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CORAL ISLAND HYDROLOGY

A training guide for field practice

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NEW ZEALAND

WATER AND MINERAL RESOURCE PROGRAMME

Rapid method of Evaluating Freshwater Resources on Small Islands
(REFRESHR)

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FOREWORD

The Commonwealth Science Council has long had interest in freshwater resources in developing countries. It has supported courses, workshops and studies in the Pacific and the Caribbean. This present training guide brings together information developed from a study initiated by the South Pacific Regional Environmental Programme in association with the South Pacific Commission and the Cook Islands Government. Staff of the New Zealand Department of Scientific and Industrial Research carried out the field studies and the New Zealand Ministry of Foreign Affairs purchased equipment.

This guide is intended as a background document for training courses for water technicians and other technical workers who wish to have a broader understanding of the many disciplines involved in such a multifaceted activity.

I strongly support the co-ordination of the efforts of water chemists, hydrogeologists, geophysicists, botanists, meteorologists, surveyors and local users so that water supplies are accorded the importance they deserve. I trust the microbiology of these water supplies will also receive attention because of the need to identify bacteriological quality in a region where so many ground water supplies are contaminated with human, animal or industrial wastes. The interaction of all these different disciplines can only help to improve the quantity and quality of available water.

The New Zealand DSIR has had a history of involvement in Pacific Island water resources stretching back for more than 20 years. In association with other Government departments and most commonly, supported by funds from the New Zealand Ministry of Foreign Affairs (MFA), the DSIR has made a significant contribution to the understanding of ground water of small islands of the region.

I am delighted that this helpful experience has been brought together under the aegis of CSC, SPC and SPREP in terms of "technology transfer" to the people of the Pacific region. I commend the authors of the various papers for their determined collaboration in both the field studies and the more demanding preparation of their written contributions.

DSIR is pleased to support this publication, the CSC welcomes the opportunity to contribute to a useful regional programme and both are happy to be associated with the United Nations Environmental Programme (UNEP) through the South Pacific Regional Environmental Programme (SPREP) and the South Pacific Commission (SPC).

I am sure this training guide, written in simple non-technical language will go a long way to helping technicians, scientists and engineers of the small island nations to fill a gap in their own expertise.

A J Ellis
Director-General DSIR and
Chairman Commonwealth Science Council

PREFACE

This guide sets out the desired steps for carrying out a reconnaissance survey to identify fresh ground water on small islands, coral atolls and motu. It was prepared for the Commonwealth Science Council and the South Pacific Commission (under the South Pacific Regional Environmental Programme).

The text is in three parts with the sequence of steps identified in appropriate order to indicate to the less experienced how a survey for ground water may be undertaken on a small island. It has been written mainly as a reference for short training courses for water supply technicians in the Pacific region. It has not been written for continuous reading but for section by section reference. Hence there is some deliberate redundancy.

The authors do not consider that most small island nations will have sufficient local staff with the necessary academic skills to undertake this type of survey but with training and some outside assistance local staff could make substantial contributions to their own studies of ground water.

The field teams who helped to develop the Rapid Evaluation of Freshwater Resources on small coral islands (REFRESHR) included Gordon Dawson, Duncan Graham, Denis Petty, George Risk, Barry Waterhouse and Dick Dale who had been responsible for integrating Pacific Island water studies for DSIR.

Individual authors contributed the papers as attributed but there was a good deal of collaboration between authors and other consultants.

W R Dale
October 1986

ACKNOWLEDGEMENTS

We warmly acknowledge the support and technical advice generously given by Dirk Rinckes and Jeremy Maseyk, Department of Lands and Survey, New Zealand; Alex Gilmore, Division of Marine and Freshwater Science (DSIR) and the Directors of NZ Geological Survey and Geophysics Divisions (DSIR). Workshop staff of Physics and Engineering Laboratory (DSIR) designed and constructed special drill bits for the project. Mr C S Thompson, NZ Meteorological Office, gave permission to use his unpublished data on Aitutaki.

Illustrations were prepared by staff of the General Drafting Section Department of Lands and Survey, New Zealand for which we are most grateful. Many people in the Cook Islands were generous in their support and we would like to thank George Cowan, Ken Browne, Ron Make, Vahua Vahua and Pumati Pumati for their help and interest. Fa'atoia Malele of Western Samoa also accompanied us on part of the field studies and contributed in many ways. Mr John Campbell gave special help during our study of the Totokoitu area. Duncan Graham and Gordon Dawson both made significant inputs to our field studies which we acknowledge.

The difficult task of the final word processing compilation was tackled by Gwen Rowlands and Pat Gibbons with their customary good humour.

Parts I and III were contributed by W R Dale, after consultation, particularly with Mr B J Amey. Sections of Part II were contributed by W R Dale, G F Risk (geophysics), B C Waterhouse (surveying, hydrogeological drilling, pump testing and evaluation) and D R Petty (water level recording and sampling).

The REFRESHR team fully acknowledge the support provided by DSIR, funding of equipment by MFA as well as funds and encouragement from CSC

REVIEW OF THE RAPID METHOD OF EVALUATING FRESHWATER RESOURCES

In 1983 Dr Jeremy Carew-Reid of the South Pacific Regional Environmental Programme invited DSIR to develop a rapid method of fresh ground-water resource evaluation which could be applied to small islands of the Pacific and elsewhere. This text is the outcome of that request.

The idea of freshwater lying beneath the surface of coral islands and motu* is based on the knowledge that rainfall passes down from the plant cover through surface layers to about sea level. The freshwater filters very slowly down through the sand and coral rocks and accumulates in a layer above the sea water which lies everywhere beneath the island. Between the fresh and the sea water is an intermediate layer of mixed fresh and salt water.

The freshwater is just slightly lighter (less dense) than the sea water (with its dissolved salt) so the freshwater floats on the salty sea water. The freshwater is generally pictured as a lens-shaped body with more of the freshwater lying below sea level than above, as indicated in figure 1.

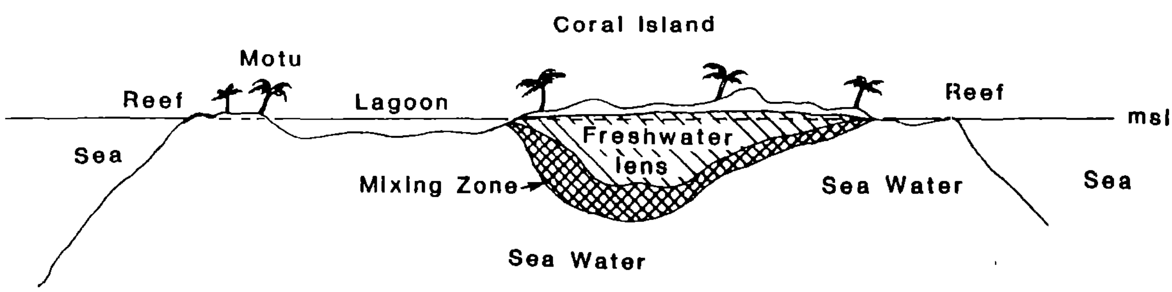

Figure 1 Form of freshwater lens for a coral island (diagrammatic).

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* motu are small islands usually associated with isolated outer parts of coral reefs. The term does not take an "s" in the plural.

Our ideas about the form of freshwater lenses were first developed in a study on Matakana Island, a sandy cay in New Zealand. The integration of geophysics, hydrogeology, water analysis, meteorology and automatic water-level gauging were modified for application to coral atolls and islands of the tropics. The steps in this procedure are set out below as an introduction to the details which follow in later sections.

At first you should study the records of rainfall, past reports on water supplies, sites of wells, ponds or drillholes and their yields as well as other relevant documents about the proposed area. This will provide an insight into the study site and indicate the most appropriate season to carry out the survey. (Some geophysical equipment can't be used in the rain during the "wet" season). Meetings, and where appropriate discussion with local authorities to ensure correct procedures are followed, are very important before starting field work.

A word of caution. Don't rush into the field and start into an enthusiastic programme before the team has carefully walked or driven around the wider area under consideration - you may wish to modify your initial ideas once you have done a reconnaissance. It is most desirable that a representative of both the geological and geophysical teams should travel over the area - then sit down together and work out the field programme. Hopefully this programme would be developed between local staff and any overseas experts who are to be involved and should fit in with the local water-development plans.

Generally it will be necessary to have an expert in geophysics and/or hydrogeology to supplement local skills as the techniques involved need experienced manpower. However, much of the work can be done by local staff who have experience in water supplies and surveying.

The field team will first decide where lines need to be cut through the vegetation, if necessary, for access by the geophysicists to resistivity sites. The approach is to provide an adequate coverage of resistivity soundings to allow the geophysicists to develop a model of the layers of "dry" (coral) sand, freshwater, the mixed layer of fresh and salt, and sea water.

When the geophysicist has indicated where the freshwater is thickest the next step is to drill a few (one to three) holes down to the water table or deeper, according to the capability of the equipment available. These drillholes allow you to carry out pump tests, to estimate how freely the water flows in the lens, evaluate the conductivity (and salinity) and to take water samples for analysis.

The drillhole also allows you to confirm the depth from the surface to the water table which the geophysics has already indicated. You can do this with a conductivity probe with a tape measure attached.

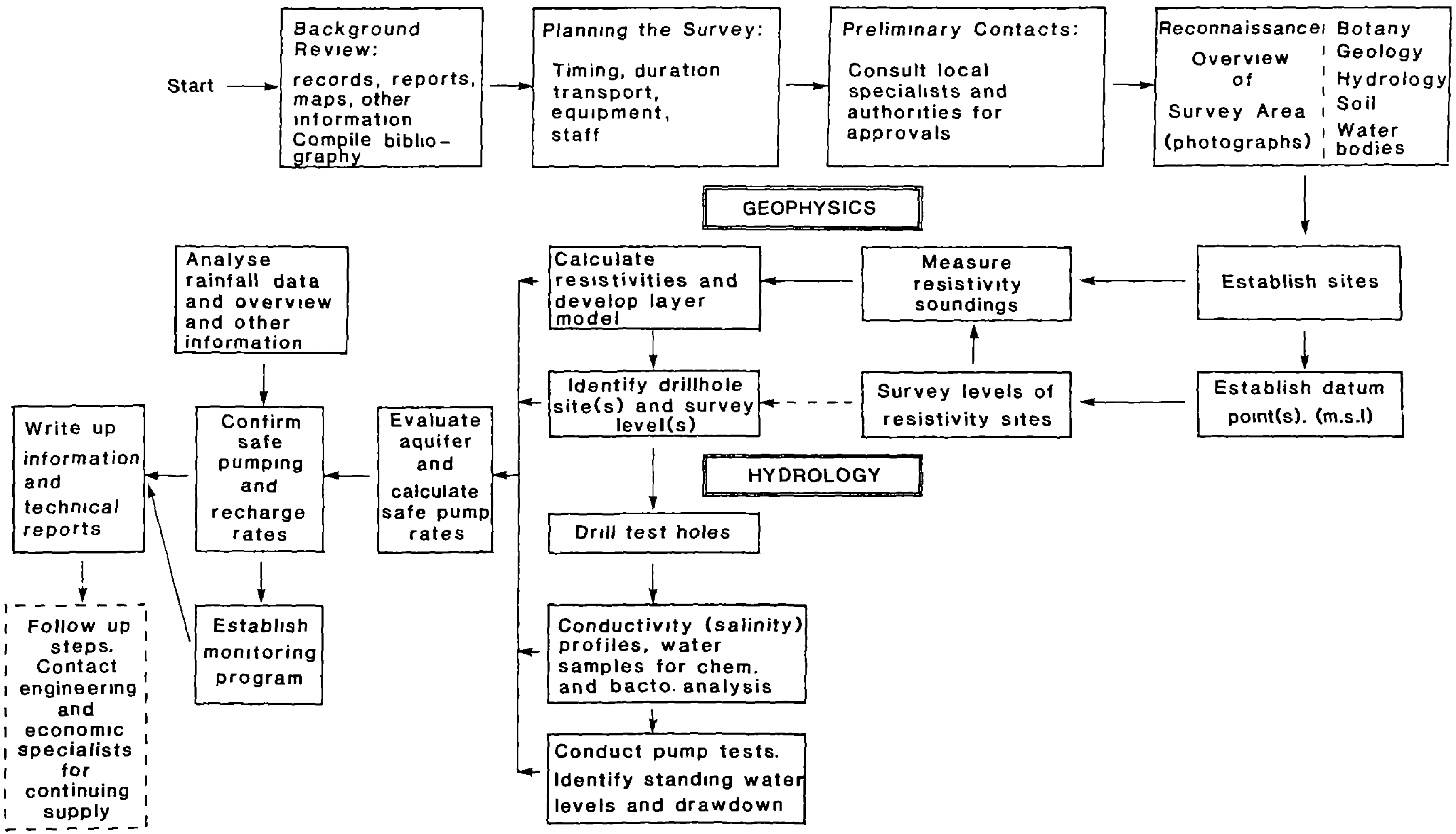
But one vital piece of information must be measured before you can proceed. To measure height you must have a base line to measure from. This is known as the datum. Most commonly mean sea level is used as the datum and height measurements are expressed as a height (elevation or depression) above or below mean sea level (msl). If a previous land survey has left an identifiable mark which you can find then you won't need to establish your own. If you need to set your own datum you'll find notes about this later.

With this datum set you can measure distances and heights from this fixed point and so measure the top of the freshwater and its various levels under pumping. By comparing rainfall and other data, you can identify safe levels of pumping which will allow continued withdrawal of freshwater without overpumping and so avoid contaminating the well with salt water.

To use this rapid evaluation method you'll need to move quite a lot of equipment to the site - some of it is quite heavy. You might have to cut tracks through heavy bush and cope with mosquitoes and other nuisances.

You'll find it helpful to have a number of local people to help with this transport and field work but especially for their local knowledge. The concept of a flow chart for rapid evaluation is given in diagram 1. The idea of an integrated approach to water resource investigation is not new. Some years ago Peach developed an approach for Fiji. In the REFRESHR project we have tried for even better co-operation between the various branches of science.

Diagram 1 Flow Chart for Rapid Evaluation of a Coral Island Freshwater Resource.



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Part I

INTRODUCTION TO A FRESHWATER RESOURCE SURVEY

THE HYDROLOGICAL CYCLE

All natural freshwater comes from the sky, usually as rain. There is no simple, cheap way to obtain freshwater from brackish or salty water although there are costly ways of distillation or using special expensive membranes to extract salts. Solar distillation is effective but most units have a moderate cost and limited production (a few litres a day usually).

The hydrological cycle is the name given to the processes by which water vapour is drawn up from the earth's surface, condensed into drops which then fall to earth as rain, hail or snow. The cycle is completed when the water passes over or through the ground into rivers, lakes or the sea and then evaporates again or is passed out directly into the atmosphere by plants and animals - including your own breath. Figure 2 is one representation of the hydrological cycle.

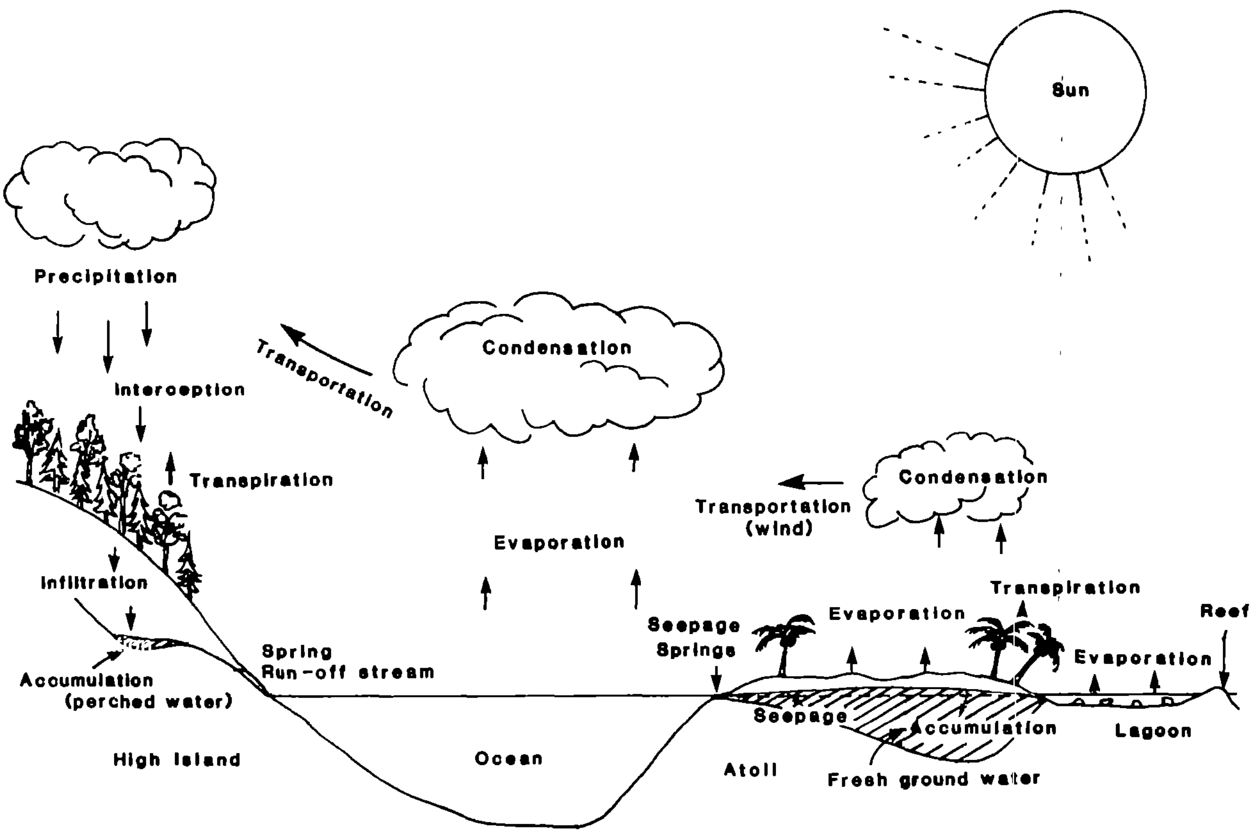

Figure 2 The Hydrological Cycle

There are several natural processes in the cycle. These are evaporation, transpiration, transport, condensation and precipitation. As well, there are the processes taking place within the soil and rocks and water bodies like rivers, lakes and oceans.

Evaporation

Energy for the hydrological cycle comes from the sun. Evaporation takes place when the sun's energy heats water to form water vapour. This then rises from the warmed land or water surfaces into the atmosphere where it condenses into clouds due to the colder temperatures there.

Transpiration

Growing plants require large amounts of water. A coconut palm requires at least 50 litres every day. The water is mostly taken in through the roots and passed out at the top of the plant through special cells which can open and close according to the weather. The process of water passing from plants into the atmosphere as water vapour is known as transpiration. Scientists sometimes calculate the combined value for evaporation and transpiration as evapo-transpiration in order to determine water needs of crops.

Transportation

Clouds are transported by wind, as part of the atmospheric circulatory system, which is again powered by the sun. Small isolated countries may receive moisture which has evaporated from within their own boundaries although clouds commonly form above land masses because the land surface warms up more quickly than the surrounding ocean. This gives greater upward transportation of water vapour often drawn in from offshore.

Precipitation

Precipitation is the term applied to falling rain, hail or snow and is the opposite of evaporation. Dew, mist and fog are special types of precipitation which occur when water vapour in the air is cooled and the moisture either separates out as fine water drops on the cooler surfaces of vegetation (in the case of dew) or as tiny droplets on dust particles in the air (in the case of mist or fog). These last two are usually due to colder air flowing into an area of already moist air causing the water vapour to precipitate quickly in fine droplets. Generally this requires fairly still conditions. Most of us are aware of the difference between humid and dry conditions. Warm air can "take up" a considerable amount of moisture but when temperatures fall (as the air rises, say) it reaches a point where the moisture can no longer remain as a vapour (the air becomes saturated). The extra moisture forms droplets which coalesce into larger drops which finally become too heavy for the rising air to support and they fall to earth.

Interception

Any rain or other precipitation which falls is first intercepted (caught) by whatever vegetation is present on the land surface; or it falls directly onto rocks, soil or water bodies like the sea. Studies of interception have mainly been done in forested areas of the subtropics. There is little data from the tropics. Anyone who has taken shelter from the rain in the outdoors will be aware how quickly rain runs off curved shiny vegetation like coconut palms compared with trees which have hairy leaves and layers of branches which tend to retain at least light showers of rain. Interception is an important factor in working out the water balance. There is considerable difference between the rainfall and amount of water which gets into the ground water as we will see later.

Meteorologists measure normal rainfall in gauges which are carefully placed in clear, open spaces but special studies are required to take account of vegetation. It is easier to calculate interception for a uniform stand of one species of trees than for mixtures of different types of vegetation.

Infiltration

Once the rain has passed down through the canopies of foliage onto the ground surface it can be absorbed by the surface litter of fallen vegetation. Only when that is saturated will the water pass on down into the soil. Because we are dealing with predominantly coral islands, the land will have a cover of coral limestone formations, rocks or sands. Each of these will allow the water to infiltrate or percolate downward in different ways. Soil scientists have long studied the movement of water through soils and geologists the movement through rocks but few measurements have been made on tropical atolls.

Seepage

Rain water seeps slowly down through the soil, rocks or sandy layers to join the ground water After heavy rain any surface pools or temporary lakes will also contribute to the ground-water aquifer. If this ground water extends out to the coast seepage of the freshwater will also take place into the sea. This can be seen at low tide when freshwater from higher up the beach seeps out to the sea.

These coastal seepage "springs" are commonly used in the Pacific for bathing and washing. Because these areas are flooded with sea water at full tide they are never quite free of salt.

Accumulation

The commonly-used term, for the freshwater body we have described, is a "lens". Now a lens shape usually implies a symmetrical shape, circular in outline and thickest at the centre. We are not aware of many freshwater bodies with quite this shape. Some are doughnut-shaped with a hole in the middle, others are long and narrow with a bulge of deeper freshwater towards one coastline.

We mention this so you will be aware that a lack of symmetry can sometimes be a guide to locating the deepest part of the freshwater. Otherwise, the thickest part of the lens is likely to be the point furtherest inland from the sea (at the widest part of a low island).

As the freshwater slowly accumulates above the sea water the lens which forms does so because the freshwater is very slightly lighter in weight than the salt water. The freshwater is fairly pure when it falls as rain but it dissolves many chemicals as it passes down through the vegetable litter, the soil and rocks. Nonetheless it still has much less dissolved salt than sea water. This will be reviewed later.

Because the freshwater seeps slowly downward there is little mixing of the fresh and salt waters although some mixing takes place due to the rise and fall of the tide.

Ground Water Flow

Any rainfall which is added to the ground water will tend to make the lens thicker at the point of entry. The whole water body will respond by evening out the level and, if it can flow away downhill, it will. This causes springs, seepages, or streams on high islands and outflow to the sea on low islands.

THE GHYBEN-HERZBERG LENS

A balance is established between the body of freshwater and the surrounding sea water and this was first studied in Northern Europe by Ghyben and refined in mathematical terms by Herzberg in 1901. They explained the relationship of large bodies of fresh and sea water for the areas of northern Europe.

Until more fundamental studies are done in tropical regions, for the small islands you are concerned with, we have to continue to use the Ghyben-Herzberg theory as a first approximation to the size and shape of freshwater bodies. As information accumulates we think the fundamental ratio, of one height unit of freshwater above mean sea level for every 40 height units below, is not proving to be generally applicable to small islands.

The Ghyben-Herzberg approximation is based on laws of physics. It relates the depth of the interface between fresh and salt water to the densities of those waters.

If we let the thickness of the freshwater above msl = hf
and the thickness of the freshwater below msl = hs,
as in figure 3, assuming a sharp interface between the fresh and salt water then the simplified Ghyben-Herzberg formula can be expressed as

$$hs = \frac{\rho f}{\rho s - \rho f} . hf$$

Where ρf is the density of freshwater (usually taken as 1.000)
and ρs is the density of salt (sea) water (usually taken as 1.025).

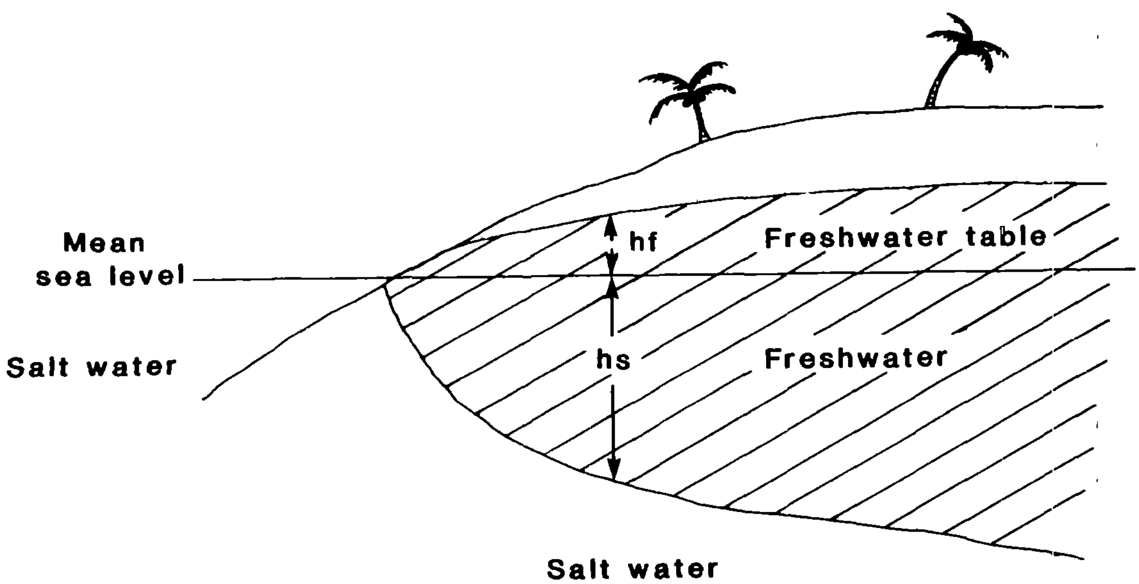

Figure 3 The Ghyben-Herzberg lens

By substituting these density values in the above formula we see that

$$hs = \frac{1}{1.025-1}.hf = 40hf$$

That is, the thickness of the freshwater below mean sea level is 40 times the thickness above mean sea level. As you will see from the Ghyben-Herzberg formula the 1:40 ratio depends on the density (specific gravity) of the fresh and salt water. The greater the difference between these two the greater the ratio will be. "Pure" rain water and salty sea water (at 34.7 parts per thousand of sodium chloride) may give a 1:40 ratio but rain water contaminated with salt spray, dissolved limestone and other chemicals will give a lower ratio with the same sea water.

