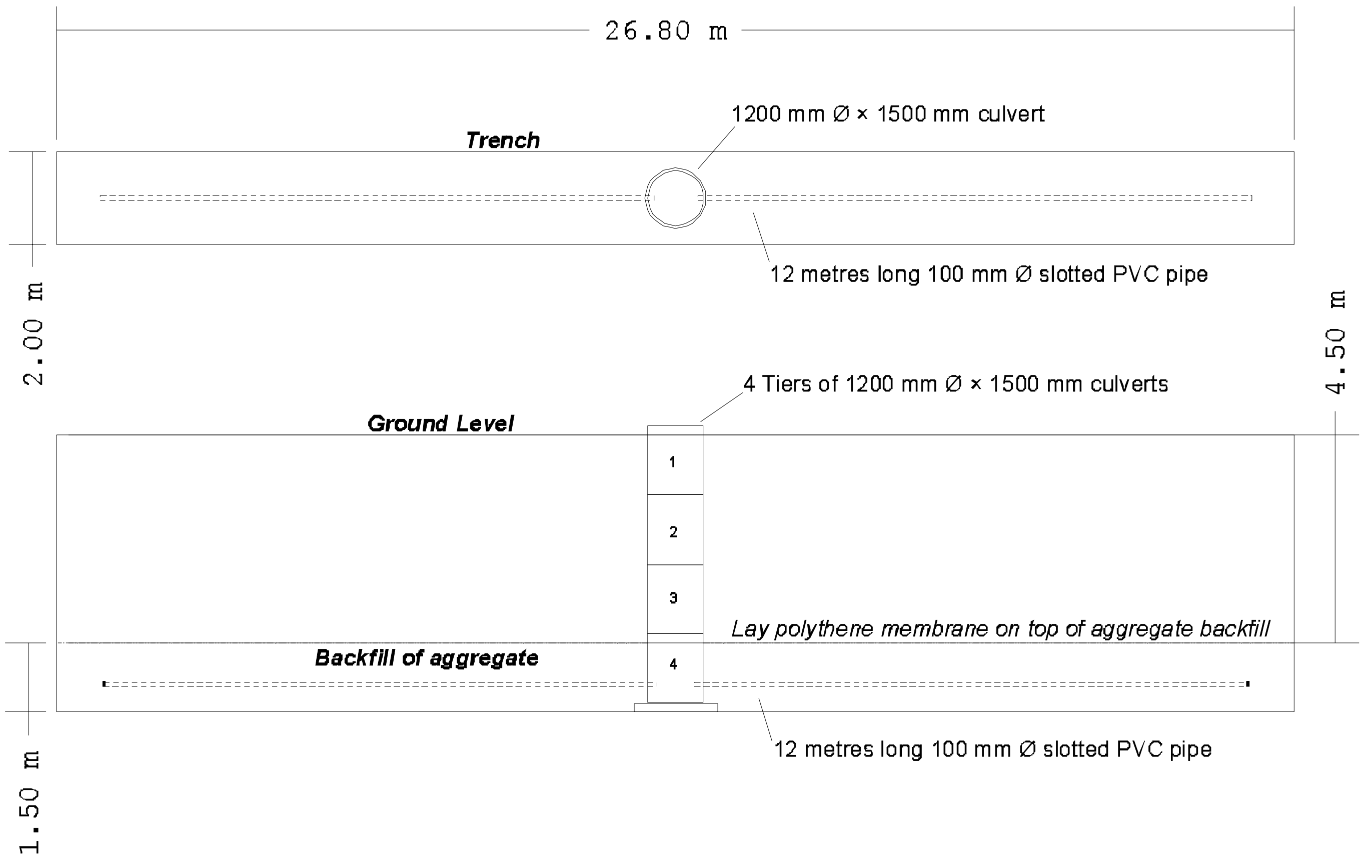


Figure A4-1: Groundwater levels recorded at Muri Beach

APPENDIX 5

Design and estimate for a horizontal gallery well



Cost for Installation of a Gallery Well (NZ Dollars)

Item	Unit	Qty	Rate	Amount
1200mm Ø × 1500 mm high concrete culvert	No	4	400	1,600
12 m × 200 mm PVC pipe	No	2	450	900
Aggregate	m3	78	38	2,964
Allow for culvert cover and padding				
cement – 40 kg	bags	19	20	380
sand	m3	0.50	45	22.5
aggregate	m3	3.8	38	145
665 HRC wiremesh 1.2 m × 2.4 sht	sht	1	75	75
Excavation and backfilling	hrs	24	120	2,880
Labour	hrs	40	10	400
				9,366.5
Contingency 20%				1,873.3
				11,239.8