What is important from a practical point is to measure mean sea level as accurately as you can. Using that level, measure the top of the freshwater body as accurately as you can. Make sure then not to drill below mean sea level for production wells. Don't be trapped into relying on the prediction that there will be 40 times the thickness of freshwater below mean sea level that you have measured above it.

A theoretical idealised Ghyben-Herzberg lens may be shaped like the following (figure 4).

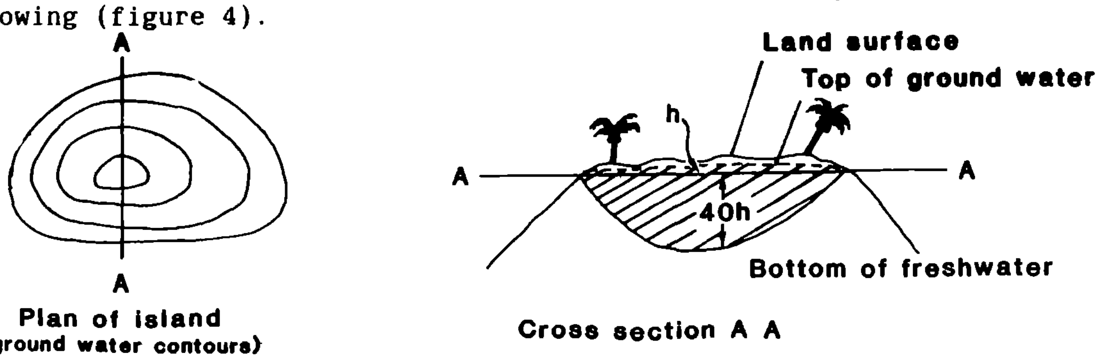

Figure 4 Diagram of a Ghyben-Herzberg lens

In practice many atolls have freshwater bodies more like that in figure 5, where "h" is the height of the freshwater table above mean sea level.

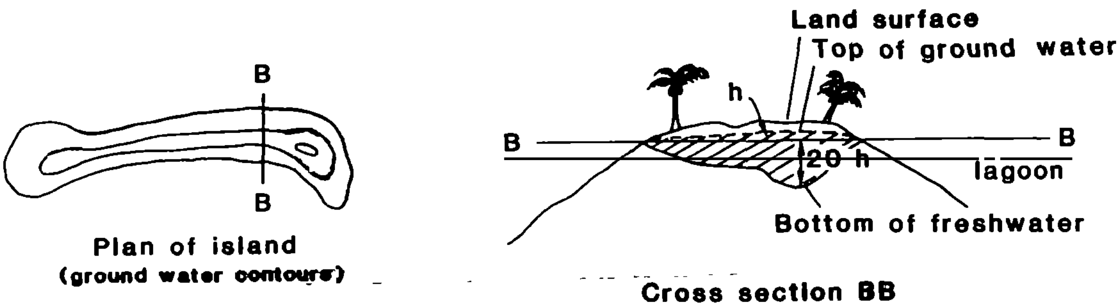

Figure 5 Diagram of typical coral atoll lens

Notice the ratio is about half that expected from the normal Ghyben-Herzberg (G-H) ratio and that the asymmetric shape of the freshwater puts the thickest part well off centre. There are a number of explanations of this asymmetry but so far they are only theories. It is important to determine accurately the thickest parts of the freshwater lens and place production wells in those places.

Let us now return to the G-H formula by considering the four-layer model (shown in figure 6) which is the background to this manual.

The upper layers of the ground are normally dry or moist, unless heavy rain is falling. Next we can detect the layer saturated with fresh water, which contains the main body of freshwater. Below this is a layer of mixed fresh and salt water which may be quite thick. This lies above the 4th layer, the salt (sea) water, which moves up and down with each tidal movement particularly at the coastal fringes. The idea of a mixed layer between the fresh and salt water is used as a model only. In practice the salinity (of the "freshwater") increases with depth due to mixing. The "layer" is usually defined by the salt concentration.

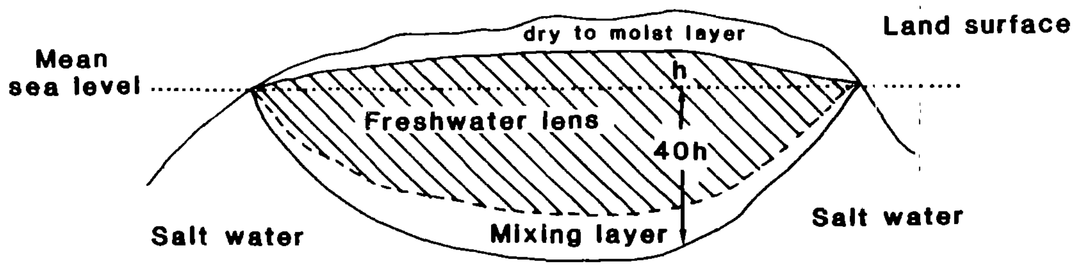

Figure 6 Theoretical Ghyben-Herzberg layered model

Measurements we have made tend to support the work of others on small islands which suggests that the freshwater layer extends seaward at the margins of the land and that generally the boundaries between various layers are not smooth.

In our experience the layers may be better represented as in figure 7, with a band of freshwater flowing out to sea at the coast, especially at low tide. The mixing layer tends to follow the shape of the bottom of the freshwater as in figure 7.

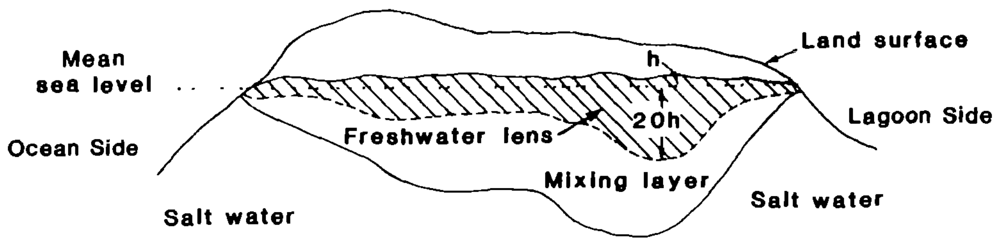

Figure 7 Simplified layered model of a small coral island

Although there may be a difference in interpretation and of detail between the theoretical model and practical experience we again emphasise the need for as accurate measurements as possible to establish the thickness of the different layers. Any wells should be measured regularly to follow changes caused by rainfall and tides. The water levels will change with every tide and each substantial rainfall as well as with pumping.

On Kwajalein Atoll, where a US Airforce base is established, they have extremely detailed studies of the ground water. They restrict pumping to four hours, during the low tides each day, to disturb the freshwater body as little as possible (Hunt and Peterson, 1980).

The greatest risk to the freshwater lens is the damage due to overpumping. This will be dealt with in detail later but generally what happens is a phenomenon called "coning".

In the case of pumping from a lens we find that as the water is extracted it is replaced by other freshwater flowing in from the surrounding rocks or sands. This flow rate can be calculated and is an important part of estimating safe pumping rates.

If water is pumped out faster than it can be replaced naturally, then the freshwater layer gets thinner mainly about the point of abstraction (well or drill hole). This causes down-coning of the water table above the pump intake and up-coning of salt water below it. This is why it is very important to pump from above mean sea level as shown in figure 8a. In 8b the pump has drawn in salt water.

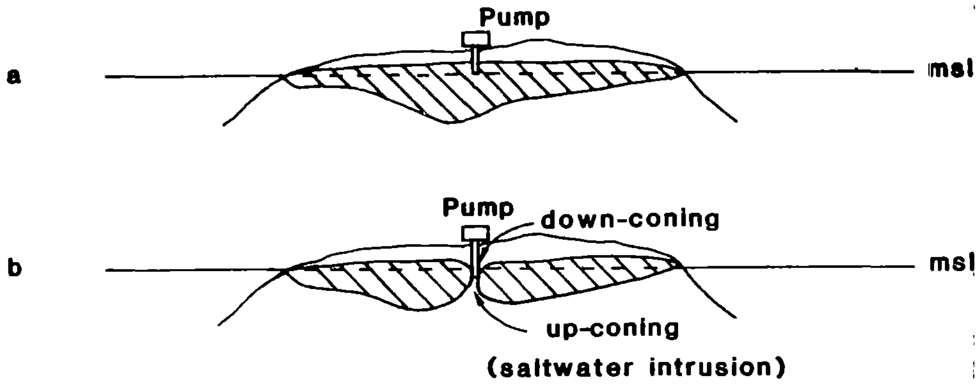

Figure 8 Effects of over pumping
(a) pump intake at msl
(b) pump intake below msl

Overpumping can cause salt-water intrusion and destroy the freshwater body and it may take many wet seasons to repair the damage.

At the same time unsound waste-water disposal can add to the problems.

We have said the lens is not static. In populated areas there may be additions every day from washing water, showers, baths and other household wastes and of course from pit latrines, septic tanks and so on. As we pump out "freshwater" this is easily replaced by water contaminated by human, industrial and animal wastes. This is well documented for the Pacific (Brodie and others 1983, 1984; Prasad, 1984) and is illustrated in a simple way in figure 9. Under these conditions there is a grave risk of ending up drinking your own sewage.

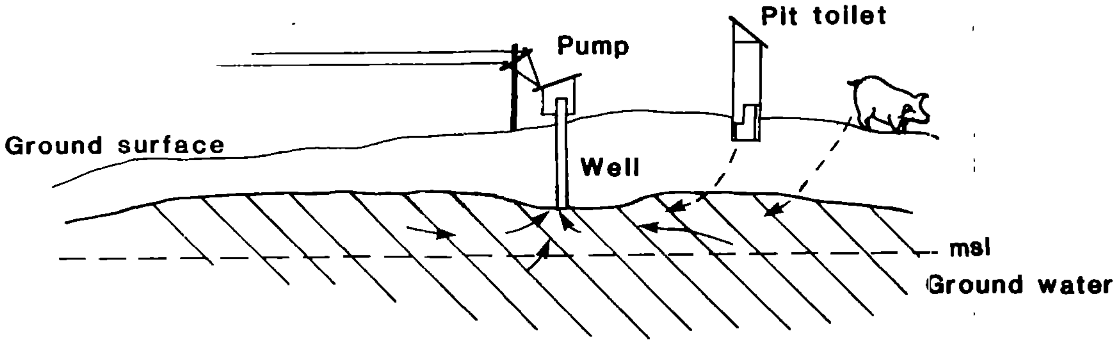

Figure 9 Contamination of ground water

Methods of protecting the lens include isolating or fencing off areas where water is withdrawn or removing sewage and waste by separate drainage systems (piped and pumped sewage). The age-old provision of lagoon-side drop toilets was one solution but this runs the risk of contaminating seafood. An alternative is to pump suspected or contaminated ground water, chlorinate and hold the water in storage tanks for some hours to ensure all harmful bacteria are killed.

BACKGROUND INFORMATION AND RECORDS

Unless you are very familiar with the survey area it will pay you to read whatever material you can get about it, especially any earlier reports related to water resources. The following list may help identify some of the information you should study.

Climate

Your meteorological service will have rainfall data and may have evaporation or evapo-transpiration information too. Rainfall should be reviewed on a monthly basis rather than just looking at annual totals. At some times light rainfall may evaporate from the ground cover or the soil surface and never enter the ground water. Temperatures and wind effects will alter frequently and so influence evaporation. Evapo-transpiration is a calculation which takes into consideration both evaporation and transpiration. Transpiration is the moisture which is expelled into the atmosphere from growing vegetation and is a significant part of the total.

Geology and Soil

You will need to have the background geology of the survey site. Descriptions and maps of the geology should be available for most areas even of many smaller islands. Within the South Pacific a list of geological maps is available.[1] Similarly, soil surveys have been widely conducted and published for most Pacific islands.[2]

Botany

The plants growing in the survey area will have an important bearing on the amount of water intercepted (caught) during rainfall. Some plants have very broad leaves, others have very fine needle-like foliage; some are shiny so that water will run off very quickly, others dull or with hairy surfaces which can hold large amounts of moisture

Coconut palms channel water quickly to the ground but at the same time coconuts draw up large amounts (about 50 litres a day) of water from the ground to fill growing nuts and meet the needs of transpiration.

Some understanding of the vegetative cover helps with your interpretation of long-term use of the ground water and may help in identifying boundaries of the freshwater lens as explained later.

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[1]See Thompson, B.N. 1984: Geological Maps of the South Pacific. South Pacific Technical Inventory No 4. DSIR Wellington.

[2]Readers should contact NZ Soil Bureau, Private Bag, Lower Hutt for soil maps and descriptions.

Reports

It is most likely that other specialists will have visited and reported on the selected survey area. There may be technical reports by overseas visitors in an appropriate technical field of interest. Many have been prepared by consultants for aid organisations, some by interested scientists and others at the request of local Government departments.

Tide Tables

Perhaps there are no tidetables for your specific survey area but information may be available for an appropriate nearby area. More details about tides and calculating the mean sea level are given later.

PLANNING A SURVEY

Before getting too heavily involved in your survey you had better have a clear idea of why a survey should be done. There may be a need for more water for a local village supply; perhaps a small food processing unit which needs a calculated quantity of water for washing or raising steam; maybe it's a hospital water supply, or perhaps the survey is just to get some definite information about a resource. The reason is not as important as having a specific purpose as you can place a proper interpretation on the results by matching the supply with the needs. Hopefully, local authorities have a written programme for developing water supplies and your objectives should fit into this programme.

You cannot reasonably develop an approach for the survey until you have reviewed the literature and other data available. Reference to a bibliography or help from a librarian could save you time here. Next, you will need to know what equipment, staff and finance is available before you can decide how long you can afford to stay on site. For example soundings at only about 4 or 5 geophysical sites can be completed each working day. Seasonal timing is important because some equipment can't be operated in the wet. You might already have some equipment; some may need to be purchased or borrowed. Make arrangements for insurance for loss or damage to equipment and set aside some funds to pay for likely repairs.

Well in advance you will need to sort out transport, accommodation, equipment, cartage and the availability of some items, such as batteries, at the local site.

Staffing is very important especially if you are going to spend quite a while living and working together. The members need to be complementary in both skills and personality so they form a real team in which everyone knows exactly what he is expected to do in the field, calculating results and in looking after himself and his colleagues in the domestic scene. Local staff must fit in too and be clearly instructed about their duties and responsibilities.

A minimum staffing seems to be:

1 Team leader for organisation and co-ordination.

3 Geophysicists. It requires two staff in the field for measurements and a third member can process the previous day's field data to accelerate interpretation.

2 Hydrogeologists who can also undertake surveying, drilling, pump testing and associated work.

The team leader must have a full understanding of the project and its objectives as well as the work of every other team member (so he can take anyone's place in the event of temporary illness or any other reason). He should also have skills in dealing with people at all social levels. His role is to liaise with local authorities, organise transport, accommodation, and domestic arrangements, provide funding, equipment and any other resources. He should be the key contact with funding agencies, sources of equipment and government officials.

The other two groups constitute the main field teams and at different times need the support of two full-time (local) workers to assist with carrying equipment, marking sites, cutting tracks, and surveying.

The first step is for the team leader, in consultation with the specialists, to develop the field programme and visit the area in advance of the field party. This is the best way to ensure accommodation and transport arrangements are correct. He can also meet local officials and other dignitaries to make sure that there are no problems or delays with arrangements. This visit may be made some months in advance of the field party.

The geophysicists would visit and undertake their field work first and perhaps return to base to confirm, or refine by computer, the initial layered model (developed in the field using hand calculators and sets of master curves). This information will identify the thickest parts of the freshwater lens.

The hydrogeologists, armed with this information, can then visit and drill in this thick part of the lens and carry out detailed pump and other tests to prove the resource. In some instances there could be 3 or 4 weeks' interval between visits of the two parties although with experience, the interval could be reduced.

The geophysicists, hydrogeologists and the team leader will then write up their particular activities and prepare an agreed text which accurately interprets the field information. Recommendations may then be passed to the appropriate authorities for action in developing the ground-water resource.

EQUIPMENT CARE

Lists of the equipment you will require are provided in appendices 2 and 5. In both the hydrological and geophysical lists are instruments which require special care and treatment for use in tropical conditions. Spare parts and repair equipment will need to be included - things like 12 volt soldering irons (and solder) which can operate from batteries in the field.

Large strong plastic sheets are needed to protect equipment from sudden downpours and if special tools are required to disassemble special equipment these need to be taken or the equipment will have to be shipped back to home base.

All equipment should be thoroughly checked out in a mock work situation prior to departure from home but may fail nonetheless. Be sure to take photocopies of wiring diagrams of electrical circuits with you. Access to electric power for charging batteries (and an effective battery charger) will be required. Remember too that generally commercial aviation rules forbid the carriage of batteries filled with electrolyte. One solution is local purchase of "dry-charged" batteries and sulphuric acid of the correct strength. Make sure in advance that the number of batteries you want are available.

Drilling rods will not be available locally and any special drill bits or pipes will need to be made up in advance and forwarded to the survey area.

We would strongly advise taking out insurance against loss of equipment especially if it has been borrowed or has been specially constructed or purchased for the survey.

On completion of the survey all equipment should be rechecked, repaired and returned as appropriate. Most electric/electronic gear will corrode more readily if not in regular use so either arrange for occasional use or store under dry conditions. Batteries have only a short life and after the survey are best disposed of to a regular user.

Part II

FIELD PRACTICE

In this part we deal with field activities which follow up the section on Planning a Survey. We take a step by step appraisal of each of the field activities.

Contacts with local authorities and officials must always precede any action in the field. Once the survey area has been appraised the scientists can formulate their field programme with the establishment of a height datum as an early essential. Resistivity soundings, and evaluation of these to develop a layered model, can then be checked by hand drilling, water sampling and water level recording.

INITIAL FIELD CONTACTS

It is essential to involve the local Chief Administration Officer (CAO), the staff of the local water authority (Ministry or Department of Works (and Development) or Water Board), and the local district council Chairman (Island Council or Matai) in discussions of the survey objectives and expectations. In some instances land may be tapu for some reason or may be privately owned so that clearance for the survey team's visit will need to be obtained.

Arrangements for transport, especially air transport, can be made in advance with useful savings. Local shipping is usually infrequent so that booking freight (and passenger) space may need to be done in advance. Motor (and water) transport may be arranged possibly through a local department.

Special technical skills are required in some fields such as electronics, electrical circuitry, fitting and welding, motor maintenance and plumbing. It would be useful to locate organisations capable of carrying out repairs and servicing in these fields.

Motel accommodation in off-shore islands may be limited and renting a vacant house may be a practical alternative. Enquiries and possible arrangements for renting and daily servicing (cooking/laundry/ cleaning) may be concluded at this time. Check local habits too, such as expected attendance at Church, so that the field party is aware of social requirements when they visit.

Because scientists tend to spend long hours in the field you are wise to find out the availability of food supplies and if any local market operates. A list (and locations) of eating places is useful if you have to arrange your own evening meals.

Banking facilities need to be checked out because you may need to handle substantial sums of money to pay for various services and salaries/accommodation/daily allowances.

Most of these field contacts as well as interviews with land owners can be handled during the initial visit by the team leader.

OVERVIEW OF THE SURVEY AREA

Field staff should have a wide range of scientific skills and experiences but you may also need to call on local knowledge to provide an effective overview of the survey area. You should arrange brief descriptive reviews of the area in terms of geology, soils, botany (or plant cover), hydrology - streams, wells, boreholes, open drains, lakes, ponds or other standing water - as well as a generalised geographic description of the area in relation to its surrounding features. Topographic maps are particularly useful, if available.

The geology clearly limits the movement of water and can influence the chemical changes to ground water which take place over time. The nature of the soil will influence the drainage pattern and may also alter the water chemistry.

The plant cover will affect the amount of rain which is held up in the foliage (interception) as well as the amount of water taken up and transpired from the leaves into the atmosphere. Large, deep-rooted forest trees may draw up much more ground water than small surface-rooted vegetation. Some plants such as Guttera may indicate the seaward limit of the ground-water table and help to define the freshwater resource.

Hydrology will be taken into account by marking on a map the locations of wells (open or pumped, together with the height above m.s.l.) the presence of streams (absent on atolls) including any available flow data, the presence of any open drains, lakes and pits used for crops but close to the water table. Seepages around the coastline are also useful indications of freshwater. Together all these observations assist in building up a picture of the water resource.

Following a team appraisal of the above information a start can be made on developing a programme of field work.

DEVELOPING A FIELD PROGRAMME

This must be a co-ordinated approach between all technical branches. The geophysicists will rely on advice about the geology, soil and botany and general observations about surface features and ground heights above sea level. In turn the geologists will rely on calculations by geophysicists to site their drillholes. The chemists will appreciate the information from all these sources to help interpret the chemical constituents of the ground water. The presence of animals, humans and areas of swamp vegetation may hint at biological contamination.

One effective approach is for the whole team to visit the survey area together and agree which specific observations each will undertake. There is no need for the whole team to stay together but the senior hydrogeologist and geophysicist at least should get a feel for the area. A "walkabout" or "drive-about" will give them a good overview and identify the general geological and physical dimensions of the area while other members can survey the hydrology (visit wells, water holes, seeps etc), make notes and collections on the botany, locate a suitable site for a datum point and make initial land survey measurements and relate these to the (outline) map.

The group can then sit down together and identify the most appropriate directions for the resistivity lines and determine the order of work. The leader can then co-ordinate with local helpers to see the necessary work is done in the right order.

While the geophysicists are making their resistivity soundings the other members will be proceeding with their allotted tasks. Each of these are spelled out in some detail below. If the team does not all arrive and start at the same time the hydrogeologists will need to accept the decisions of the team leader and geophysicists when they get on to the site. This will be helped by preliminary meetings before leaving for the survey especially against the background of previous reports, maps and other information.

ESTABLISHING A POINT OF REFERENCE

Whether you are on an isolated islet (motu) or a major land mass, before you can determine the height of any point you must establish a basic point of reference From this point all measurements will be made. This point is commonly called a datum (from the Latin, meaning a "fixed starting-point of a scale or measurement"). If the area has already been surveyed the field staff may have established a permanent survey mark (bench mark).

A bench mark is easily recognised as a brass plug set in a concrete block with a specific number marked on it for identification. A bench mark is a useful starting point for your survey and may be found on a map by the designation BM. The positions of bench marks (and other major survey points) are usually accurately known and mapped. Both the elevation (height) and distance, both linear (measured in a straight line) and angular (the angle between different points) are known and plotted on the surveyor's map. So if you already have an established point of reference all your surveying should be based on that datum. If not, you will have to establish your own.

In most isolated areas you will not have any reference point so you will need to fix a point from which you can carry out your elevation survey (see later), and from which you can measure distances. If you do not even have an outline map of the area, your datum could act as a starting point for your map too. We are assuming, however, that you have a map with a north point and a scale that you can at least identify a permanent feature such as a building or structure on the ground <u>and</u> on the map.

The standard reference datum for land elevation is mean sea level (msl). In the absence of any other established height you will have to measure as accurately as you can where the mean sea level is at the coast. High tide marks, the debris left on the shore, are quite useless as points of reference and should not be used as a basis for any measurement.

ESTABLISHING MEAN SEA LEVEL

Although mean sea level is not precisely the same as a geodetic (earth related) level surface at different places, for practical purposes it is the only reliable measurement you can take as a reference surface.

Mean sea level varies according to the density of ocean waters and this can change due to changes in temperature, salinity (saltiness), evaporation, rainfall, the presence of rivers, variation in barometric pressure (influenced by weather patterns) as well as other effects. Where msl is to be used for measuring accurate land elevation, surveyors usually require observations over quite long periods to work out the "mean" of the high and low tidal points. Msl varies with each tide and usually a minimum of 29 day's records are necessary. For more accurate measurements, analysis of a year's records are used. Clearly this is not practicable for quick surveys when you have only a few days at a field site.

There are three methods which can be used for rough estimates of msl. Two methods use a series of observations taken over one day. These use the mean (average) of 24 or sometimes 25 hourly values. The third method uses a more accurate 39-hour "weighted" average. (A weighted average means using a mathematical factor to reach a better value).

This last method was developed by A T Doodson and published in the UK Admiralty Manual of Tides (1941). It involves some complicated mathematics and we would recommend you seek guidance from your nearest Hydrographic Department, Ministry of Transport or Harbourmaster or equivalent before applying this method.

The difference between the 24 and 25 hourly measurements is to give a better completion of the cycle of tide heights. When we plot the height of the tide, hour by hour, we get a series of points which under ideal conditions can be joined up to produce a smooth symmetrical curve (a sine wave) above and below mean sea level as in figure 10. Measurements over 39 hours provide a more suitable duration.

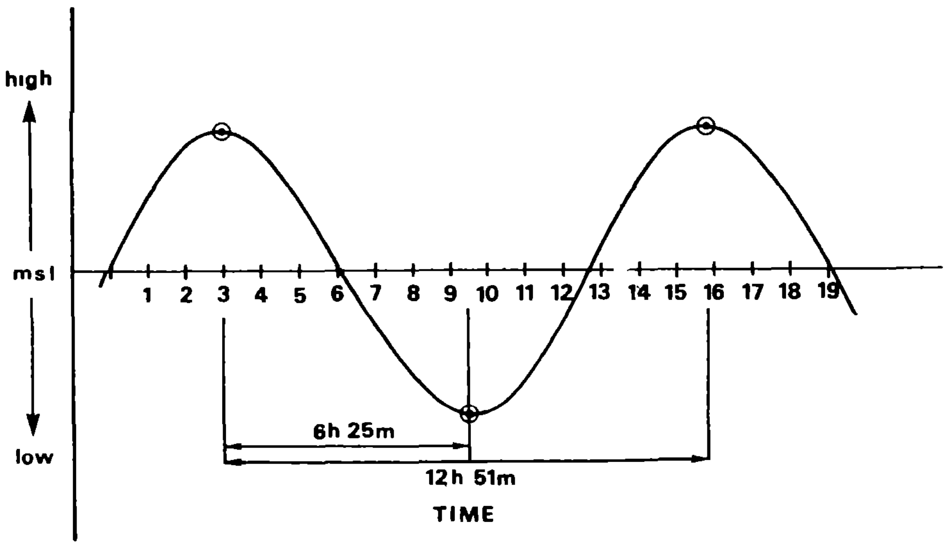


Figure 10 Plot of hourly tide heights.

In practice, however, we will see that there are quite a number of disturbing effects which should be taken into account. Doodson's method takes the most important of these "errors" and "filters" them out of the calculations.

The simplest estimate of mean sea level is the midpoint between the two extremes of high and low tide. See figure 11.

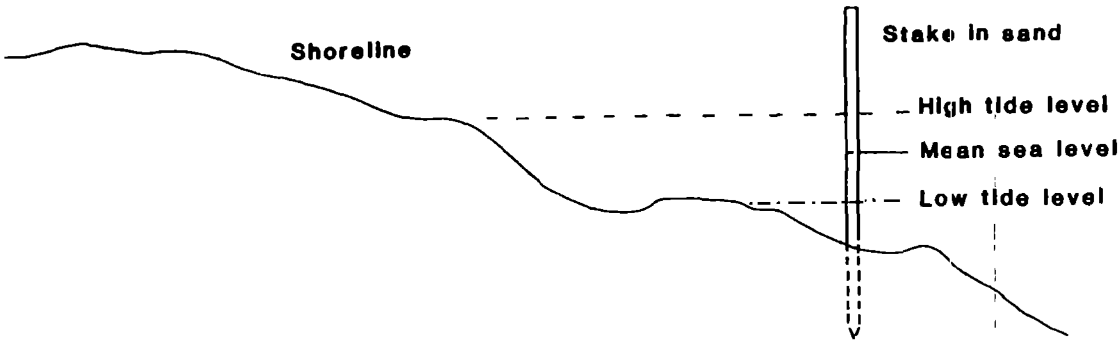


Figure 11 High, mean and low tide levels at the sea shore

This "stick in the sand" approach may be the only way to establish msl for an isolated place (where no other datum exists) if an automatic tide gauge is not available.

Scientists have identified over 400 constituents which effect the rise and fall of the tide. These are called the tide generating forces. Normally only a few constituents are used to calculate tidal predictions. Measuring high and low tides on a stake is a relatively simple, if tedious, task but it does not necessarily give as accurate a measurement of msl as the more detailed studies would do.

Appendix 1 provides a review of these various factors and explains how neap and spring tides occur under the gravitational, local and regional effects.

RESISTIVITY OF THE GROUND

Concept of Resistivity

Resistivity is a measure of the specific resistance of the ground to the flow of electrical current. You can think of it as representing an attempt by the ground to "resist" the passage of the current. It is measured in units of ohm metres (Ωm) and is the opposite of conductivity.

Resistivity Values for Various Ground Layers

Usually each different type of ground has a characteristic resistivity value which depends on the makeup of the ground in question, the degree of its water saturation, and the salinity of this water. For example, a rock saturated with seawater will have a low resistivity value (1 to 5 Ωm) and it is often referred to as conductive. The low resistivity value indicates that there is only a small ability to resist current flow which comes about because the charge-carrying ions in the sea water can move easily. At the other extreme, "dry" rock containing little or no water will be called resistive and have a very high resistivity, perhaps 1000 to 3000 Ωm. It strongly resists current flow. Table 1 gives resistivity values for some of the fluid and rock types you're likely to meet.

Table 1: Typical Resistivity Values

Material		Resistivity Value (in Ωm)
Pure Fluids		
sea water		0.25
brackish water		20
freshwater		50 to 200
distilled water		1000 to 3000
Rock/water mixtures		
coral sand	saturated with sea water	2 to 10
porous basalt	saturated with sea water	2 to 10
hard coral or basalt saturated with sea water		5 to 15
sand or rock saturated with freshwater		50 to 300
dry sand or rock containing very little water		500 to 3000

Use of Resistivity for Finding Freshwater Lenses

You can see from Table 1 that resistivity values vary over a wide range. Resistivity soundings make use of this to detect several layers in the ground, each with a different resistivity value. Usually, with help from Table 1, the different layers can be identified (or interpreted) hydrogeologically as, say, a dry surface layer, a layer of sand saturated with freshwater, or a layer of sand saturated with salt water.

Resistivity Sounding

A resistivity sounding (to be described shortly) is a technique for determining the resistivity of such layers. It involves laying wires along the ground, injecting current into the ground, and measuring certain voltages that result from the flow of current. A list of the equipment required for a geophysical programme is given in Appendix 2.

SELECTING RESISTIVITY SITES

Inherent in the measurement and interpretation processes for using the Schlumberger (pronounced Slum-ber-jay) or Wenner or Off-set Wenner methods for resistivity soundings is the assumption that the ground being investigated comprises several horizontal layers each of which has a characteristic uniform electrical resistivity. Thus care needs to be taken in choosing measurement sites to ensure that such conditions are met. Many sites where it might be desirable to obtain resistivity information will have to be avoided because the resistivity structure of the ground is likely to be "disturbed", and if the measurements were to proceed, unusable or misleading data would be obtained.

This section discusses how to choose sites so as to avoid these difficulties.

Likely Resistivity Disturbances

Coral atolls, in their natural state, usually have horizontal layers over most of their area. Such natural features as sand ridges or points of raised coral could be expected to be electrically disturbed, as would the root structures of large trees, and the ground around isolated boulders of coral imbedded in the sand.

However, man-made objects more often disturb the electrical structure of the ground The foundations of roads, buildings and bridges, as well as buried metal pipes and fences all alter the electrical properties of the ground. Landscaping, cultivation and reticulation of water pipes and electrical wiring have similar effects.

In choosing sites for making resistivity soundings the geophysicist has to make a conscious effort to search out such regions of disturbed ground, and avoid them.

Traverse Lines and Coverage of the Region of Investigation.

When you plan the investigation of a small island, say 1000 m by 500 m, you would probably budget to make resistivity soundings at about 10 to 15 sites How should these sites be located throughout the island? Rather than have the sites located randomly over the island, it is better to lay them out along several traverse lines. This allows you to make more readily comprehensible presentations of the sounding interpretations usually in the form of resistivity cross-sections. Following this approach the self-consistency of the data and trends from site to site should be evident. Choose your traverse lines to give a good coverage of the island. Perhaps two traverse lines across and one along it would be best, but other considerations may force the use of a different arrangement.

Geological Considerations

In selecting traverse lines and sites, you must remember that the objective is to detect layers representing different hydrogeological conditions - e.g., dry coral sand, coral sand containing freshwater, coral sand containing salt water, various hard coral formations, and perhaps other formations such as basalt. Hydrogeological considerations, such as knowledge of the way formations are laid down may often point to the advisability of choosing certain sites instead of others.

Measurements near the Shore

It is not usually satisfactory to measure within 50 m, or so, of the high tide mark, because the rising and falling wedge of tidal sea water will influence the data. There is a strong danger of misinterpretation since, while this conductor (the salty ground) is actually at the surface to one side of the sounding centre, it could easily be misrepresented as being a deep conductive layer directly beneath the centre. To minimise this effect wires must be laid out parallel to the shore-line for all measurements within 100 m or so of the sea.

Sounding Sites along Traverse Line

Each sounding requires laying out about 200 m of wire in a straight line, preferably at right angles to the line of the traverse. In open or sparsely-vegetated country there should be little difficulty in doing this. In difficult going, you might have to make some compromises

In densely forested land, it is usual to cut a track along the traverse line to provide access. You should seek out patches of uniform ground at regular intervals along the line. These will become the centres of the sounding arrays and should be as free as possible of the disturbing influences mentioned above. It is beneficial to clear a small region (say, 10 m at right angles to the traverse line by 2 m along it) of any coral boulders, coconut husks or other disturbing objects. This is done because the centre part of the array is the part most susceptible to disturbance You can then lay out the resistivity wires to about 100 m either side of the cleared centrepoint. In dense bush, you may have to cut lines to achieve this. It is important that the central 50 m, or so, of the resistivity array be as straight as possible but a small amount of deviation is allowable (and often unavoidable) at the ends of the lines. Figure 12 shows how you might lay out the traverses and resistivity sites on a typical small island.

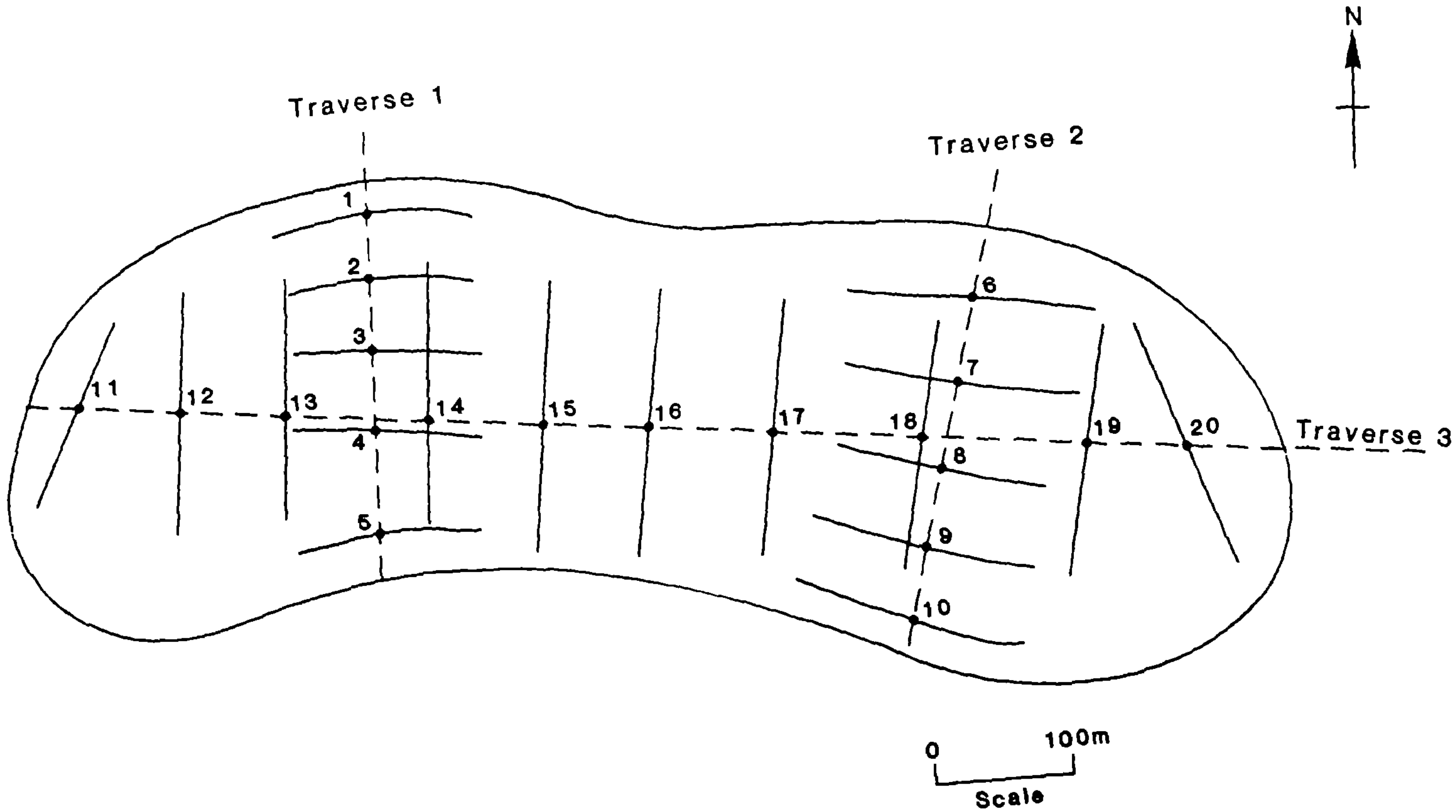


Figure 12 Hypothetical coral island showing layout of resistivity lines.
Three traverses; 20 soundings.
Note lines close to the coast 1, 5, 6, 10, 11 and 20 are set parallel to the coastline.

FIELD RESISTIVITY MEASUREMENTS

Equipment

Field equipment consists of a transmitter, a receiver, a pair of multicored cables to conduct the current and a series of electrodes, spaced at selected intervals along the cable.

Transmitter:

As shown in figure 13 the transmitter consists of several components. An electronic console generates a current (I) which you must read in milliamps (mA) on the meter. The current flows along a wire to an electrode (called a current electrode) made from a steel rod. On passing down the electrode, the current enters the ground where it spreads out and moves through the ground towards the second electrode. It is gathered up by this electrode and returns to the transmitter console via a second wire A switching device causes the direction of current flow to reverse every few seconds.

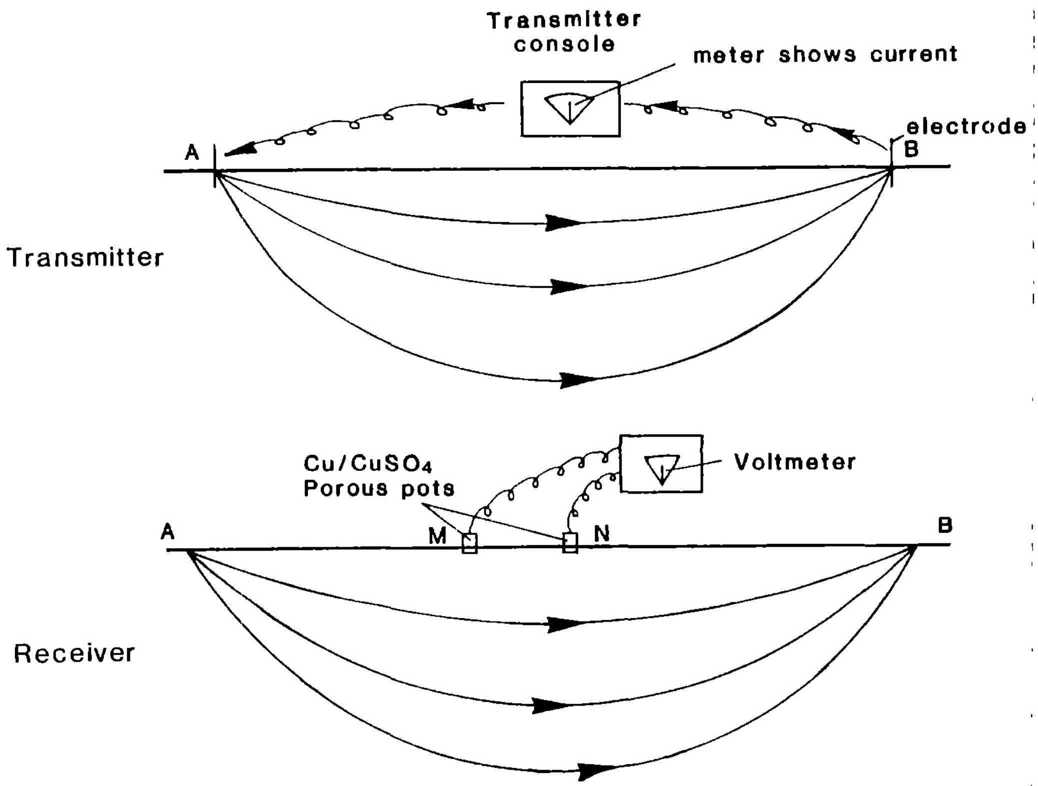


Figure 13 Transmitter, receiver and electrode array

Receiver:

The receiver (shown in figure 13) detects the signals produced by the transmitter. The receiver consists of an electronic console for measuring very small voltages which are measured in millivolts (mV). The receiver console is connected to the ground through a different pair of porous pot electrodes, called potential electrodes. These have a porous ceramic base and contain a copper sulphate ($CuSO_4$) solution with a copper rod making contact with the wire The meter shows the voltage difference arising between the two porous pots as a result of the current flow in the ground.

Schlumberger Array

A wide variety of arrangements of transmitter and receiver is available for making ground resistivity measurements. But, we shall deal with just one layout - the Schlumberger array - which has the particular array of wires and electrodes shown in figure 14.

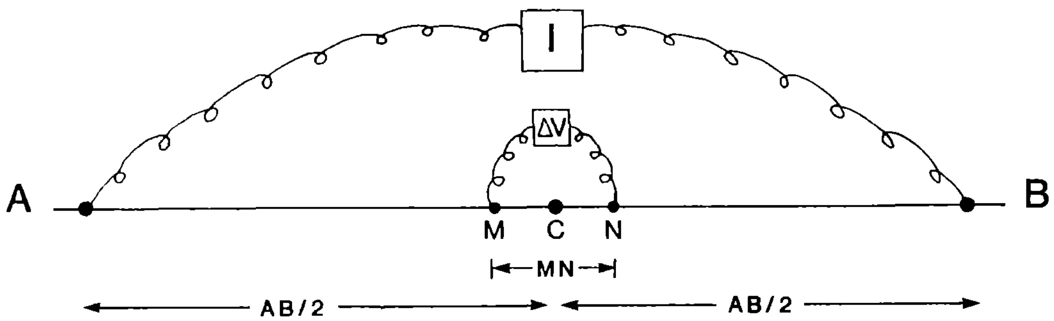


Figure 14 Layout for Schlumberger array

The array is centred at a point C, with current electrodes at points A and B. The distance AC is referred to as half the distance between A and B or AB/2 and must be the same as CB. The potential electrodes (porous pots) of the receiver M and N are placed a small distance either side of the centre C. The distance MN must be small compared with AB/2, usually MN is less than a fifth of the distance AB/2 i.e. MN <0.2 AB/2.

If this electrode array is sited over reasonably uniform ground, and a current I (in mA) is injected into the ground by the transmitter, and a change in voltage ΔV (in mV) measured by the receiver, then we can measure the "apparent" resistivity of the earth ρ_a (in Ωm). This is given by the mathematical formula

$$\rho_a = \pi \left[\frac{(AB/2)^2}{MN} - \frac{MN}{4} \right] \frac{\Delta V}{I}$$

You can think of "apparent", in describing the apparent resistivity, as indicating that the measurement represents an approximate average of the resistivities of the rocks beneath the site. You must remember that the current and voltage have a regular waveform and it is usual to record the "peak-to-peak" values for both the current I and the voltage difference ΔV on a paper roll. This wave form is illustrated in figure 15.

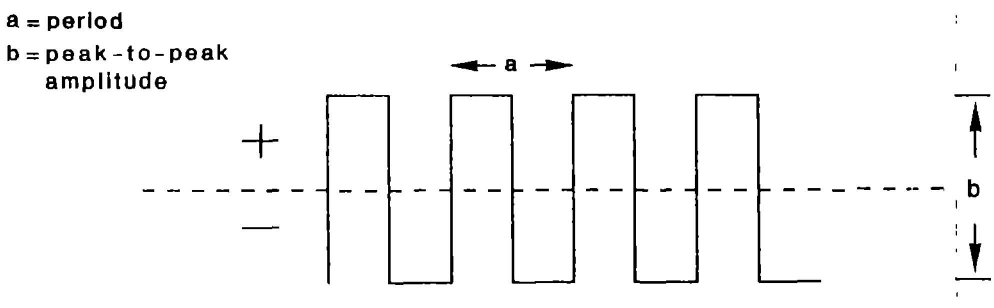


Figure 15 Wave form for current flow
Note: This is called a square wave and because the direction of the current flow is reversed every few seconds the wave form is equally spaced above and below the centre line (zero voltage).

Making a Sounding

A sounding consists of a series of 20 to 30 apparent resistivity measurements all based on the same centre but with an expanding range of values for AB/2. You can see from figure 16 that, as AB/2 is increased, the current penetrates deeper and deeper into the ground. Although AB/2 is related to the depth of current penetration the two are not exactly the same.

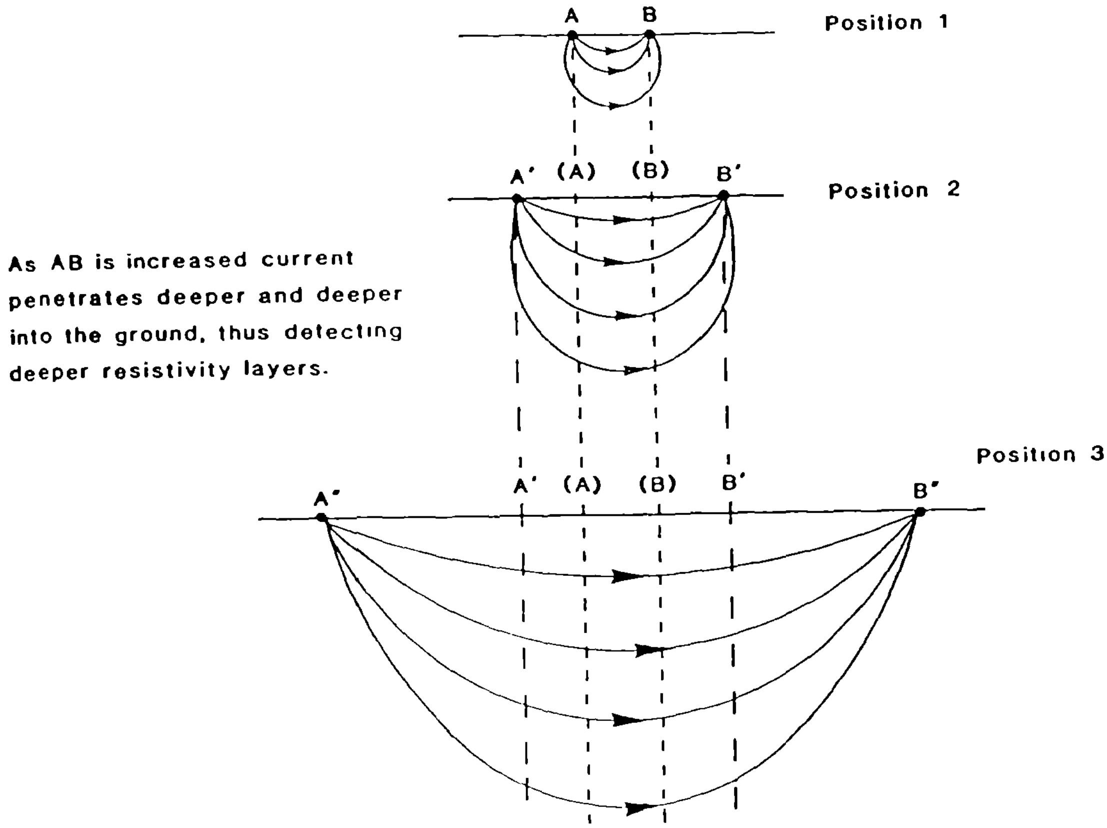


Figure 16 Expanding range of A and B electrode positions outward from the centre

In our scheme, the first measurements are made with AB/2 = 0.63 m. This is followed by measurements at spacings increasing in logarithmic steps up to AB/2 = 100 m. The distances are

AB/2 =	0.63,	0.8,	1.0,	1.25,	1.6,	2.0,	2.5,	3.2,	4.0,	5.0
	6.3,	8.0,	10.0,	12.5,	16,	20,	25,	32,	40,	50,
	63,	80	100	(metres)						

The first few measurements are made with MN = 0.1 m. When AB/2 is increased to about 4 0 m we change to MN to 0.8 m, and repeat two measurements. The spacing of MN is increased again to MN = 5.0 m when AB/2 reaches 25 m. Thus we have made three overlapping sets of measurements.

RESISTIVITY DATA ANALYSIS AND INTERPRETATION

Apparent Resistivity Sounding Curve

We record all the data measured while making each sounding. This produces a list of values of AB/2, ΔV and I as shown for some data from Aitutaki Airport in table 2.

Table 2: Data from sounding #22, made at Aitutaki Airport, 30 September 1985. Elevation above sea level = 2.645 m.

MN = 0.1 m				MN = 0.8 m				MN = 5.0 m			
AB/2 (m)	ΔV (mV)	I (mA)	ρa (Ωm)	AB/2 (m)	ΔV (mV)	I (mA)	ρa (Ωm)	AB/2 (m)	ΔV (mV)	I (mA)	ρa (Ωm)
0.63	2290	50	567	4.0	376	50	468	25	16.5	120	53.5
0.80	1448	50	580	5.0	191	50	373	32	7.22	120	38.5
1.00	981	50	615	6.3	89.2	50	277	40	3.11	120	26.0
1.25	640	50	627	8.0	38.6	50	194	50	1.61	140	18.0
1.60	383	50	615	10.0	35.6	100	140	63	0.65	130	12.4
2.00	247	50	620	12.5	17.0	100	104	80	0.28	130	8.7
2.50	79.4	26	599	16	8.32	100	83.6	100	0.17	170	6.3
3.20	85.7	50	551	20	4.2	100	65.9				
4.00	47.0	50	472	25	2.11	100	51.8				
5.00	23.4	50	367	32	0.95	100	38.2				

The first block refers to data measured with MN = 0.1 m, the second with MN = 0.8 m, and the third with 5.0 m. The last two AB/2 measurements at the bottom of columns 1 and 2 have been repeated at the top of columns 2 and 3, respectively, i.e. AB/2 = 4 and 5 and 25 and 32 m appear twice.

These data can be plotted on log-log graph paper to form what is called a sounding curve as shown by the dots in figure 17. The next step is to interpret the sounding curve to obtain discrete layers. (For the example in figure 25 this has been done by a computer.) The theoretical section obtained consists of three layers with layer resistivities and depths of interfaces as shown in the inset on figure 17. The theoretical curve corresponding to this best-fitting layered model for table 2 data is given as the solid line in figure 17, and you can see that it matches well with the observations.

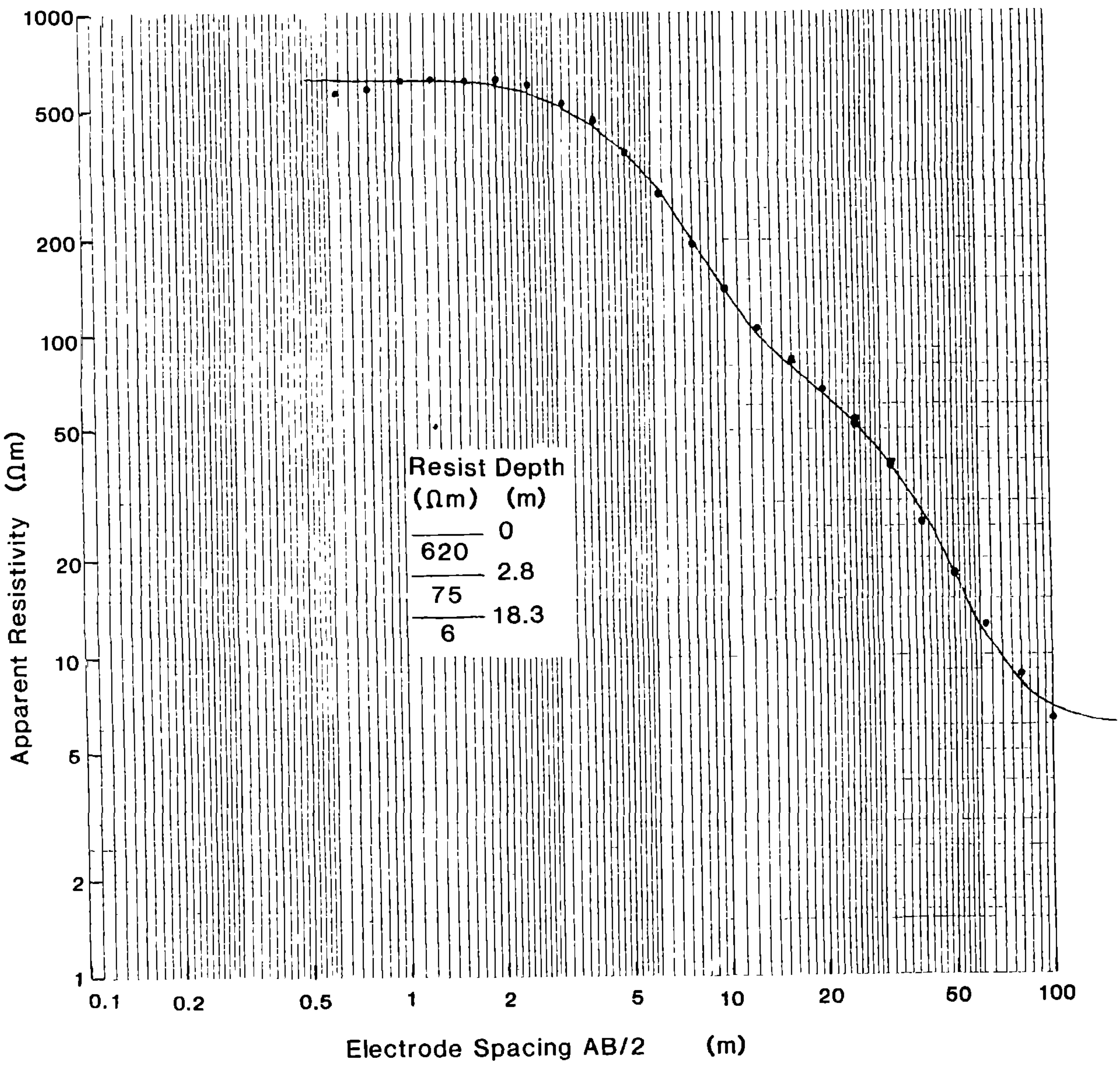


Figure 17 Plot of sounding curve for site #22, Aitutaki airport, 30 September 1985. Dots represent field measurements; the solid line represents the theoretical curve corresponding to the section shown in the inset. Note the slight flattening of the curve at 75 Ωm.

By comparing the layered section with the curve, you'll see that some of the features can help to demonstrate that the given section is the correct interpretation

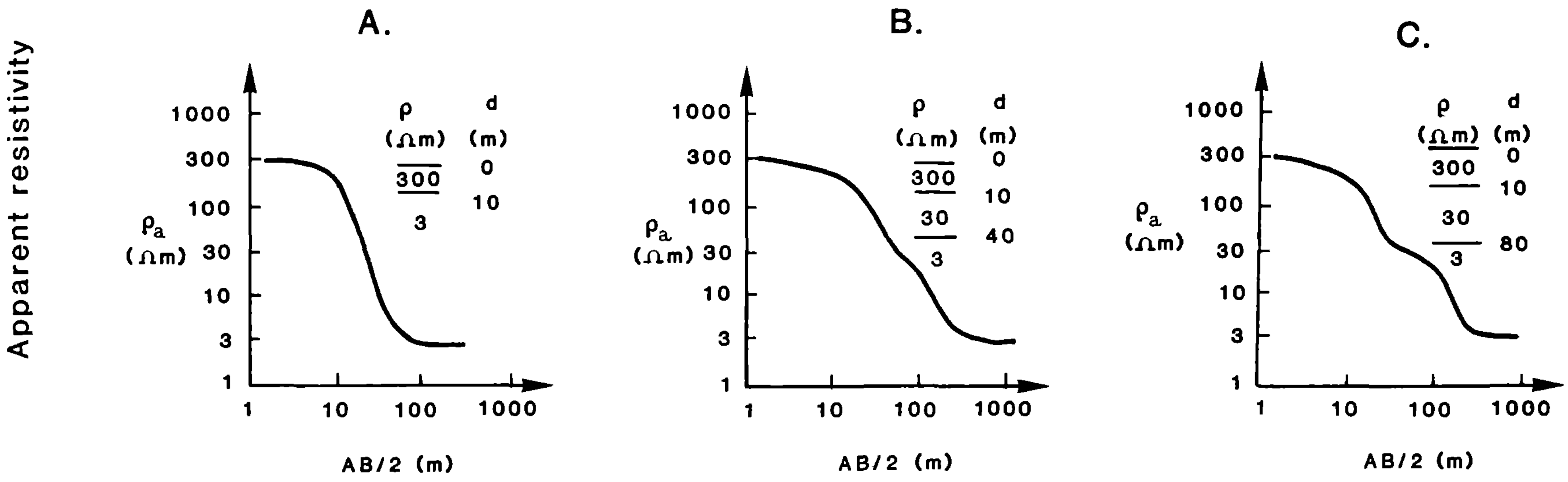
1. The left-hand portion of the curve begins at a constant value of about 600 Ωm and stays at this level until AB/2 increases to about 2 m. This, of course, reflects the surface layer of resistivity 620 Ωm and a thickness of 2.8 m (see figures in the inset box).

2. Because the curve is falling as the current penetrates deeper and deeper, the second layer must have a smaller resistivity than the first. The resistivity value for this layer can be deduced to be about 75 Ωm because of the slight inflection (kink) of the curve about halfway down the steeply sloping part. However, estimating the exact depth of the interface at 18.3 m depth becomes very difficult from visual inspection of the curve.

3. The sounding curve levels off at a value of 6 Ωm corresponding to the deepest layer detected.

The portions of the measured curve where the overlaps occur (at 4.0/5.0 m and 25/32 m) show quite small and acceptable mis-matches in the example shown in figure 17. Quite often, the overlapping portions match poorly, and therefore one of the segments will need to be corrected. This is usually done by applying a constant correction factor to all the data in the mis-matching block.

The main objective of this work is to detect the freshwater layer which will have an intermediate resistivity value (the 75 Ωm layer in figure 17). The difficulties of detecting this layer are illustrated in figure 18 where the 30 Ωm layer represents a freshwater lens. In curve A it is absent and the curve descends very steeply. In B, where the 30 Ωm layer is thin, there is only a slight inflection (levelling out) of the descending curve to indicate its presence. Where the layer is thick, as in C, the inflection shows up clearly. From this you can see that a layer must be quite thick to be detectable by this resistivity technique (Risk, 1977).



In A the curve decends steeply and no freshwater (30Ωm) layer is detected; in C the inflection is quite noticeable indicating quite a thick layer of 30Ωm between 10 and 80 m (see inset values).

B is part way between A and C. Because the 30Ωm layer is thin it is barely detectable.

The intermediate layer of freshwater must be thick to be readily detectable

Figure 18 **Interpretation of different apparent resistivity sounding curves.**

Interpretation by Curve Matching and Using a Computer

There is no room in this manual to describe the details of how to obtain the multi-layered interpretations from the field measurements, but we can outline the two main methods.

Curve matching involves comparing the field curve with a selection of theoretical curves in a published catalogue of master curves to find one whose shape matches. Usually, an exact fit cannot be obtained and it is necessary to interpolate between several master curves to get the best solution. More complicated procedures using so-called "help curves" can assist this process. Considerable experience is required to gain a satisfactory level of skill in curve matching

Computer analysis is available in most geophysical institutions which run mainframe computers, but cannot usually be done in remote locations or with small "personal" computers. The computer usually requires the inputting of an approximately correct trial solution which could be obtained using the curve-matching process. The trial solution must have the correct number of layers. The computer then follows a cycle of adjustments of both the resistivity and thickness of each layer until it finds the theoretical curve which best matches the field data. Computer analysis yields a more accurate solution than is possible with curve matching.

In remote Pacific Island locations computer analysis is usually not available, so we are left with curve matching as the only on-site way of interpreting the data. A new approach, which is proving to be successful elsewhere, is to transmit the field data by facsimile copy to a geophysical processing centre and receive back the computer-interpreted data by the same means.

Resistivity Cross-sections and their Meaning

In a resistivity survey such as the example shown in figure 19, measurements are usually made at sites regularly spaced along a profile. In this case sites were measured at 200 m intervals along the length of the Aitutaki Airport runway. First we had to develop a layered interpretation of the sounding curves obtained from each site. From the levelling information, the height of the land surface above mean sea level at each measurement point was drawn in. Below each measurement point the depths of the interfaces and resistivities of the layers were also drawn in. A line representing sea level should be shown, as well as lines connecting the interfaces between layers. Thus, the cross-section shows the resistivity values measured along the traverse line at all levels down to about 20 m below sea level.

We now need to associate a hydrogeological meaning to each of these layers. The surface layer, down to about sea level, has resistivity values varying from about 1250 Ωm to 500 Ωm. From table 1 we can interpret this as being either coral sand or hard coral containing very little water

The interface at about sea level represents the water table (top of the freshwater), this must move up and down with the tide, always being slightly above the momentary sea level. The portions of this interface which are shown below sea level are, presumably, slightly in error such as at site 20, figure 19. Some unexplained influence has slightly upset these measurements. You must learn to expect that there will always be a certain amount of error and approximation in interpretation of resistivity soundings.

The middle layer with resistivities between 230 and 38 Ωm represents the freshwater lens, as indicated in table 1. Its average thickness is estimated as about 12 m and it seems to thin towards the east (site 28).

Below the freshwater layer we found resistivities of 12 to 2 Ωm all along the traverse line. Table 1 shows that this layer is most likely to be made of hard coral saturated with sea water.

The interface between the freshwater layer and the sea-water layer is shown in figure 19 as a sharp boundary with some undulations. In reality there is probably a broad transition zone, several metres thick, between the fresh and salt water. Unfortunately, the resistivity sounding method cannot detect such a transition zone, so it cannot be shown on the cross-section.

Follow up Work

In order to convince yourself that the interpretations of the resistivity soundings are approximately correct you'll need some independent measurements based on levelling, shallow drilling, and the application of the Ghyben-Herzberg principle. If this work yields results in agreement with the resistivity analysis, you can have more confidence in the validity of the resistivity cross-sections as shown.

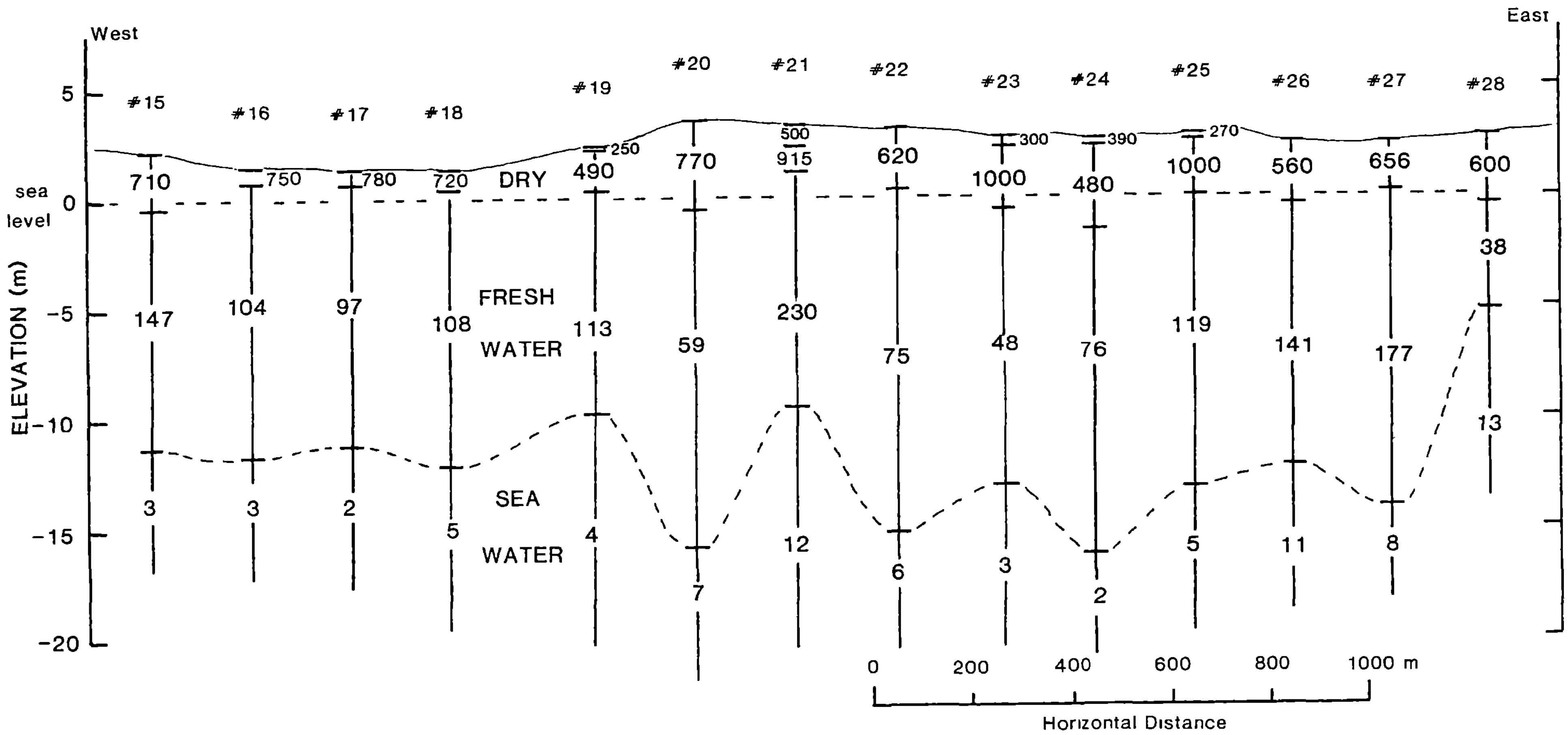


Figure 19 Cross-section of resistivity (in Ωm) for soundings made along the runway at Aitutaki, Cook Islands, 1985. This leg runs from the centre to the eastern end of the runway where it meets the sea.

MEASURING HEIGHTS

A vital part of water resource assessment of any small island is determining the difference in height between mean sea level at the coast and the water table under any part of the island. The actual levelling can be accomplished quite easily with a survey levelling instrument and survey staff, and requires little more skill than the ability to add and subtract in metres and understand decimals. In many cases an accurate survey reference level, from which elevations can be calculated (a datum level) relative to sea level, will not be available, or, for practical purposes it may be too far distant from the proposed line of traverse. In such cases a rough indication of sea level can be established by direct visual observation of the sea level halfway between high and low tides. Because tide heights differ from day to day, it follows that the more observations that are made, the greater will be the accuracy of the assumed datum. However, a line of levels can be carried out at any time, without reference to mean sea level datum, provided that a firm starting point is established which can be tied in to mean sea level later when that has been determined.

Tide gauges

Establishing a tidal datum is one of the most important but time-consuming operations in a small island's water resources assessment. The mean sea level established from the tidal range is the datum for all subsequent ground-surface and water-table heights. In nearly every case it will be a manual operation and will require an observer to record times of high and low tide at each tide station. The more observations that can be made at any one station the greater will be the accuracy in establishing mean sea level, which in itself is the prime reference point for all subsequent measurements.

Immediately on arrival in the area of investigation, select one or more sites where sticks or some other measuring device (coral blocks, coconuts) can be set up at "guessed" high and low-tide mark. The sites can be either on a jetty's piles, a wall or simply be sticking sticks in the sand or mud, bearing in mind that the low tide mark must always be covered when the tide is out. Ideally sites should be chosen both on the lagoon side and open reef side, because tide ranges, may differ between the open ocean and the lagoon.

Some form of protective shield (stilling wells) should be built around the tide gauge to dampen the effects of wind and wave surges. This can be made from coral blocks, concrete slabs, or a drum with bottom cut out and small holes punched in the sides. If sticks are being regularly moved up or down the beach in response to rising or falling tides, protective shields are not required, but the maximum and minimum tide level marks on the ground should be clearly displayed.

Some difficulty may be encountered in setting up tide stations on the reef side because of the more turbulent conditions there. As a result, the measurements taken on the open coast may be less accurate, but since the rise and fall of tide will probably be less than a metre, errors should not be significant if taken over a period. It should also be borne in mind that times of high and low tides may differ between the reef and lagoon side of islands, and even within the lagoon itself. This 'lag' time may be important in developing a water supply as it may, in conjunction with other factors, help to determine the setting of the pump intake relative to sea level in inland wells or drillholes. More details were given earlier in part II (Establishing a Point of Reference).

Equipment : Levelling instrument and staff

The levelling instrument is a relatively delicate optical tool designed to measure very accurately the differences in height between points on the ground (or indirectly, the water-table surface). As such, the equipment should be treated with respect. The instrument should always be carried in its specially-designed case, and should not be dropped, bumped, or otherwise mistreated. Together with the measuring staff (graduated in metres and centimetres) it forms an essential part of any small island's water resource project equipment.

The level consists of a telescope, mounted on a flat disc which can rotate through 360 degrees so it can be swivelled to "look" in any direction. It cannot point up or down when properly set up but gives a view only in a perfectly horizontal plane. This is done by adjusting the three legs to roughly place the viewing telescope plate in a horizontal plane (by eye) then finely adjusting the telescope using a built-in spirit level.

The plate has a small bubble in a round spirit level and beneath the plate are three adjustable screws set in a triangle, as in Figure 20.

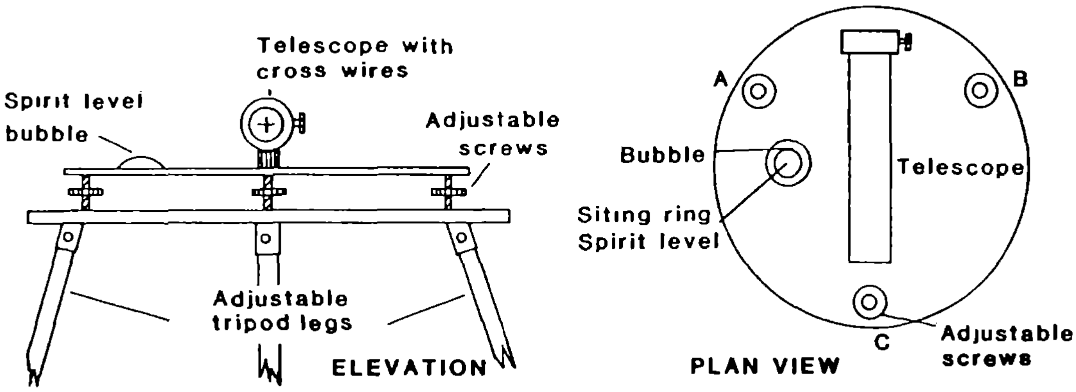


Figure 20 Levelling instrument : Simplified drawing

First centre the bubble by adjusting A and B so that one side of the triangle is horizontal. Then rotate the telescope to AC and adjust C only. Then A, B and C will all be in the same horizontal plane and the telescope will be exactly horizontal. Recheck by rotating the telescope and adjusting if necessary.

The telescope has an adjustable lens so that the surveyor can focus the cross wires in the telescope on the reading on the staff.

The staff is composed of three sections which telescope into one another for convenience of carrying. To use the level correctly the staff must be held vertically, with the face on which the numbers in metres and decimals of a metre are printed,facing the levelling instrument. With experience you will soon be able to judge how far the telescope can "see" in the prevailing light conditions. It must not lean backwards or forwards or to either side. Clear the debris so that the staff is standing on firm ground as you will need to rotate the staff on exactly the same spot to undertake a traverse. Ensure you hold the staff rigidly so it doesn't wave around but don't wrap your hands around the front of the staff and obscure the numbers from the surveyor.

If the staff is too short at a given site one or two further sections can be extended so that the surveyor can get a reading. Each section automatically locks into place when extended. The surveyor will instruct the "chainman" (who holds the staff) to move right or left, come forward or go back. The name "chainman" comes from his other role in measuring distances between sites (using a chain measure in the days before tapes were available).

Running a Traverse

It requires two people to run a traverse, one to hold the staff vertically, and the other to read and record the height as seen through the instrument. A field notebook and pencil are also essential.

The first reading, always termed the back sight, is normally related to a known datum, called the reduced level (RL), which is the reference for all subsequent calculations. The staff only is then moved to the next point along the line of traverse and a further reading, the fore sight, is recorded by rotating the telescope to face the staff. The level must not otherwise be moved. The difference between the two readings is recorded in the appropriate rise or fall column in the field notebook. If another (intermediate) height, or heights, are to be established between the back sight and fore sight, they are written in the intermediate column and calculated in the same way. The steps are shown graphically in figure 21. In most long traverses the distance between stations is not so important as long as the well, drillhole, or final measured site can be plotted on a base map. If an accurate map is not available, a tape and compass traverse should be run for plotting purposes. The remarks column in your notebook should include a brief description of the features or points to be noted. These may include wells, swamps, buildings, fences, trees etc, that would be useful reference points on a base or final map.

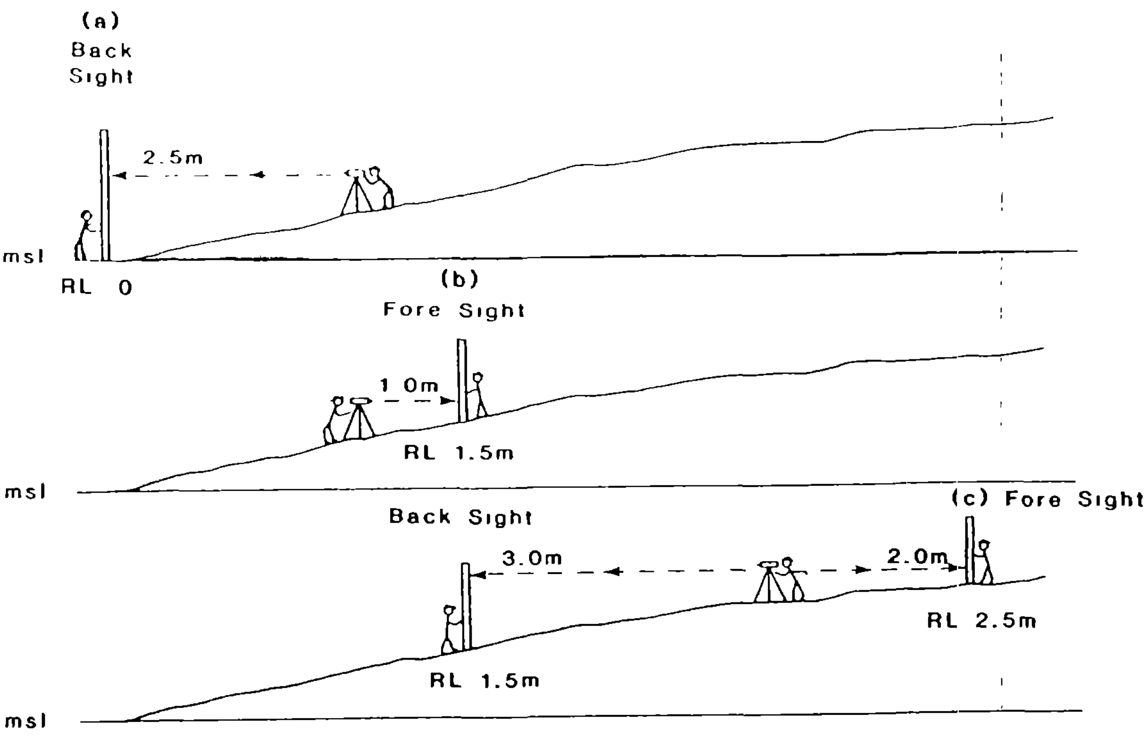


Figure 21 Running a Traverse

In determining whether the difference between back sight and fore sight (or intermediate sight) should be in the rise or fall column, it is useful to remember that when the back sight is greater than the fore sight (or intermediate sight) it is a rise. Conversely when the back site is smaller than the foresight (or intermediate sight) it is a fall A simple addition or subtraction from the preceding reduced level determines the ground height of the new staff point.

The whole process really entails leapfrogging along a line to a final destination, and back again to 'close' the traverse at the original starting point or to another known datum. To 'close' a traverse allows the surveyor to determine whether or not any errors have been made or whether a resurvey is necessary. When the traverse finishes at a previously unknown point relative to sea level, it is termed 'open ended', and any error that may have crept into the recordings would go undetected. It is also worth noting that both intermediate sights and foresights are either added or subtracted from the reduced level of the preceding backsight. Intermediate sights are really side shots and do not form part of the running traverse which should end with the foresight (Figure 22) An example from a levelling field book is shown in table 3.

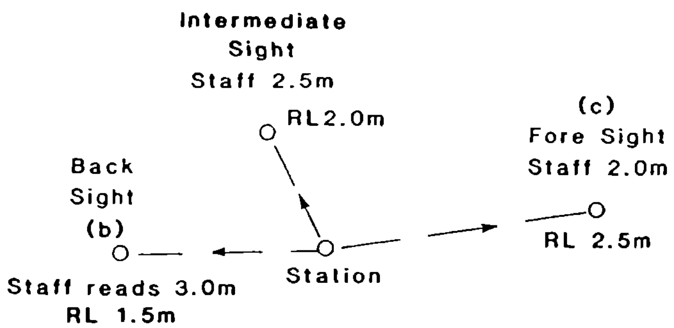


Figure 22 Plan view of traverse between two sites (b)&(c) with an intermediate sight.

SELECTING SITES AND HAND DRILLING

Site Selection

Elsewhere we have described the procedures to establish a resistivity layered model and so indicate where the freshwater lens is thickest. We have also established a datum. Now we are ready to drill our test bores as deep as possible Select an area in the deepest part of the lens where surface conditions allow you to set up your equipment. You'll need a reasonably flat site where the ground conditions suggest drilling might be easiest. You'll need to clear all the surface debris away and select a spot so that the outlet hose from your pump will lead well away from the drill site and no water will run back into the drillhole. It may be prudent to drill near a tree stump or palm log, which is suitable to stand on as a drilling platform a metre or so above the ground, or provide a portable platform.

Drilling

Drilling may be by hand augering or hand percussion (using a steel, sleeved, fence-post driver) to thump the drill into the ground or by vibrating with a hand-held, motorised, air-percussion drill. Selection of the correct hand equipment will depend on the ground conditions. If the water is expected to be close to the surface a pick and spade may be the quickest method If the ground conditions are thought to be dry and sandy or you're drilling into wet sand, a slotted waterpipe will be needed to prevent collapse of the hole (caving) If hard coral is encountered you may find it necessary to drill or break the coral ahead of the casing pipe with a hardened "steel" rod specially designed for the percussion drill. These systems are illustrated in figure 23

Because this rapid method of evaluating ground water will usually be carried out in a remote area we will not discuss the more sophisticated mechanical drilling rigs. These would of course be quite suitable The essential need is to provide a minimum 40 mm inside diameter sleeve down which various probes can be lowered. A list of equipment is included in Appendix 5.

Table 3 Part of field notes of a levelling traverse.

Item 1068

Back Sight	Inter-mediate	Fore Sight	Rise	Fall	Reduced Levels	Distance	Remarks
0.972					3.661		Bench mark Nº 10/2
	2.235			1.263	2.398		Top of drillhole casing
	2.887			1.915	1.746		Resistivity station 46
		3.585		2.613	1.048		
1.145							
		0.520	0.625		1.673		Resis stations 42 & 43
2.350							
		1.077	1.273		2.946		Resis station 41
1.875							
		2.656		0.780	2.166		Resis station 40
2.172							
		0.675	1.497		3.663		Resis station 39
2.170							
		1.000	1.170		4.833		Tomato patch
1.635							
	0.985		0.650		5.483		Resis station 38
		0.610	1.025		5.858		

Part of levelling traverse carried out in September, 1985, at the Totokoitu Research station, Rarotonga.

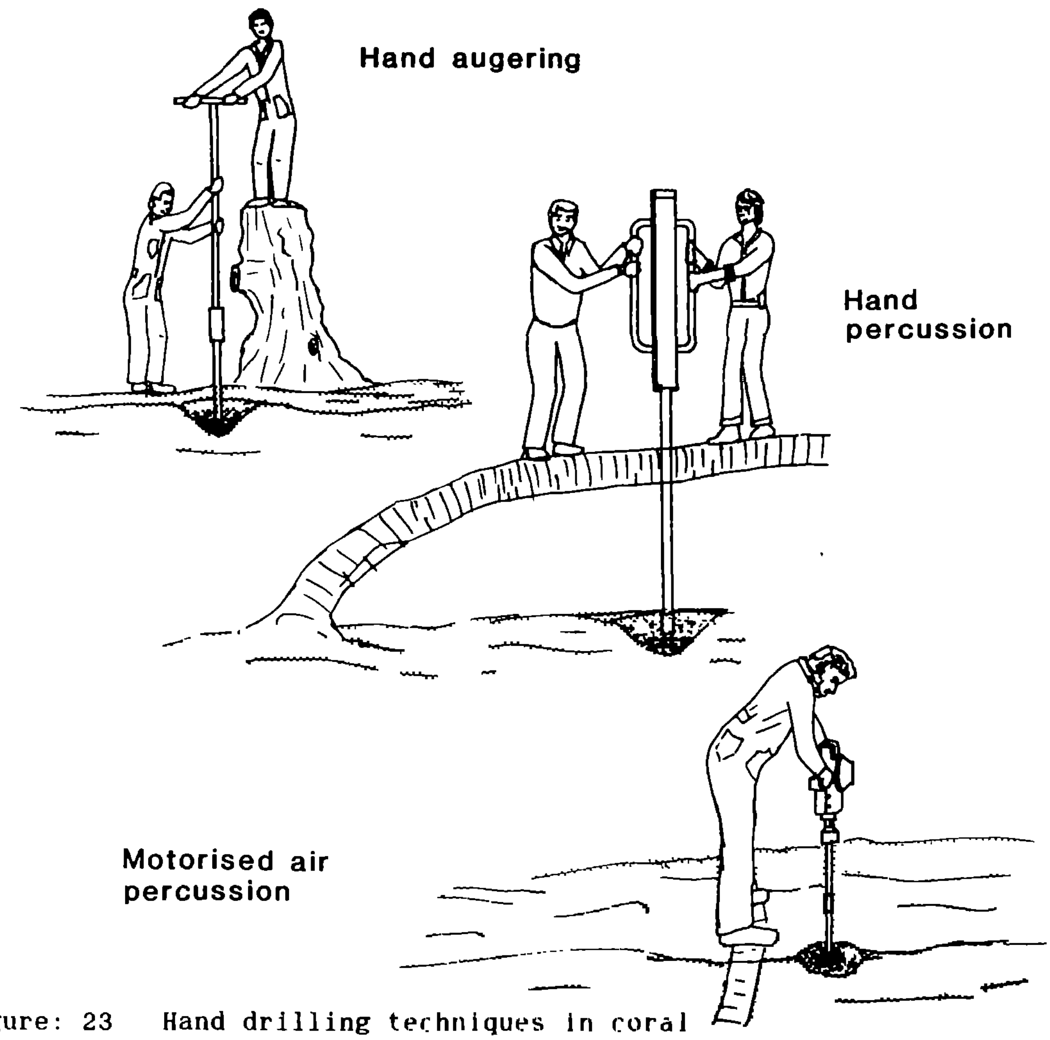


Figure: 23 Hand drilling techniques in coral

Data Recording: Drilling information you must record is -

1. A drill log indicating the strata intercepted (using metric depths) clearly written at the time in a field note book or drill log sheet

2. Rock and sand samples for grain size analysis and to assist with the reconstruction of the drill log as well as for comparison with other drill holes and for designing the screen to be used.

3. All physical changes encountered during drilling such as hardness, presence of hard-pan layers, depth to water level, temperature of the water (and air), and once you have entered water-saturated ground, the conductivities of the water profile as deep as possible (to check on the salinity with depth).

4 Water samples are also taken according to directions of the testing authority. (The NZ DSIR Water Laboratory (Chemistry Division) instructions are given in Appendix 3).

5. When the total drilling depth is completed, i.e. as deep as is practical into the aquifer, the height of the drill collar and ground level should be surveyed and its height above mean sea level noted. All downhole measurements will be based on this.

CONDUCTIVITY MEASUREMENTS

Portable, field conductivity meters, of which a number of makes are available, can be used to provide a quick on the spot guide to the salinity of the ground water. Two separate lengths of cable with attached probes are useful. A short length about 1 m long is useful for surface samples; the other of 10 m length is used for wells and shallow drillholes. The meter measures the Total Dissolved Solids (TDS) but usually common salt (sodium chloride) is the main contaminant.

Ensure measurements are carried out on undisturbed bodies of water or on water in drillholes that have been left (overnight) to stabilise. The conductivity probe should be lowered 0.1 m (10 cm) at a time so that a graph of the conductivity/salinity can be plotted against depth. If little variation is encountered, especially in thick aquifers then the measuring distance can be increased (doubled) until some change is recorded.

A "Synthetic Water Curve" can be plotted by comparing the conductivity expressed in micro-ohms per metre with total dissolved solids. The World Health Organisation recommends limits of between 500 g/m^3 (desirable) and 1500 g/m^3 optimum for total dissolved solids.

All water sources should be tested for conductivity as this data may help confirm the geophysical model. Special salt-resistant probes will be needed for measuring conductivities in lagoonal or estuarine areas where the salt concentrations are high. Freshwater probes do not give correct readings under these conditions.

WATER SAMPLING

It is very valuable to take a water sample for chemical analysis when any new underground source of freshwater is being examined. This will give a basis against which any changes may be compared. In general water held in limestone rocks will be fairly alkaline and although "hard" to lather with soap may be quite suitable for household purposes. It may cause white scaling in kettles or hot-water jugs because the lime (calcium) will separate out onto the inside surface when it is heated. The same thing will happen in steam-generating boilers so in these cases the water may require treating with chemicals to reduce scaling.

Samples may be drawn at the time of pump testing. Initially fine sediments in the borehole will be pumped out and after a while relatively clear water will accumulate about the drillhole. It may be useful to take two samples, one at the start and another towards the end of pump tests (especially where the water lens is thin) as the second sample may indicate any salt water intruding into the lens near the drillhole.

An efficient system of transport of water samples has been developed by Chemistry Division, DSIR, who have undertaken full analyses of the few samples we have submitted. Their system provides 3 plastic bottles. Two contain small traces of a chemical to prevent the growth of micro-organisms which would alter the levels of some analyses. The third sample is used to test for chemicals like metals which are not affected by biological changes.

If you need to sample the water lens down through a small diameter pipe (50 mm) the Petty sampler allows you to do this, and indeed to sample at a preselected depth. The equipment consists of a small plastic test tube with two thin plastic tubes inserted into the top. The tube is dropped into the well (using a lead sinker) to a predetermined level. It then fills and can be withdrawn when it is full. The water is transferred to the sample bottle and other samples taken further down the hole until the full depth has been sampled (Petty 1985).

Accompanying the sample bottles is a form which indicates the source and other details about the supply. A copy is returned to the laboratory for records and guidance of the analyst.

Although field tests for salt (chloride) may be carried out it would be preferable for those who might wish to learn these special techniques to undergo a specific course of training such as that provided for hospital laboratory technicians who undertake water analyses. Details of field chloride tests are given in Appendix 4.

PUMP TESTS

The prime object of the entire hydrogeological exercise is to determine the water resources potential in the area under investigation and to determine a pumping rate that will not exhaust the aquifer. In some instances yields will vary markedly, particularly in the volcanics which for example may produce as much as 200 million litres per day from skimming tunnels on Oahu Island, Hawaii, to a few thousand litres per day from drillholes in the Cook Islands.

To determine potential yields from wells or drillholes, pump test results are plotted graphically to show what the long-term effects of pumping at that rate are likely to be. In most cases they will be single-well tests, and although not entirely suitable for long-term predictions, they can be used as a guide to future performance.

It is thought that these simple pump tests have application throughout the Pacific and can be used to determine elementary aquifer characteristics locally, and for comparative purposes on an island to island basis (Waterhouse, 1984).

Test Procedure

On completion of levelling and drilling and/or digging a well, standing water levels are measured, relative to mean sea level, with an electric probe or string line before setting up the test pump and ancillary equipment. The pump discharge hose should be taken as far as is practicable 'downstream' in the direction of ground-water movement to minimise the chances of water gravitating back to the aquifer. The pump inlet should be placed no lower than mean sea level, although the hole may be deeper than this.

The type of test will depend on the amount of water that can be pumped, and whether the aquifer can sustain a steady yield indefinitely. The test period will vary from perhaps 2 to 24 hours, but clearly the longer the better to allow the overprint of the tide effect to be seen on the drawdown curve.

Two types of test that might be undertaken on small islands are:

1. Constant Discharge Test.

2. Constant Drawdown Test.

1. Constant Discharge Test

As the name implies this test involves pumping the bore at a constant discharge rate and measuring the variations of drawdown throughout the test. Drawdown is the fall of the standing water level as the pumping proceeds.

Holding the discharge constant, drawdown measurements are taken at frequent intervals during the test. The following times are recommended once pumping starts; 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, 30, 45, 60, 75, 90, 100, 120 minutes. After these two hours, measure the drawdown each half-hour to six hours and then hourly until the end of the test, for say 24 hours or longer.

The rate of discharge measurements are taken at least at the start of the test, after 15 minutes, then 30 minutes and every half-hour thereafter, but at more frequent intervals if possible. However, care should be taken to maintain the discharge rate constant throughout the test by regular inspections of the tube on the orifice meter, the orifice bucket or by timing the filling of a container of known volume, whichever method is being used.

1a. Constant Discharge Residual Drawdown Measurements

At the end of the constant discharge test, residual drawdown (recovery) measurements are taken. These measure the rate at which the level of water rises in the hole without pumping. If possible, heights should be taken at the same times after pumping ceases as in the constant discharge test. After two hours, hourly records should be taken until the water level has fully recovered or is within 15 centimetres of the standing water level. If for any reason a reading at any of the above times is missed, then take a reading as soon as possible thereafter and note the actual time of this reading. It is more important to know the time when the drawdown was measured, so it can be plotted, than to have the drawdown measured at the exact times indicated (Morton and Hazel, 1979).

2. Constant Drawdown Test

In this type of test the drawdown is held at a constant depth and variations in discharge are measured. This type of test may be required when it is not otherwise possible to measure drawdown.

The drawdown is held constant by making sure that the pump breaks suction soon after the test begins and the water level is maintained by adjusting pump suction throughout the test. Breaking suction is clearly heard when the water level in the well drops to the same level as the pump intake.

Because of the air/water mixture for this type of test an orifice meter cannot be used with any reasonable accuracy for the measurements of discharge and it is preferable to use a container of known volume or, if one is available, an orifice bucket

If a container of known volume is used to measure the discharge rate, then measurements should be taken as soon as the pump test breaks suction, then at 5, 15, 30, 45, 60 minutes and every half-hour during the remainder of the test The size of container should be suited to the likely discharge, since it is important to complete the measurement in as short a time as accuracy permits, e.g. a 500 litre tank is unsuitable for a discharge of 5 cubic metres per day - a 1 litre container would be a better choice.

As the duration of the measurements may have a bearing on the plotting and analysis of the test, the actual time at which the measurements were commenced should be recorded.

MEASURING WATER LEVELS

Equipment

Using two, automatic, water-level recorders is preferable; one of which should be used for recording tidal fluctuations. Numerous types of manual water-level probes are available ranging from the basic "plopper", (a weight on a string), to meter-connected downhole electrodes. A conductivity meter and probe can double as a manual water-level measurer.

Siting

As many recording sites as practicable should be used so as to provide a reasonable coverage of readings over the island. In reality, however, the number of sites may be less than that which provide total coverage, and could even be down to only one at the main site on the thickest part of the lens, as determined by resistivity. One site should have an automatic recorder set up on it and if possible two other sites should be regularly monitored. Ideally these would be along a line bisecting the island from the lagoon to the ocean with the main central site being on this line.

Any existing wells, swamps, drillholes or pools should be measured regularly especially if not being disturbed by abstraction (pumping or bailing)

Techniques

We would recommend taking manual measurements of the water table and noting the times on the automatic, water-level recorder chart at regular intervals, if possible, as a check when interpreting the data later on.

For manual recordings accuracy based on a stable, and always the same, measuring point is essential. Regular times for readings i.e. hourly should be maintained throughout the length of the study time and the results plotted on graph paper.

Results

The graphed results can be compared with other graphs of rainfall, tides and barometric pressures to find out what effects these factors have on the water table.

Vertical profiles or cross sections of the island and iso-contours of the standing water level can be drawn which will show the areas where the freshwater lens is thickest. A list of field equipment required for an hydrogeological programme is provided in Appendix 5.

Part III

CRITICAL EVALUATION OF FIELD RESULTS

A FIVE-STEP REVIEW

This is the synthesis phase in which we bring together the results of our detailed measurements in the field. From these we hope to decide if the lens has a potential to supply potable water and to calculate a safe pumping rate, keeping in mind possible rainfall recharge.

We use a system of cross checking; using one method or approach to confirm the results of another. This follows the initial 5 steps which we used in the field (Part II) and here we will discuss the calculations and results rather than the methods which were described in that part. Where appropriate we have explained the terms used. The steps were:

1. Making resistivity soundings leading to a layered hydrological model.

2. Establishing a height datum for mean sea level.

3. Drilling to confirm the prediction of the resistivity survey.

4. Conductivity testing to determine the quality of any freshwater (and taking supplementary samples for analyses).

5. Pump testing to calculate drawdown and transmissivity and so demonstrate the ability of the aquifer to sustain pumping.

To illustrate these steps we will use a study on Akaiami Motu, an atoll off-shore from Aikutaki, in the Cook Islands. This motu is broadly crescent shaped about 1 km long by 200-500 m wide and generally rising up to 2.5 m above sea level. It is covered with a mixed vegetation of coconut palms and scrub species and is composed of coral blocks and sand built up by storms. There is no soil but a thin layer of rotting vegetation covers most of the motu.

This motu is about the smallest-sized unit of land under the rainfall regime (1800-2000 mm rain, with a 6-months dry period) which could sustain even a thin freshwater lens. It is also about the lower limit of detection and evaluation of a freshwater lens by our methods. Approximately 6 days were spent on the motu and this required us to travel to and from the island each day by boat. The fieldwork took place in September, 1985.

Step 1. Resistivity soundings were made at 14 sites as shown in figure 24. A layered model for line 1 was constructed and interpreted as in figure 25.

The map shows the drillholes (D_1 and D_2) and the jetty where we established msl. A well and a pig wallow were the only other hydrological features. (A sow, 6 piglets and a few wild domestic fowls were seen on the motu.)

The general resistivity interpretation showed that the freshwater lens, though thin, was thickest at the northern end of the island and thinned out to the south. (The wallow was later shown to be brackish so that no layer of freshwater was present there). Our activities were therefore largely confined to the northern traverse (resistivity sites 1-5 and 14). Site D_1 was chosen for the drill hole. Further details are given in Appendix 6 resulting from recent research which supports the interpretations of figure 25.

Step 2. Using a tide gauge, mean sea level was established on a metal post on the jetty between sites 6 and 12. From there, relative heights were established at all resistivity sites and at the drillhole collar. The relative heights of water in the pig wallow and the well were used to further confirm the resistivity model. This model predicted freshwater at about 2 m depth below ground level at point D_1 and at shallower depths in the second and third traverses.

Step 3. Two 50 mm drillholes (D_1 and D_2) were driven close together to a depth of 0.185 m below our calculated mean sea level. The drillhole reached a total depth of 2.355 m below ground level. Water was present in the lower 0.32 m (32 cm) confirming the resistivity estimate. (See later under pump testing step 5). For the purpose of pump testing the drillholes were driven approximately 30 cm apart. One hole was used for pumping, the other left undisturbed for measuring purposes but were together considered to be the drillhole.

Step 4. An electrical conductivity probe in the ground water confirmed that it was indeed freshwater. Figure 26 shows the plot of conductivity convertible to salinity) against depth in drillhole D. The profile indicated acceptable salinity levels. Similar conductivity measurements in the well showed just acceptable salinity levels in the shallower depth of freshwater (29 cm) in the well near site 12. Only brackish water (over 1000 µS/cm)[1] was measured in the surface layer in the pig wallow. These alternative independent assessments further confirm the resistivity model of a freshwater layer thinning out from the north to south (and from the centre towards the coast).

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[1] µS/cm = micro Siemens per centimetre - the unit of measurement of conductivity.

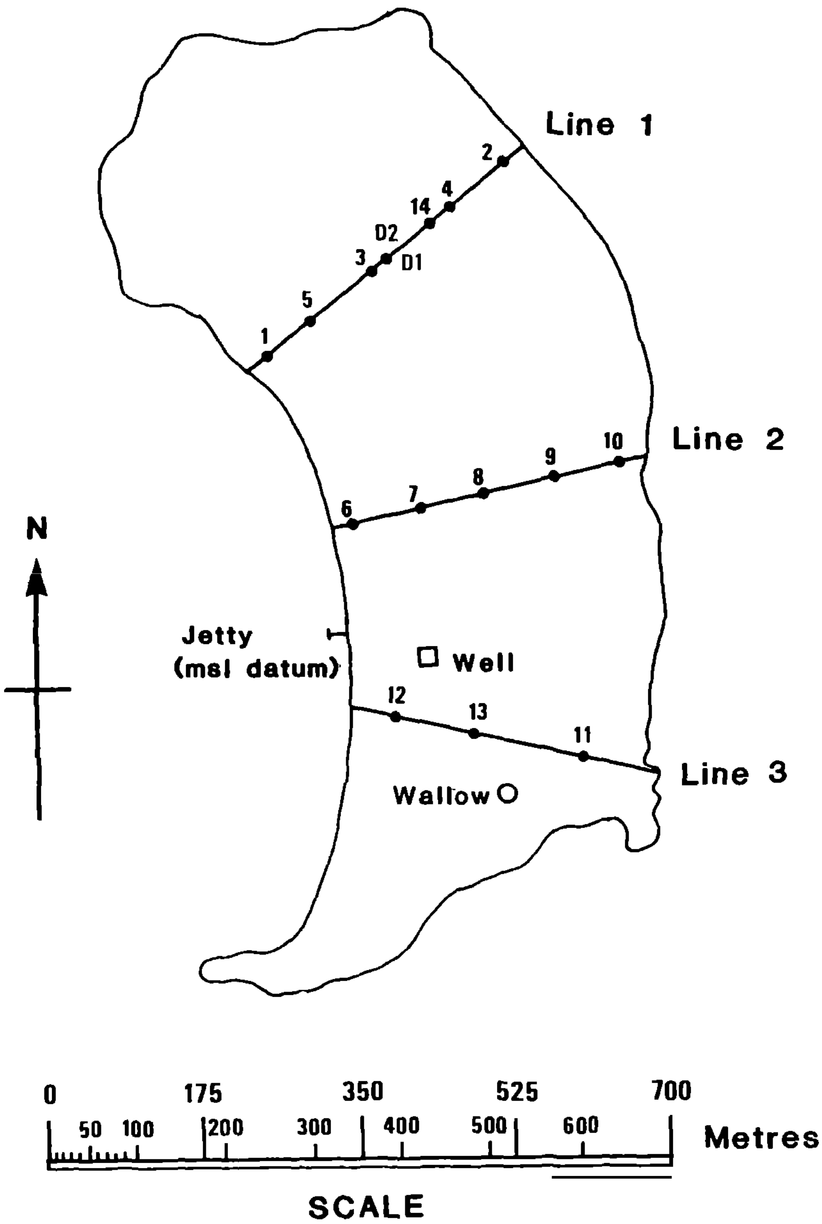


Figure 24 Map of Akaiami motu with sites of resistivity soundings and drillhole.

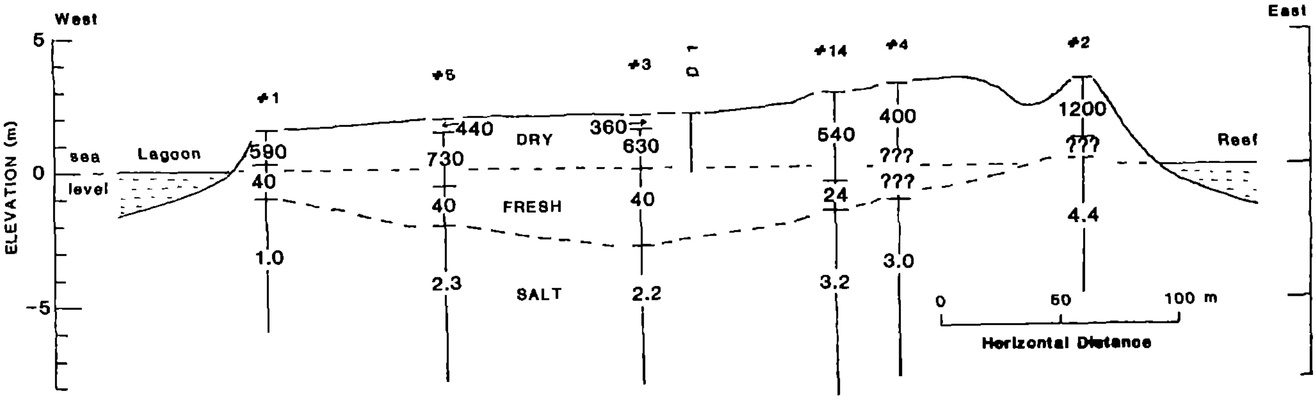


Figure 25: Interpretive cross section of apparent resistivity soundings and drillhole, Akaiami motu, September 1985. (Resistivity values in Ωm).

Notes 1. The freshwater layer was only just detectable across most of the motu. It is difficult to assign an accurate apparent resistivity or thickness to layers under these conditions. Values could be in error by up to 50%. The value of 40 Ωm represents a compromise between the values of the fresh and mixed (brackish) water of the lens as drawn.

2. The presence of the piled-up coral blocks, and the underlying reef flat, at sites 2 and 4 contributed to irregular sounding curves so little value can be placed on the presence of freshwater on the eastern side. Salt water was detected at a shallow depth and the resistivity of the salt water increased eastward (away from the lagoon). Values 1 - 4.4 Ωm.

3. The inferred water table at sites 5 and 14 appears too deep (below sea level) and this could be due to tidal influence (lag) at the time of measurement.

4. The general interpretation is one of a surface layer of one to 2½ metres of dry sand or coral rock, with moist sand below; a freshwater layer (resistivity 40 Ωm) at or about mean sea level down to about 2 m below msl at the deepest point (site 3). The shape of the lens is slightly asymmetric towards the lagoon with some freshwater apparently seeping into the lagoon.

A sample of the undisturbed water lens was taken for full chemical analysis from drillhole D. (A second sample was taken after pump tests to check on any changes due to pumping - such as drawing up salt water from below).

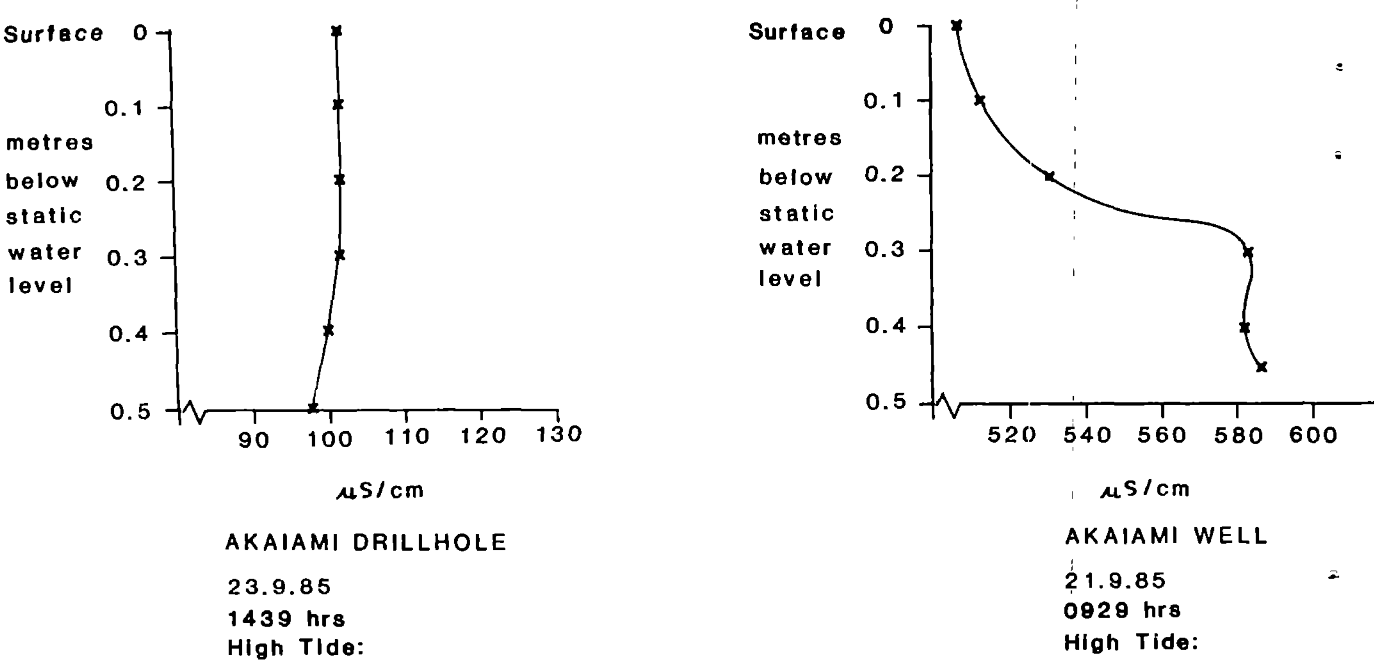


Figure 26: Conductivity profiles in drillhole and well, Akaiami motu, September 1985

Step 5. Pump tests at constant discharge provided drawdown and recovery data for the drillhole and the surrounding rock strata. Data were used to evaluate a sustained continuous flow of freshwater. Details of carrying out pumping tests were included in Part II. Here we explain the results for the Akaiami drillhole and interpret their meaning.

As water is pumped from a well the water level in the well will tend to fall - slowly at first - then later at a fairly constant rate if the pump is itself kept at a constant discharge. This fall in the water level is called drawdown, but as water is pumped from the well it is replaced by water from the surrounding "rocks." In the case of Akaiami the motu was built up by the sea, particularly during storms which have thrown up coral debris of all sizes from large blocks to very fine sands. The sands tend to fill some of the pores between the blocks. In parts the coral debris has become cemented together to form large masses. However, there are many continuous open channels between the blocks and approximately 30% of the volume is open space.

Using a constant rate of pumping the drawdown can be measured and plotted against time (or more correctly the logarithm of time using log graph paper). This gave us the graph in figure 27.

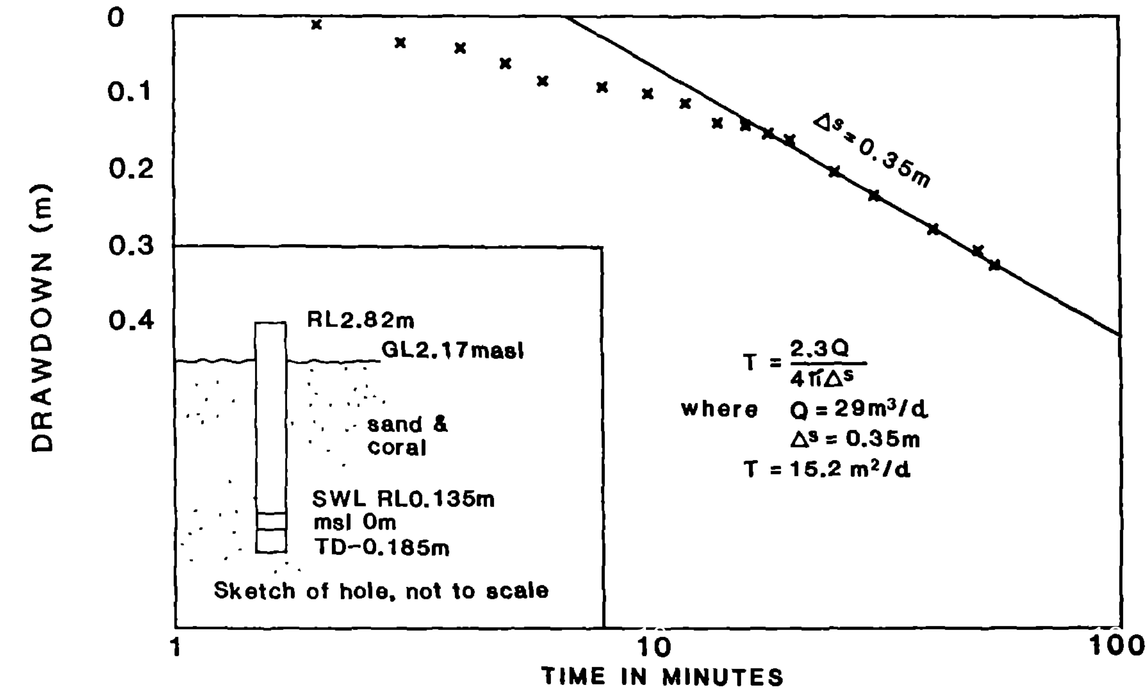


Figure 27: Constant discharge test Akaiami motu, September, 1985.

Once the fall (drawdown) becomes steady the rate of fall (Δs) over one log cycle (i.e. from 10 to 100 minutes) can be calculated. [In this case Δs = 0.35 m i.e. the drawdown height at 100 minutes less that at 10 minutes or 0.415 - 0.065 = 0.35 m. See figure 27].

To determine transmissivity, which is the rate at which the water flows into the hole to replace that pumped out, the formula is T (transmissivity) = $\frac{2.3Q}{4\Pi\Delta s}$, where Q is the quantity of water pumped in a day (which we measured at 29 m³/day), the constant 2.3 is used to convert to the logarithm of time, and 4Π refers to the area involved.

(You will note that transmissivity was formerly expressed in gallons, per foot of drawdown, per day. Using metric measure we divide the volume Q (in cubic metres = m³) by drawdown in metres, so that transmissivity is expressed in m² per day). If we substitute our figures for Akaiami in the formula we get the daily transmissivity as

$$T = \frac{2.3Q}{4\Pi\Delta s} = \frac{2.3 \times 29\ m^3}{4 \times \frac{22}{7} \times 0.35\ m} = 15.2\ m^2/day$$

You will also note from the inset that the reconstruction diagram gives an idea of the relative heights of the ground level, the static (standing) water level, the mean sea level and the total depth (bottom of the hole). The top of the drill pipe was measured at 2.82 m above mean sea level.

A transmissivity of around 15 m^2/day is high. For comparison basalt rock in the Cook Islands is usually only capable of about 1/3 of this transmissivity indicating the very open nature of coral limestone debris. However, other basalts elsewhere can have quite high transmissivities.

If we also measure the rate at which the water level in the drillhole recovers without pumping we have a second estimate of drawdown. This is called the residual drawdown and figure 28 shows the results for our drillhole D. These data were obtained immediately after pumping ceased.

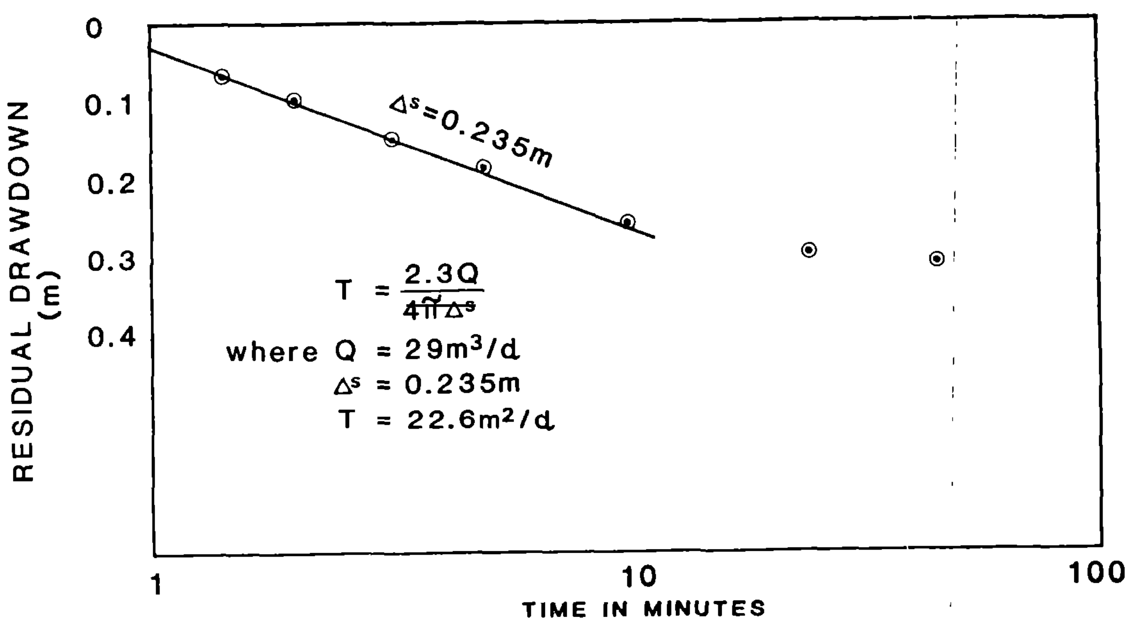


Figure 28: Residual drawdown test, Akaiami motu, September, 1985

We use the same formula and assume that the same volume Q = 29 m^3/d, which had been pumped out, will flow back into the drillhole at the same constant rate. (This makes assumptions which may not be justified for this site and so lead to errors in calculating transmissivity.) In this case we use the first log cycle of data as this tends to have a more constant flow rate. (The return drawdown rate tends to slow down as the hole becomes nearly full of water; in addition the height of the freshwater takes some time to regain the original level (static water level) which was measured on the undisturbed aquifer before pumping.

Measuring Δs over the first log cycle in figure 28 gave a value of Δs = 0 235 m. Substituting this new value in the formula we get

$$T = \frac{2.3 \times 29 \text{ m}^3}{4 \times \frac{22}{7} \times 0.235 \text{ m}} / \text{day} = 22.6 \text{ m}^2/\text{day}$$

Clearly this is quite a lot higher than the 15.2 m^2/day determined in the constant discharge test but can be partly explained by the fact that during the discharge test a large volume of fine sand was pumped away from the area of the bottom of the drillhole. This allowed water to move very freely into the area being pumped. Of course the lens is very thin and the problem of recording the water levels with sufficient precision all contribute to the difficulties encountered.

Because coral atolls have these high transmissivities, freshwater can be too easily pumped out to be readily replaced by seawater. This has happened in some places in the Pacific and the problem is made worse because septic sewage can just as easily flow through the aquifer contaminating it.

It should be made clear at this point that the single rapid pump test we carried out has a number of limitations. In order to penetrate to the water table we drove a steel pipe with a special hardened tip down through the surface layers. The pipe had a number of holes drilled in the lower 20 cm to allow water to enter the pipe. This was not an appropriately designed screen such as water engineers would use to prevent fine sands being drawn into the pipe and pump. The limited number of holes, as distinct from a steel mesh, naturally restricted the flow of water into the pipe so we may well have underestimated the transmissivity of the aquifer and the rate at which water may be pumped out. Pump tests on open wells will give the best indication. The calculations from the pump tests are therefore only an initial guide of what will need to be measured more fully later on. We have, however, confirmed that there is a freshwater lens and water can be easily abstracted. This is not the same as identifying the best pumping rates.

In practice we cannot yet do this from our Akaiami results. Our pump tests extracted only 30 ℓ/day and at that low volume the drillhole was dewatered in just a few minutes. This type of vertical drillhole well is probably not appropriate for a thin lens where shallow trough-like collecting areas are more appropriate. Here the lens is thin and could only supplement a roof catchment supply for say one dwelling or provide an emergency supply for anyone isolated on the motu.

We would need to turn to a much larger land area to develop a commercial type of piped water supply which might provide say 60 ℓ per person per day (Dale, 1984a). (WHO recommend a daily minimum of 70 ℓ per day.)

An example of a pump test from another island on the Cook Group is provided to illustrate how single pump tests are used to determine a proposed yield. It is important to note here that although considerable study has been made on pump test data they remain a somewhat academic calculation and must be supported by regular monitoring data from unpumped observation wells. This requires monthly measurements of height of the freshwater level and conductivity tests on these observation wells.

DETERMINING QUANTITY AND QUALITY OF GROUND WATER

Quantity

Because the very shallow Akaiami drillhole has been shown to be unsuitable for regular pumping we have provided another example of appropriate pump test calculations for determining water quantity. This is the Kaauvo No. 1 drillhole on Mangaia, Cook Islands, a basalt aquifer with different hydraulic conditions from a coral atoll. The principles, however, are the same. Table 4 provided the information from the field notebook entries for the 43 hour test. The drill hole was 100m deep and had a collar height of 87.3 m above msl. Freshwater was encountered at 17.35 m down and the pump intake set at 61 3 m deep

Table 4 Constant Drawdown Test, Kaauvo No. 1, August 1979.

Time (hrs)	Time since pump started (mins)	Time to fill 9l container (secs)	Yield (l/hr)	Remarks
				14 8 79
1440	0			start, water clear
	1			water discoloured
	4			" dirty
	17	11	2927	
1512	32	11		
	39	13		
1556	76	14	2330	breaks suction
1610	90	14		
	95	14		
	97	14		
	101	14	2330	
	107	14		
	120	16	2043	
	130	16		
1700	140	16		clean water
	158	14	2330	
1809	209	13	2510	
2000	320	20	1630	
2100	380	18	1810	
2200	440	17	1920	
2300	500	20	1630	
2400	560	19	1720	
0030	590	19		15 8 79
0100	620	19		dirty water
0200	680	19		
0300	740	19		clean water
0400	800	19 5	1680	
0500	860	19	1450	dirty water
	892	19		
0600	920	21	1560	
	962	19		
0700	980	20	1630	clean water
0800	1040	20		
0900	1100	20		
1000	1160	20		
1100	1220	20		
1400	1400	20		
	1440	20		
1500	1460	19 5	1680	
1600	1520	20	1630	
	1546	20		
1700	1580	20		
0833	2533	21	1560	16 8 79

Figure 29 sets out the plot of the drawdown data based on the data in table 4.

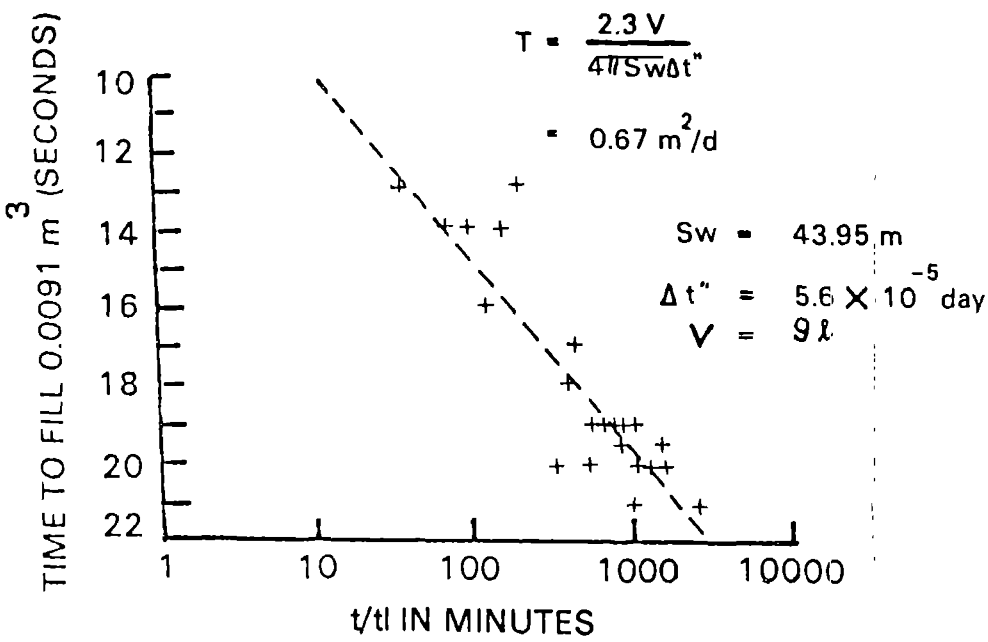


Figure 29 Plot of constant drawdown test, Kaauvo No. 1, August 1979.

This figure indicates the low transmissivity (T) of 0.67 m^2/day and a drawdown (Sw) of almost 44 m (i.e. lowered from 17.35 m to 61.3 m down the hole) The slope of the graph over one log cycle Δt" was 5.6 x 10^{-5} days. As table 4 indicates the pump broke suction at 76 minutes so the hole was no longer suitable for a constant discharge test and it was switched to a constant drawdown test.

Over the 43 hours of the test the hole yielded an average of 1940 ℓ per hour of water at the pump depth of 61.3 m below the drill collar. The reader will note the fairly constant yield after about 9 hours pumping implying that the hydraulic conditions had more or less stabilised (each 9 ℓ container took 19-20 seconds to fill). This implies that water was being supplied to the pump intake at about the same rate as it was withdrawn. Initial fluctuations may have been caused by differences in permeability of the rock, dewatering of some pockets, the presence of (temporary) hydraulic barriers or from recharge due to rain which fell much of the time. Experience suggested that lowering the pump intake by 26 m to 87 m below ground level (at or about mean sea level) and reducing the yield to 1600 ℓ/hour would provide a sustained yield without salt-water intrusion. In the case of this drillhole subsequent use has confirmed these recommendations.

Quality

Quality is measured in both chemical and bacteriological terms. We have already discussed the main chemical constituents - salt and lime. Some useful simple measurements can be done when the well is being evaluated by pump tests. At this time we can see if, for instance, the salt levels change. For most uses we have to accept the calcium (lime) content and that is something Pacific people have long accepted although treatment may be needed for use in industrial boilers and such ground water is definitely not suitable for storage batteries. Chemical and physical quality limits for the major substances are given in appendix 7.

Chemical

The chemical quality of fresh ground water in the Pacific was surveyed by Brodie and others (1983). The relationship between the World Health Organisation (WHO) recommendations and actual results from a number of samples was discussed by Dale and Waterhouse (1985). Table 5 sets out the range of WHO recommendations and the analyses for a few elements for samples taken before and after pumping from the Akaiami drillhole Full analytical data are given in Appendix 8.

Table 5: Comparison of WHO recommendations and Akaiami analyses, 1985. (Except pH, all in $g/m^3 \equiv ppm$; LT = less than.)

		WHO levels		Akaiami 1	Akaiami 1
Chemical	Symbol	Highest Desirable	Maximum Permissible	Before Pumping	After Pumping
-	pH	7.0-8.5	6.5-9.2	7.5	7.5
Calcium	Ca	75	200	150	138
Magnesium	Mg	50	150	20	20
Chloride	Cl	200	600	110	110
Sulphate	SO_4	200	400	22	21
Total Hardness	as $CaCo_3$	100	500	457	426
Manganese	Mn	0.05	0.5	0.005	0.005
Iron	Fe	0 1	1.0	0.31	0.46
Copper	Cu	0.05	1.5	LT 0.01	LT 0.01
Zinc	Zn	5.0	15.0	0.25	0.14

Some of these results confirm the data from the conductivity meter readings (100 μ S/m) which equate to about 100 g/m^3 of chloride. In general the water meets the WHO standards. Calcium (lime), chloride (salt) and the hardness figures, though high as expected, are not unduly so.

There is no evidence of elevated levels of metals (copper, iron, zinc, manganese or magnesium) and sulphur levels are also low. Because of the proximity to the sea some salt (sodium chloride) contamination would be expected. The elevated calcium levels are due to the coral limestone (calcium carbonate) aquifer.

Reference to details in Appendix 8 also indicates low levels of ammoniacal and nitrate nitrogen showing that although a few pigs and poultry are present on the island their excreta appear not to have contaminated the groundwater at the point of abstraction.

As an untapped and apparently uncontaminated ground-water source these samples serve as useful examples of motu water in the Pacific. Analyses were undertaken by the Water Laboratory, Chemistry Division, DSIR, Christchurch

Biological

Bacteriological quality is extremely important because there are a number of serious human diseases which are spread by water. Brodie and others (1984), listed 25 individual or groups of water-borne organisms. Typhoid, Cholera and Salmonella are some of the more common tropical disease organisms carried by water which infect pigs and humans and can contaminate seafood. Human and animal waste which wash into the ground water carries bacteria, viruses and other disease organisms. Bacteriologists use one particular bacteria (Escherichia coli - the coliform bacteria) as a useful indicator of the presence of human and animal wastes as they are normally present in the alimentary canal. It is ideal then to have a portable microbiological kit (and someone competent to use it and interpret the results) for your field visit Dr J E Brodie, Institute of Natural Resources, University of the South Pacific has developed such a set of equipment. It is essential to conduct some bacteriological tests immediately the sample is taken as some results will not be reliable if there is any delay. Bacteria just keep on multiplying unless refrigerated and of course a preservative destroys the organisms you might wish to identify.

Our small expedition to Akaiami was not equipped with a bacteriological test kit so we cannot report on the presence of any harmful organisms. We did, however, report the presence of pigs roaming the motu so contamination must remain a possibility. Because the motu is visited by a number of tourist and local family fishing parties who occasionally disappear "into the bush" further contamination is likely. Until adequate bacteriological assessment of a new water supply has been made it must always be suspect.

EVALUATING RECHARGE AND SAFE YIELDS

Water Balance

In our introduction on the hydrological cycle of a coral island we showed that the presence of ground water depended on rainfall. Recharge of ground water by rainfall, however, is not easily measured and is usually determined by calculation. This is done by subtracting all the other measured or derived effects from the rainfall figure and assuming that what is left is recharge. There are various mathematical expressions used to account for the "income and expenditure" sides of the water balance equation. The simplified version already used is

$$P \text{ (precipitation)} = E_i + R_f + E_s + R_c$$

where E_i = interception and re-evaporation by vegetation
R_f = surface run off, including streams and seepages
E_s = evapotranspiration by vegetation, soil and water surfaces
leaving R_c = recharge water entering the ground water.

This expression, and the others which are more complex, may be suitable for the situations for which they were derived but they are unsuitable for coral islands and especially atolls.

Interception

There are a limited number of studies which apply to the tropics and these do not generally identify the type(s) of vegetation involved. West and Arnold (1976) adopted 15% of total precipitation for Male (Maldives) while Lloyd and co-workers (1980) used half this value (7.5% of total rainfall). Grimmelman (1984) applied a value of 6% for Palau (N Pacific) but for Peleliu he used 20% of rainfall for his interception figure. He then determined that only 25% of recharge was recoverable. Thus his actual recharge was 25% of 20% of rainfall = 5% (similar to his 6% for Palau). Jacobson and Taylor (1981) used a recharge value of 25% of annual rainfall for their studies on Tarawa while Hunt and Peterson (1980) in a year-long study on Kwajalein (Marshall Islands) calculated that around 50% of rainfall on the sealed airstrips entered the ground water. Each of these studies were conducted in different climatic areas of the tropics so that no appropriate value for interception and re-evaporated rainfall can be applied to the Cook Islands.

Surface Run Off

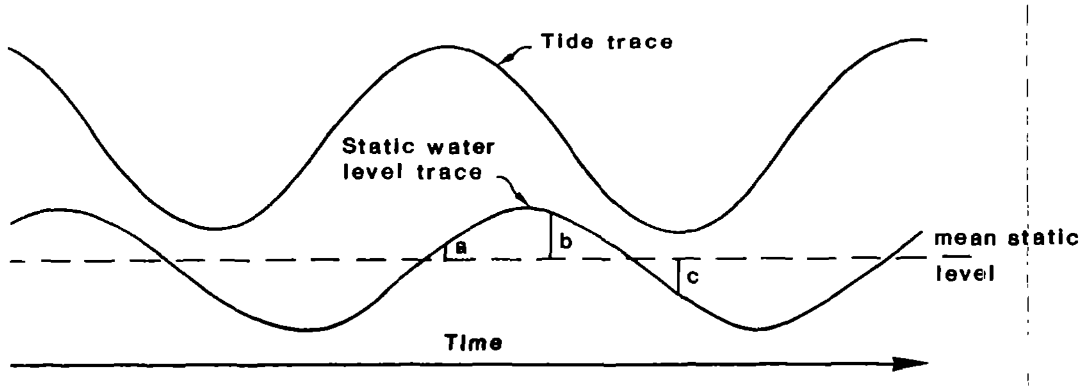
In practice this is zero. Surface run off does not occur on the coral atolls of the Pacific except on the exposed reef flat, where this is present, or on areas of beach sand usually on the lagoon side. In neither case can the freshwater enter the ground water as these areas are outside the ground-water catchment area.

Evapotranspiration

This is usually calculated by the Penman or Thornethwaite methods both of which were developed in the sub-tropics for short uniform grassland and assumed the evaporating surface was horizontal. Some meteorological stations measure the evaporation of water from open tanks to calculate evaporation (related to temperature and wind strength) The calculated methods use a soil moisture value as part of the calculation and since soil is usually absent on most atolls this value cannot be determined. Using the Penman method, Thompson (1986) calculated an evapotranspiration deficit for every month of the year for Aitutaki.

Recharge

Although some authors like Fox and Ruston (1976), have discussed the problem we were unable to calculate the recharge to coral island ground-water systems in the Pacific in the absence of reliable data for the "expenditure" side of the equation. It is clear, however, that if more freshwater is removed from the lens than is replaced by rainfall recharge the lens will become exhausted or contaminated with sea water. The only safe procedure is to monitor the levels in all wells and check for increased salinity Remember that the lens is a dynamic system constantly moving up and down with the tides but somewhat delayed in its response as shown in Figure 30. This pumping action probably results in an overflow of seepage water at each high (spring) tide Estimating this loss to the system would be a long-term project.



Examples of corrections.

At full tide reduce static level by height represented by a.
At half tide ebb reduce static level by height represented by b.
At low-water increase static level by height represented by c.

Figure 30: Illustrations of tidal corrections to static water level.

It appears from studies by Ayers and Vacher (1986), that in an unpumped aquifer the freshwater will tend to flow outward in all directions unless there is a confining barrier such as the reef platform on Deke Islands (Eastern Caroline Islands) and on Akaiami (Aitutaki).

Rainfall Pattern

If recharge is dependent on rainfall then an understanding of the long-term rainfall pattern is necessary so we can judge the best time to pump and when to reduce the pumping rate to match rainfall recharge. Waterhouse and Petty (1986) provided mean monthly rainfall patterns for the Southern Cook Islands. The pattern for Aitutaki is reproduced in figure 31.

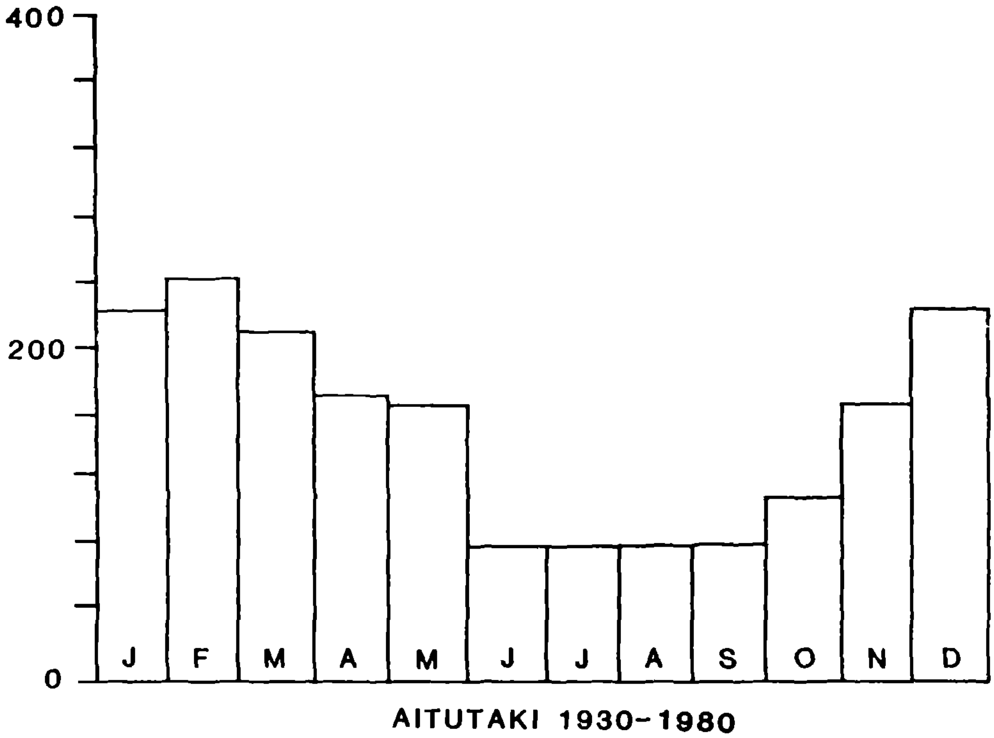


Figure 31 Pattern of mean monthly rainfall values (mm).

Thompson (1986) provided detailed monthly rainfall data for Aitutaki as presented in Table 6.

Table 6: Monthly rainfall data (mm) - Aitutaki, Cook Islands 1930-82.

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Monthly	221	244	212	178	164	86	82	84	85	116	174	234	1880
Highest	715	649	521	513	495	268	383	288	259	492	645	789	3093
Lowest	20	22	27	17	2	5	7	10	1	8	18	4	731
Coef.Var.	60	48	56	63	70	77	80	85	72	81	71	66	25

These figures indicate high variability (as illustrated by December with a maximum of 789 and a minimum of 4 mm of rain) and clearly show a six-month dry period from May through October with monthly averages all less than 165 mm. During drought conditions the lowest recorded monthly averages of less than 10 mm of rain, are likely to fall during this period.

Nearby Akaiami will also receive a similar rainfall. Assuming the worst situation (the lowest average monthly rainfall) it would appear that the main recharge of the ground water from rainfall will take place in the first three months of the wet season, November to January. Provided abstraction is less than recharge any surplus could be pumped to storage if tank space is available or it will simply overflow to the sea.

Are we any closer to estimating recharge? - no, not yet, but we should attempt to get the necessary data or replenishment of ground-water resources will remain a mystery.

SAFE YIELDS

Until more basic studies have been undertaken it is not yet possible to recommend safe yields from the cursory study available under the rapid evaluation method. More detailed studies should be carried out once this early information has been provided to hydrologists or water engineers We can, however, summarise the purposes of undertaking pump tests

Pump Rates

By running the pump at a constant rate for a known time we can calculate the volume of water pumped in 1 hour or 1 day or 1 week. All this tells us about the aquifer is that the pump is working and that there is water in the borehole.

Drawdown

By measuring the height of the water level before and during a Constant Discharge Test we can observe whether or not the flow of water in the aquifer can keep pace with the pumping rate. On Akaiami it did not and the hole was dewatered.

In some cases a Constant Drawdown Test may be more appropriate (see Pump Tests) A negligible drawdown would indicate the aquifer has the capacity to supply the pump with water over a long period (say 48 or even 72 hours)

Transmissivity

This calculation is based on the volume of water pumped over time and the rate of drawdown. High transmissivities mean the rocks have an "open" structure allowing water to flow freely to replace water pumped out of the drillhole. High values in the 12-18 m^2/day range are common for coral debris

Low transmissivities mean the aquifer is "tight" and the movement of water is slow and restricted It doesn't mean, however, that transmissivities in a lower range cannot provide sufficient water to replace that pumped. Transmissivities only tell us something about the aquifer's ability to supply water to the drillhole but little about how rainfall gets into the ground water.

All 3 data sets, pump rates, drawdown and transmissivity, provide data about the aquifer in its state at the time the tests were carried out They need to be related to the state of the tide, climatic conditions, the nature of the "rock and ground (soil?)" and the size of the aquifer, especially the height of the static water level above mean sea level

On their own these 3 data sets are a useful guide but don't tell us anything about safe pumping rates. To calculate these we need to know something about recharge so that the stability of the lens is not impaired. Only more detailed pump tests and appropriate monitoring of both water level heights and salinity on a continuing basis can provide this vital information.

FIELD STUDY FOLLOW UP

These notes have assumed that someone with appropriate expertise from outside the country has assisted in the technical development and interpretation of the survey. After the results have been evaluated someone has to follow up and either develop a water use programme or see that the recommendations of the survey are actioned

First, however, the proposed actions should fit in with the overall written water plan for the area, or if none exists, a written plan must be developed.

Next the appropriate support should be gained from the various authorities so the action can proceed

Then financial and technical resources need to be identified and a time scale for action set down.

The outcome of a rapid survey along the lines we have proposed cannot be used directly as a basis for exploitation of ground water. It can only identify the presence of ground water and perhaps indicate the quantity of water available If a water balance can be drawn up and related to pump test data, water engineers can then use this information to develop a feasibility plan.

The development of a feasibility plan may need to be done by an outside contractor You may wish to get advice on this directly from commercial consultants, at home or overseas, or seek the support of an aid-donor government at this stage.

More detailed work may be required by geologists, geophysicists and water engineers before an exploitation plan can be fully developed. However, the essential step of follow up lies with the home people and their government advisers. When all the aid support has been provided it will be the local people who will have to pay (one way or another) for their continuing local water supply and to be concerned with safe disposal of waste water after use.

A local education programme may need to be carried out to make people at the village level aware of the hydrological cycle, and their part in it, as well as the limitations to the supply of potable ground water.

Contact points are -

- NZ Representative or High Commission (or other foreign government representative)

- Department of Scientific & Industrial Research, Private Bag, Wellington, New Zealand

- NZ Institute of Professional Engineers, P O Box 12241, Wellington North, New Zealand.

SUMMARY OF INFORMATION FROM THE RAPID METHOD FOR EVALUATION

The approach of this method is to determine whether or not a potential fresh ground-water resource is present beneath coral islands and especially atolls. The emphasis is to use measurements and calculations to determine the characteristics and potential of the aquifer and confirm these where possible by independent data.

The approaches are set out in Table 7.

Table 7: Observations, Measurements and Calculations used in the *rapid method*

Aspect	Observations, Measurements or Calculations	Confirming Measurements
Lens Identification	Resistivity soundings leading to a layered hydrological model	Confirmed by drilling
Water quality	Conductivity profile	Chemical analysis
Potability (safe for drinking)	Smell, presence of animals, human industrial waste	Chemical and bacteriological analysis
Well yield	Pumping calculations	Drawdown, volumes pumped
Flow in aquifer	Transmissivity, porosity	Drawdown, volumes pumped (metered)
Safe pump rate	Pumping calculations for min. drawdown	Regular monitoring data on water levels and salinity (essential)
Rainfall recharge	Rainfall evapotranspiration interception	Pump discharge volumes, wastage, monitoring data

Although each step is supported by independent measurements, additional research is urgently required to determine quickly and effectively both safe pumping rates and rainfall recharge in the coral island situation

APPENDICES

APPENDIX 1

CONSTITUENTS OF TIDES

Because tides are influenced by many factors you should be aware that what you measure today may be different from what you will measure in the same place at a different time - say a week later.

What follows is a simplified explanation of how tides operate remembering that there is no general theory which explains all the irregularities of tides. It might help you to understand what msl means but is not essential to measuring it. (Darwin, 1962; Gross, 1976; Press and Siever, 1974.)

If there were no tidal forces or any influence of weather systems on the ocean then the sea waters would have a level surface all over the earth. This would of course be mean sea level. As everyone who has seen the tide rise and fall and seen the changes in wave patterns on the sea will know this can only be an imagined situation.

Generally speaking there are two sets of effects - those related to global changes and those with a regional or more local effect.

Global Effects

The whole earth is influenced by a number of activities. These include the spinning of the earth on its own polar axis and the effects due to gravity. Other major influences are the depth of the water, its density, saltiness and temperature. Wind patterns, especially periodic winds (like the trade winds with blow steadily in the same direction for months) are also important.

Sir Isaac Newton was the first person to establish how the earth, sun and moon influenced one another and he developed the theory of gravity.

Centrifugal Forces

First let's consider the earth spinning on its axis. Just as water spins of a cycle tyre when you ride through water, so the same outward-flying (centrifugal) forces push the ocean waters from the poles towards the equator. (The earth's own gravity prevents the water spinning off even though the earth is rotating at over 1000 miles per hour at the equator.) These centrifugal forces do not influence tidal movements but produce a stable bulge of water about the equator. It is this bulge which is influenced by some gravitational forces. Figure 32 illustrates the direction of the forces not a continuous flow of water.

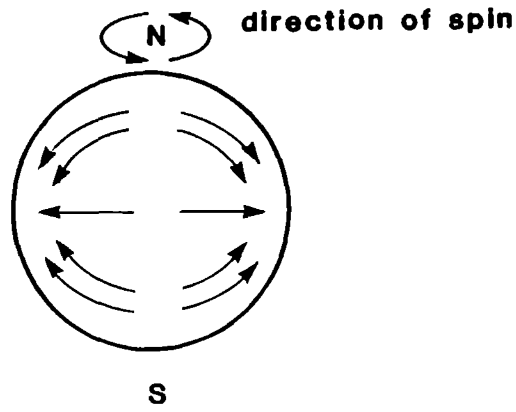


Figure 32   Effects of centrifugal forces on the earth's oceans

Gravitational Forces

The three main forces of gravity which influence tidal movement belong to the earth, the moon and the sum.

The earth draws things to itself - a falling stone is "attracted" by the larger earth and "falls" towards it.

Both the sun and the moon have a pull of gravity on the water at the earth's surface, separately and together. Alone the earth's centre of gravity would be at its centre. Together, the earth and moon have a centre of gravity just inside the earth's surface. This rotates as the moon circles the earth as illustrated in figure 33.

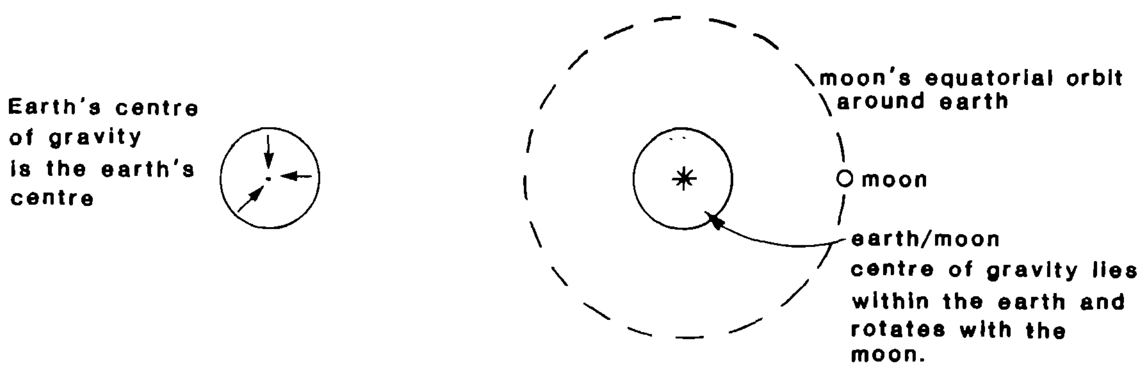


Figure 33   Centre of gravity of the earth and the earth-moon pair

The important thing is that the earth orbits about the centre of gravity of the earth-moon system. This causes two bulges of water. One is due to gravity on the side nearest the moon and one due to centrifugal forces on the opposite side of the earth. These are called the "direct" and "opposite" tides as shown in figure 34.

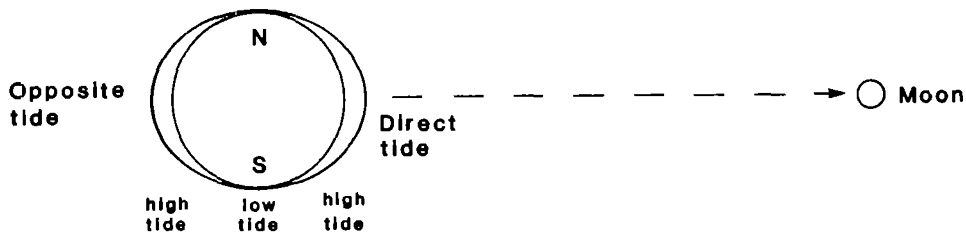


Figure 34 Gravitational and centrifugal effects of the moon on the earth's ocean tides

Now considering the moon and sun together on the same side of the earth we find further changes take place. When the three bodies are in the same line the effects of the moon and sun are combined to produce "spring" tides. This happens at new moon when the moon and sun are said to be "in conjunction". This occurs every 29¼ days. See figure 35.

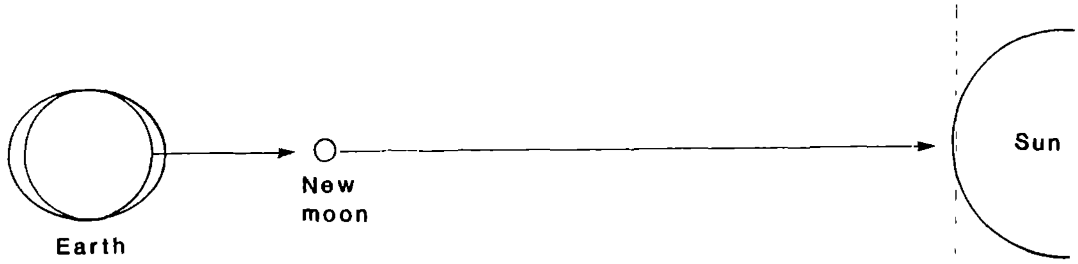


Figure 35 Combined gravitational effects of the moon and the sun (New-moon spring tides).

But when the moon and the sun are not in line, as in the first and last quarter, their gravitational effects partly cancel one another as illustrated in figure 36 The moon and sun are said to be "in quadrature", when they are 90° (one right angle) apart

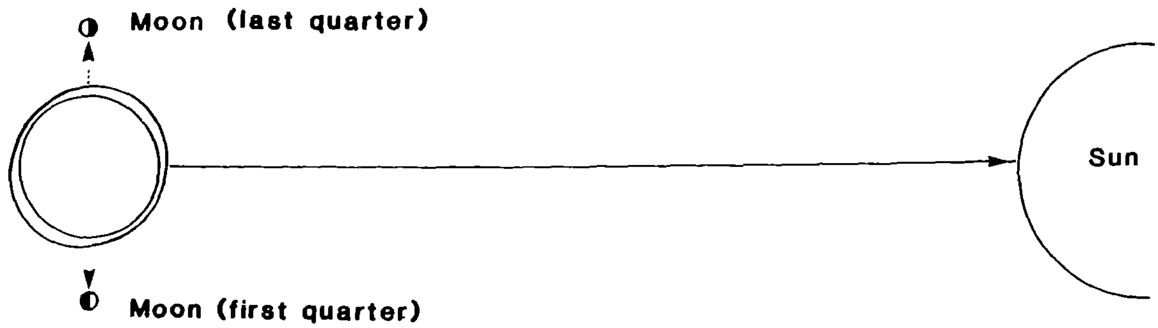


Figure 36 Competing gravitational effects of the moon and the sun. (first and last quarter neap tides).

At these neap tides the rise and fall are usually quite small because of the competing gravitational effects. You'll notice the water bulges are not at the poles but in mid-latitude.

Finally, there are the full-moon spring tides. These are often a little smaller in amplitude than new-moon spring tides. In this case the moon is on the opposite side of the earth from the sun. In this position both the moon and the sun influence the oceans by attracting the water envelope to opposite sides of the earth, again causing two daily high and low tides. This is seen in figure 37.

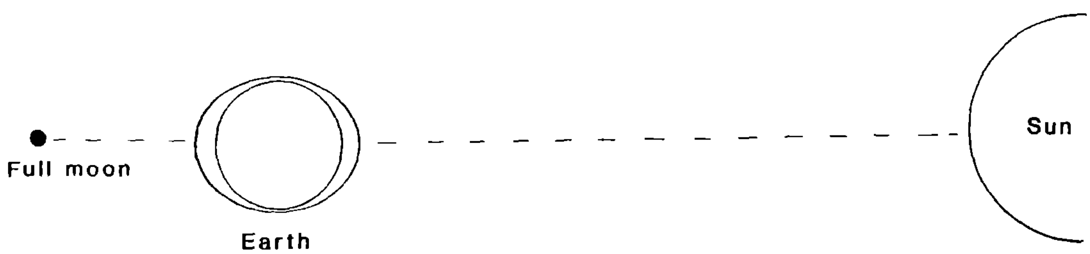


Figure 37 Full-moon spring tides

An additional influence is the moon's eliptical orbit around the earth

The closer the bodies are together the stronger the gravitational attraction will be. When the moon is nearest the earth (perigee), at new and full moon, the tidal range is some 20% greater than that at apogee (Dronkers, 1964).

Newton established that both the size (mass) and the distance which separates different bodies effect their gravitational forces. Although the sun is very large it is almost 400 times further away from the earth than the moon. So the moon is twice as powerful a tide maker as is the sun. The two moon's tides each day are called semi-diurnal lunar tides (or M_2) and the sun creates the two semi-diurnal solar tides (S_2). (Diurnal is an astronomical term for daily - 24 hours, so that semi-diurnal is twice daily.)

All water bodies are influenced by tidal effects; even very large lakes and water reservoirs. For example the Great Lakes of North America have a 50 mm tidal effect due to the moon and sun tides.

The earth rotates on its axis once every 24 hours. The moon however, orbits the earth a little slower so that it "rises" 51 minutes later each day. This is why the main high tide (M_2) is 51 minutes later each day.

Because of the complexity of the relative motions of the sun, earth and moon, some of the less significant constituents of the moon and sun's gravitational forces have a dominant effect in some parts of the world. For example in McMurdo Sound (Antarctica), the Gulf of Mexico, the Gulf of St Lawrence, and the China Sea there is only <u>one</u> rise and fall of the tide each day. At some places, as explained below, the tidal effect is negligible.

Local Effects

Although the general effects of the sun, moon and the earth's rotation and its own gravitational effects explain the main tidal constituents, local effects too are important in determining the amplitude (range between high and low water marks) of tides. The shape of the land, wind force and direction, and the depth of water all play a part. For instance scientists have shown that there is a 10 cm difference in mean sea levels on the East Coast of New Zealand at different seasons (Heath, 1976).

As the main bulge of water travels westward round the earth it has to flow round the obstructing land. Again, scientists have measured how the shape of New Zealand (which lies more or less in a north/south line) influences the movement of the tides around the country. Tides flow northward up the east coast and around North Cape then southward down the west coast. When it is full tide in the north east, it is low tide in the south west and vice versa. For a small mid-ocean, circular island the tidal bulge just flows around it like water round a rock in a river.

Water depth will also have an influence because of the way the bottom friction effects the water flow. For most of the Pacific Ocean the water is deep but where the tidal bulge meets shallow water the height of the tidal wave may increase considerably and be slowed down. High tide in a large shallow estuary usually lags behind high tide at sea.

Locally the influence of a coral reef around an island has the effect of allowing only the upper part of the wave to flow above and around the general level of the reef. The physical shape of the reef and the number of gaps alter the time sequence so that it may take only 4 to 5 hours for the tide to rise (flow) and 8 to 9 hours for it to fall (ebb).

Weather conditions on both a large scale and at a local level will alter the tide level too. The El Nino (Southern Oscillation) may have a major effect over a large area of the South Pacific and local winds, like the SE tradewinds, will cause slightly higher tides on the windward side (the side facing the wind). Variations in air pressure will also alter sea level Scientists have calculated that for every 1 millibar increase of atmospheric pressure the sea level would fall by 10 mm (1 cm)

Because these local variations effect high and low tide it is important to take measurements for as long as possible to get reliable values and hence a dependable mean sea level.

Regional Effects

Generally tidal amplitude (rise and fall) is least in the tropics and greater in the mid-latitudes. Usually the tidal range is around 500 mm in open-ocean tropical areas and perhaps five times that in some shallow harbours in the sub-tropics The general concept of a broad tidal bulge travelling westward round the earth giving a cycle of high and low tides every 12 hours 25 minutes is too simple for reality. In practice, there are a number of tidal patterns and local variations at each place.

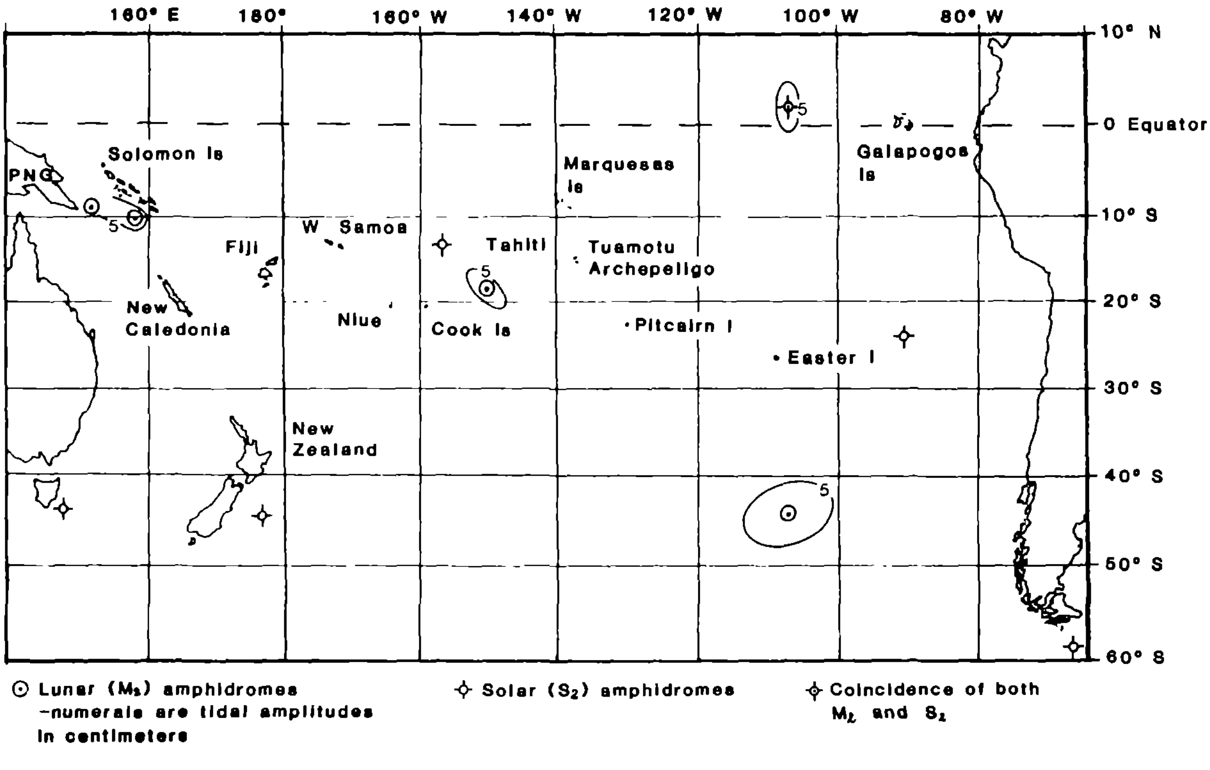


Figure 38 Amphidromes in the South Pacific. (After Schwiderski)

Each large pattern has a crest and trough wheeling about a fixed point rather like a wheel with two opposite spokes At the hub of the wheel the crest and trough merge and at that point there is practically no vertical tidal range at all. Scientists have discovered nine of these "amphidromic" points in the Southern Hemisphere. (These patterns usually rotate anti-clockwise in the Southern Hemisphere and clockwise in the Northern Hemisphere). The area about Tahiti is one such amphidromic point and accounts for the negligible tidal range there. Figure 38 indicates the amphidromes in the South Pacific.

Establishing Mean Sea Level

Although the above discussion indicates some of the complexity and variability of tidal motion our specific concern is to establish a point somewhere which we can use as a datum.

An automatic tide gauge will assist in identifying the time of the top and bottom of the tidal movement but not an actual level on the sea shore. However, in determining where mean sea level is on a fixed structure such as a wharf pile or a post concreted or driven into the sea floor you need to know reasonably accurately when both high and low tide occur so that the sea level at these times can be marked. By taking the halfway point between the marks at high and low water you can establish approximate mean sea level. Use the most accurate method available to determine msl.

A convenient type of portable tide gauge is the Foxboro. This has a bellows at the end of a tube which is anchored in the sea below the surface at all times. The cycle of varying pressures is recorded on a circular chart which traces the rise and fall of the tide and dampens (smoothes out) the effects of the surface waves. The recorder is placed on the shore and is battery or clockwork powered. If possible you should record for at least 25 hours or preferably 39 hours. A trace from an automatic recorder is illustrated in figure 39. Note that the peaks and troughs get smaller as the neap tide approaches, starting at 26 cm and declining to 16.5 cm over the week. The peaks (full tides) and troughs (low tides) get later each day.

If no recording instrument is available you will have to resort to the "stick in sand" approach. It will be helpful to use tidal prediction tables to identify low water as there is little point in not being able to measure low tide (which can happen if the sea water falls below the lagoon floor at low water). You can well be mislead in measurements in tropical lagoons which may vary by several centimetres at low tide on consecutive days because of weather conditions and may also vary with tide heights on the open sea.

Because the surface of some lagoons, or encircling reef flats on atolls, may have little or no sand you may need to prepare a tide post which can be fixed into place with coral boulders or the equivalent. Two sliding wires or other markers can then be used for marking the top and bottom of the tide.

It is highly desirable to surround the tide post with a shelter to reduce the slopping action of waves. We have already noted that within the lagoon situation a regular 6½-hour tide is not likely to happen so you'll need to use hourly measurements over the main ebb and flow period and 15 minute measurements around full and low water. You may well find that at high and low tide there is little movement of the sea level for an hour or more at these points. If a permanent structure like a jetty, wharf or sea wall is available you can identify a permanent mean sea level mark and use it as a datum.

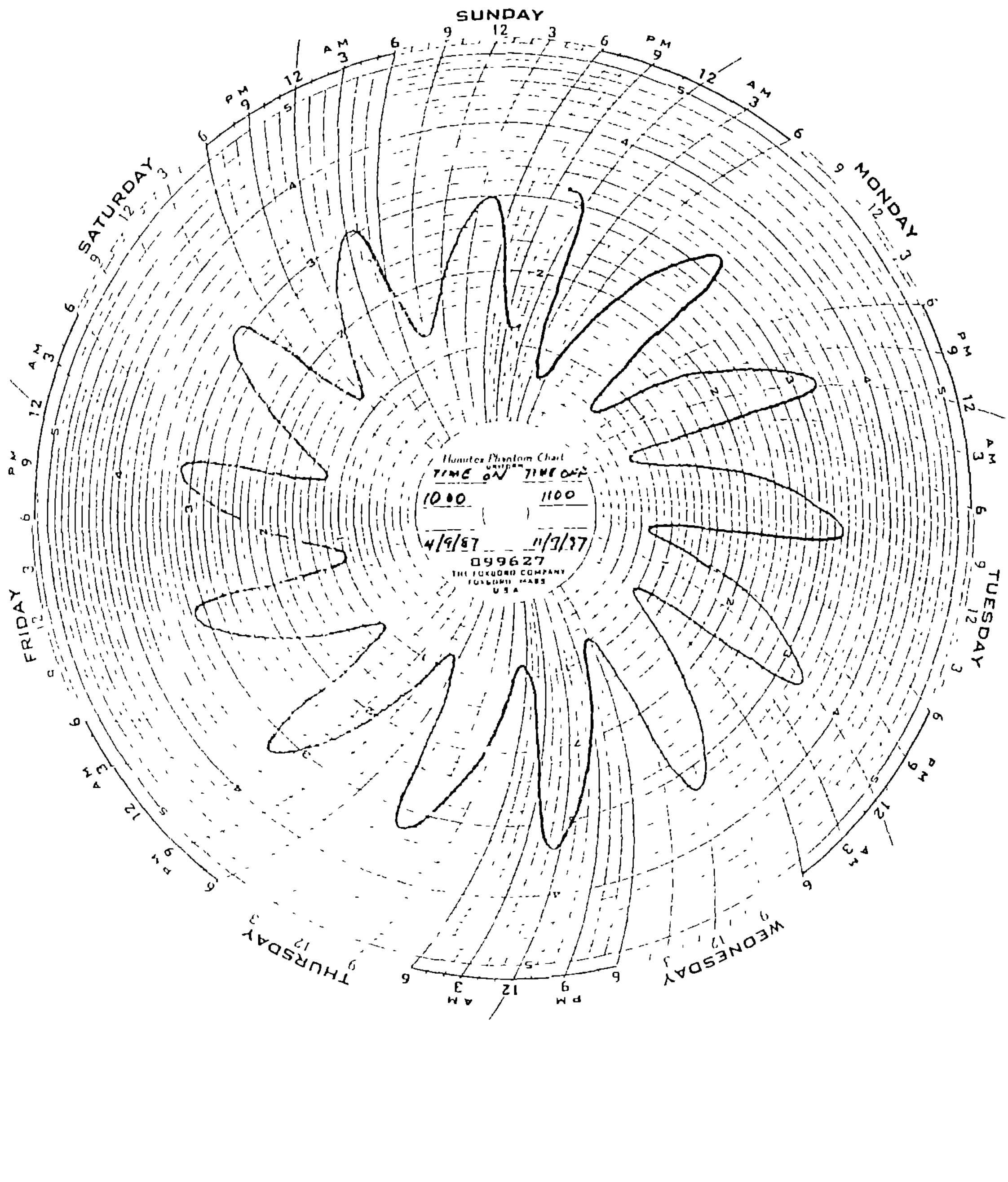


Figure 39 Trace from an automatic tide gauge.

APPENDIX 2

LIST OF FIELD EQUIPMENT REQUIRED FOR A GEOPHYSICAL PROGRAMME

This list has been compiled as a minimum list of equipment needed for a (say) two-month field programme on remote Pacific Islands. Wherever possible, light-weight and easily transportable equipment is specified, and adequate back-up instruments are necessary for all breakable and non-robust components.

A RESISTIVITY TRANSMITTER UNIT AND ACCESSORIES

A1 Transmitter electronic console
This should be lightweight, operate from 12 V supply, and have built-in 24-pin output sockets.
A2 Spare transmitter for A1 (or alternatively, spare modules for all vital components of A1)
A3 2 Multicore resistivity cables, 100m
A4 2 spare cables for A3
A5 40 300 x 12 mm (stainless steel) electrode spikes
A6 40 takeout connecting jumpers
A7 30 m tape
A8 5 m steel tape
A9 2 electrode hammers (mason's hammers)
A10 2 plastic containers for batteries
A11 4 12 V, 6 Ah, lead acid batteries (sealed "gel-cell" type)
A12 1 4 A battery charger (12 V) with overvoltage cut-out
A13 An assortment of spare clips, wire, connectors, etc.

B RESISTIVITY RECEIVER UNIT AND ACCESSORIES

B1 Recording Console consisting of
- Chart recorder (1m V) or microvoltmeter
- Charging unit for recorder
- Backoff unit (bias - preamp - filter)
- Lightweight carrying case

B2 Spares or back-up units for all breakable items in B1
B3 4 porous pots ($Cu/CuSO_4$)
B4 2 100 m lengths of connecting wire on holders or reels.
B5 1 multimeter
B6 1 kg copper sulphate ($CuSO_4$) crystals
B7 4 1 litre plastic bottles
B8 1 plastic tub (for electrodes and $CuSO_4$)
B9 Adequate supply of pens and chart paper for B1
B10 Adequate supply of dry cells (9 V and 1.5 V "AA")
B11 1 compass

C RESISTIVITY CALCULATIONS AND ANALYSIS

C1 Textbook on resistivity prospecting
C2 Comprehensive set of standard 3-layer resistivity curves
C3 3 field books
C4 1 programmable scientific calculator
C5 100 sheets calculation paper
C6 100 sheets transparent 3 cycle x 3 cycle log-log 62.5 mm graph paper
C7 10 sheets A3 linear graph paper

D RESISTIVITY ACCESSORIES AND SPARES

D1 Repair manuals and circuit diagrams for all electronic instruments
D2 Tool kit consisting of soldering iron, solder 4 screwdrivers, 3 pliers, 3 spanners, hacksaw, scalpel, knife, wirecutters, scribe, lengths of wire of assorted sizes, assorted clips, plugs, sockets, switches, nails, screws, bolts
D3 Assorted transistors, integrated circuits resistors and capacitors as spares
D4 Assorted glues, solvents and cleaners
D5 100 m spare hookup wire
D6 10 spare battery clips
D7 2 plastic sheets 3 m x 2 m
D8 6 rolls insulation tape
D9 20 plastic bags of assorted sizes with ties
D10 Assortment of stationery
D11 Assortment of drawing, writing equipment, stapler, sellotape
D12 2 trampers backs
D13 3 large durable cartons for air transport of all equipment
D14 30 m rope (light weight)

APPENDIX 3

INSTRUCTIONS FOR THE COLLECTION OF WATER SAMPLES FOR CHEMICAL ANALYSIS

(Prepared by Chemistry Division, DSIR, NZ)

Each sample kit consists of 3 sample bottles:

(1) 100 ml bottle, containing neutral preservative
(2) 500 ml bottle, containing acid preservative
(3) 500 ml bottle, containing no preservative

Each of these bottles must be filled whenever a sample is taken - the 3 bottles together constitute one sample, and should all be given the same inspector's number.

The bottles provided are already cleaned and 2 contain preservative, as labelled. DO NOT RINSE the bottles containing preservative, or overflow with sample, otherwise the preservative will be lost. Use the bottle containing no preservative to collect the water to be sampled and from this fill the bottles containing preservative, taking care not to overflow. Finally refill the bottle containing no preservative.

Immediately prior to filling the bottle, the cap should be removed in such a way that NOTHING touches either the inner surface of the cap or the upper part of the bottle. It should be placed in a safe position, where it will be kept free of any contamination until replaced on the bottle. (Contamination especially includes touching the inside surfaces of the caps or bottles with fingers).

Stream or river samples should be collected by the person concerned facing upstream and holding the bottle near its base. Lower it into the water with the opening facing upstream to a depth of at least 30 cms (10 ins) below the water level. Filling the bottle is completed by tilting it until the last of the air has escaped. When the sample bottle is full, the bottle should be closed immediately.

During the sampling operations, it is essential that nobody smoke in the vicinity These samples will be analysed for small quantities of trace elements, and minute quantities of contaminant and give rise to misleading results.

Please complete the label on each sample bottle, as well as completing the appropriate forms ('Details of Water Sample' and, where necessary, 'Details of Water Supply'). For a chlorinated supply, please indicate the level of FAC measured at the time of sampling.

(Note these forms list necessary details such as temperature, date, pumping time, and local site details.)

APPENDIX 4

FIELD CHLORIDE TESTS

These tests are useful to confirm the broad level of salt (sodium chloride) as estimated from conductivity profile tests. Water samples fall into 3 rough groups. Low chloride which is not detectable by taste (up to 200 mg/litre); flat or brackish in the 200-2000 mg/ℓ range and anything above 2000 mg/ℓ. Only samples below about 600 mg/litre are normally acceptable for drinking water and water under 200 mg/ℓ is preferred.

The method uses a silver nitrate solution which is added to the water sample to give a red colouration with any salt present in the presence of potassium chromate.

1. Chemicals and equipment

(a) Bottle 1: (Low chloride) 0.5 litre (or one pint) of $AgNO_3$ (silver nitrate solution) made up of 4.791 grams $AgNO_3$ per litre of distilled water.

This is for testing the low chloride range of samples, i.e. 1 millilitre (ml) contains 1 milligram (1mg) of Cl (chloride ion).

(b) Bottle 2: (High chloride) 0.5 litre (one pint) of $AgNO_3$ solution made up of 47.91 g $AgNO_3$ per litre of distilled water.

1 ml of this solution equals 10 mg Cl in the tested sample. This is used for the higher chloride content range of samples.

(c) Bottle 3: 56.7 gram K_2CrO_4 (potassium chromate) per litre of solution. Part of this should be stored for use in a 28 gram (1 oz) brown dropper bottle.

(d) 2 x pipettes, 5 ml capacity, graduated to 1/10th (tenths) of a millilitre (ml).

(e) 2 x porcelain mixing casseroles of 100 ml capacity.

(f) 1 x 25 ml graduated measuring cylinder (plastic preferable).

(g) 2 x glass stirring rods.

(i) distilled water

The reagents can be made up in any chemical laboratory and equipment may be available from chemist supply stores.

Keep the $AgNO_3$ solutions stored in dark glass (brown) bottles in the dark to slow down deterioration

2. Procedure

(a) Determine range of Cl either by taste, or by testing first using bottle 2 chemicals for the high range chloride test.

RANGE (mg/ℓCl)	TASTE	USE Ag NO_3 Soln
0-200	none	1 mℓ = 1 mg Cl (Bottle 1) (for low chloride samples)
200-2000	flat or brackish	1 mℓ = 10 mg Cl (Bottle 2) (for high chloride sample)
2000-20000	salty	Dilute sample (as below (b) and use $AgNO_3$ 1 ml = 10 mg Cl (Bottle 2)

(b) Measure 25 ml of sample into graduated cylinder and transfer to casserole. To avoid excessive use of $AgNO_3$, samples containing more than 2000 mg/ℓ Cl should be diluted as follows:

(i) Measure 2.5 ml water sample using pipette (do not use this pipette for $AgNO_3$).

(ii) Transfer to graduated cylinder and make up to 25 ml using distilled or rain water. If rain water is used, test this for Cl first and apply correction as in step (f(ii)).

(c) Add 5 drops K_2CrO_4 solution and stir. Solution turns bright yellow.

(d) (i) Fill $AgNO_3$ pipette to above full mark with appropriate $AgNO_3$ solution. Drain to mark controlling flow with finger on top.

(ii) Add $AgNO_3$ slowly from pipette to sample in casserole, continually stirring.

(iii) Clear yellow solution becomes turbid (very turbid if high Cl). Each drop of $AgNO_3$ makes a brick-red fleck in the casserole, which disappears on stirring.

(iv) As end point approaches, the red flashes become larger and more persistent.

(v) End point is reached as soon as whole solution in casserole acquires a faint permanent red tinge.

(e) Read amount of $AgNO_3$ used from markings on pipette.

(f) Calculate mg/ℓ of chloride content in the sample as follows:

(i) If using the dilute $AgNO_3$, bottle 1, (1 ml $AgNO_3$ = 1 mg Cl) for 25 ml sample.

The mg/ℓ Cl is determined by multiplying the number of mls $AgNO_3$ solution used x 40 (accuracy depends on the number of drops used at the end point as 1 drop $AgNO_3$ equals approx 1.3 mg/ℓ Cl). For example 2.5 ml of $AgNO_3$ solution 1 equals 2.5 x 40 = 100 mg/ℓ.

(ii) When using the bottle 2 $AgNO_3$ (1 ml $AgNO_3$ = 10 mg Cl) for the higher chloride content 25 ml sample.

The mg/ℓ Cl is determined by multiplying the number of mls $AgNO_3$ solution used x 400 (accuracy, 1 drop $AgNO_3$ equals approximately 13 mg/ℓ Cl). For example 3.2 ml $AgNO_3$ solution 2 equals 3.2 x 400 = 1280 mg/ℓ.

(iii) Use 1 to 10 dilution for very high content chloride samples.

Use bottle 2 $AgNO_3$ on the diluted sample to be tested (dilute as previously explained, 2b).

The mg/ℓ Cl in the sample is determined by multiplying the mls $AgNO_3$ (bottle 2) solution used x 400. This gives result A.

The mg/ℓ Cl contained in the rainfall sample or diluting water is calculated by multiplying the mls of $AgNO_3$ (bottle 1) solution used x 40. This gives result B.

Then to find the mg/ℓ Cl of the original water being tested multiply 10 x mg/ℓ Cl calculated for test sample A - 9 x mg/ℓ Cl of the dilutent water.

The limit of accuracy for this test is approximately 130 mg/ℓ of chloride.

The results will show whether the water sampled is less than the World Health Organisation's 200 mg/ℓ highest desirable limit, below the WHO 600 mg/ℓ maximum permissible limit, or ranging in saltiness up to sea water which has a Cl content of approximately 19000 mg/ℓ.

Note mg/ℓ (milligrams per litre) and ppm (parts per million) are for this exercise the same.

APPENDIX 5

LIST OF FIELD EQUIPMENT REQUIRED FOR AN HYDROGEOLOGICAL PROGRAMME

This list was compiled from reports and experience with work undertaking on small Pacific Islands.

Survey Equipment

Level, staff, tripod, 2 x 30 m tapes, 5 m tape, maps and reports, compass, field and level book, tide tables (if available).

Water Sampling and Testing

Drillhole sampler, conductivity meter and probe, 5 m cable, field chloride test kit, portable field bacto. Kit, 20 x 500 ml water sample bottles, 10 x 100 to 200 ml sample bottles (sterile for bacto tests), distilled water, plastic measuring container (6-10 ℓ), temperature and pH meter, standard calibration solutions.

Monitoring Equipment

2x automatic water level recorders, probe and spare charts;
2 x 12 v wet cell batteries;
battery charger;
manual water level probe;
sieves;
rain gauge;
barometer

Drilling Equipment

Drilling rigs

- hand augers
- percussion pipe (Waratah) driver and accessories
- motorised air-percussion driver
- drill rods and casing
- steels for drilling with motorised percussion drills
- spades, pick axes, crowbars
- high pressure pump
- pump and hoses for pump tests
- spare parts, tools, 2x Stilson wrenches
- fuel, oil, funnel
- log sheets
- stop watch

Extra Equipment

plastic bucket
string (about 100 metres)
rope (polyester - about 50 metres of 4 mm diameter)
spray lubricant (CRC)
tarpaulin
plastic bags, various sizes (for waterproofing and general purposes)
spray paint (fluorescent)
4 x 3 m lengths of 55 mm diameter rigid PVC pipe
(just in case it is 3 m to water table from surface)
camera and film
torches and spare batteries
insulation and wrapping tape
lightweight trestles (drilling platform)
field back pack
mirror
calculator
multimeter
motorbike (optional - but can be extremely useful for quick inspection around island)
beach umbrella (shade for resistivity meter)

APPENDIX 6

Recent Research on Freshwater Detection

A new approach to the interpretation of sounding curves for thin freshwater aquifers has been developed by Risk (personal communication, 1986). His approach seeks to depict the differences between pairs of theoretical sounding curves. The first curve is selected to give the best match with the observed data. The second curve is calculated using the same resistivity section, but with the freshwater replaced by salt water By comparing the two curves noticable divergence is evident where freshwater is present and a negligible difference appears where the lens is barely discernible. Examples of such paired sounding curves are given in figure 40 for 6 sites on line 1, Akaiami motu.

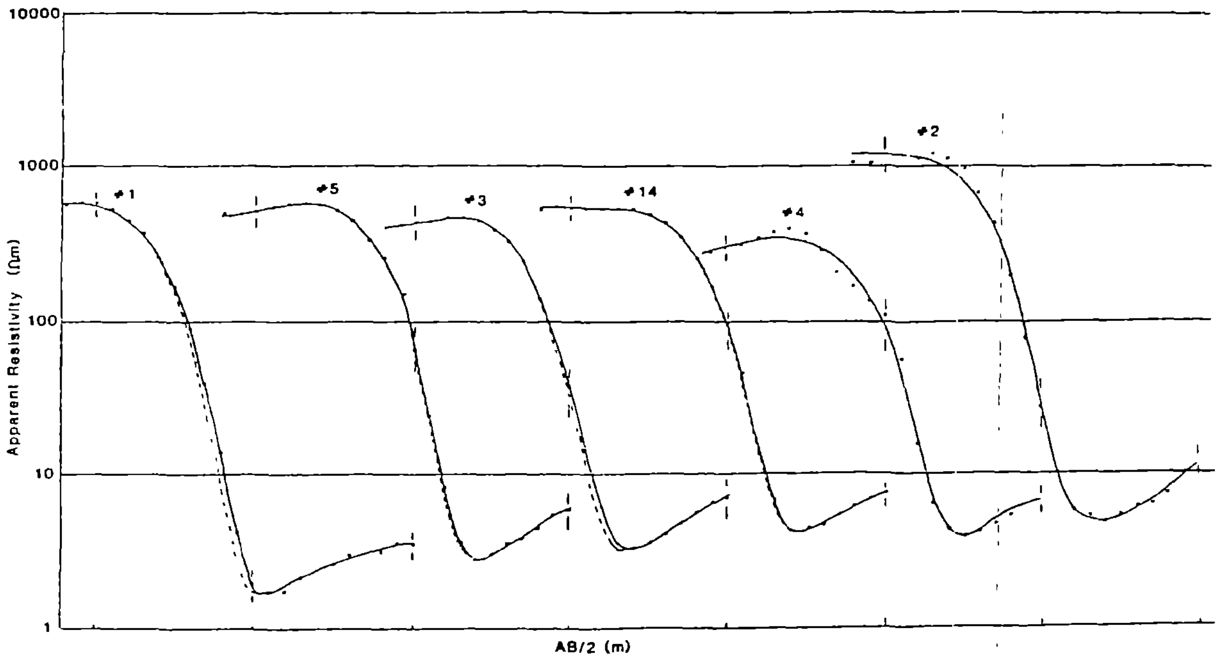


Figure 40 Paired curves for detecting a thin freshwater aquifer. Line 1, Akaiami motu, September 1985.

Dots represent field measurements; the solid lines are the best fitting theoretical curves corresponding to the cross section presented in figure 25 and include the freshwater resistivity values.

The dashed lines are the theoretical curves without the freshwater values. The vertical lines on each curve give the AB/2 distances of 1, 10 and 100 m.

Interpretation: The freshwater is clearly evident in #1 and #3 (divergent curves).
The freshwater is barely discernible in #5 and #14.
Curve #4 is too irregular to allow aquifer detection.
Curve #2 shows no sign of a freshwater aquifer.

APPENDIX 7

CHEMICAL AND PHYSICAL QUALITY STANDARDS FOR WATER

Substance	Permissible		Excessive	
Hardness	100 p.p.m.		600	p.p.m.
Total Solids	500 p.p.m.		1500	p.p.m.
Colour (Platinum-Cobalt Scale)	5		50	
Turbidity (Jackson Candle)	5		25	
Taste	Unobjectionable			
Odour	Unobjectionable			
Iron (Fe)	0.3	p.p.m.	1.0	p.p.m.
Manganese (Mn)	0.1	p.p.m.	0.5	p.p.m.
Copper (Cu)	1.0	p.p.m.	1.5	p.p.m.
Zinc (Zn)	5.0	p.p.m.	15	p.p.m.
Calcium (Ca)	75	p.p.m.	200	p.p.m.
Magnesium (Mg)	50	p.p.m.	150	p.p.m.
Sulphate (SO_4)	200	p.p.m.	400	p.p.m.
Chloride (Cl)	200	p.p.m.	600	p.p.m.
pH range	7.0-8.5		Less than 6.5 or greater than 9.2	
Magnesium & Sodium Sulphate	500	p.p.m.	1000	p.p.m.
Phenolics (as Phenol)	0.001	p.p.m.	0.002	p.p.m.
Nitrate (NO_3)	50	p.p.m.	100	p.p.m.
Fluoride (F)	1.0	p.p.m.	1.5	p.p.m.
Lead (Pb)	0.1	p.p.m.	0.1	p.p.m.
Selenium (Se)	0.05	p.p.m.	0.05	p.p.m.
Arsenic (As)	0.2	p.p.m.	0.2	p.p.m.
Chromium (Cr)	0.05	p.p.m.	0.05	p.p.m.
Cyanide (Cn)	0.01	p.p.m.	0.01	p.p.m.

Radium - maximum 10 picrocuries per litre
Radiation - maximum 1,000 picrocuries per litre.

These values are those presented by the Drillers Training and Reference Manual, National Water Well Association of Australia and vary slightly from the WHO levels for Mn, Fe, Cu and in the expression of "acceptability" criteria as expressed in table 4. Not all elements such as aluminium, boron, and bromine are included in this list.

APPENDIX 8

DSIR CHEMISTRY DIVISION CHRISTCHURCH

WATER REPORT

N2696/1
N2696/2

Supply : COOK ISLANDS TEST DRILLHOLES
Sampling location : N2696/1 DRILL HOLE #1 AKAIMI MOTU
Sampling location : N2696/2 DRILL HOLE #1 AKAIMI MOTU
Taken : 28/9/85 Received : 22/11/85 Reported : 3/4/86

Sample No. :	N2696/1	N2696/2
ANALYSIS		
Units g/m^3, except pH or unless otherwise stated.		
pH	7.5	7 5
pH after aeration	8.4	8.4
Acidity to pH 8 3 (as CO_2)	23	24
Total Alkalinity to pH4.5 as HCO_3	476	458
Alkalinity to pH 8.3 (as CO_3)	NIL	NIL
Turbidity (NTU units)	1.4 *	0.61
Absorbence units (370 nm, 1 cm cell)	0.088	0.085
Chemical Oxygen Demand (as O)	6	7
Ammoniacal Nitrogen	0.01	0.01
Nitrite Nitrogen	LT 0 001	LT 0.001
Nitrate Nitrogen	LT 0.05	LT 0.05
Soluble Phosphate (as P)	LT 0 1	LT 0.1
Sulphate	22	21
Bromide	0.50	0.47
Chloride	110 *	110 *
Fluoride	0.6	0.5
Calcium	150	138
Magnesium	20.1	20
Potassium	1.1	1.1
Sodium	68	70
Total Silica (as SiO_2)	5.6	7.1
Aluminium	0.08 *	LT 0.03
Arsenic	LT 0.04	LT 0.04
Boron	0 07	0.02
Chromium	LT 0.003	LT 0.003

Cobalt	LT 0.004	LT 0.004
Copper	LT 0.01	LT 0.01
Iron	0.31 *	0.46 *
Lead	LT 0.02	LT 0.02
Manganese	0.005	0.005
Molybdenum	LT 0.003	LT 0.003
Nickel	LT 0.007	LT 0.007
Total Phosphorus	LT 0.02	0.04
Selenium	LT 0.05	LT 0.05
Strontium	1.6	1.9
Total Sulphur	6.6	6.8
Tin	LT 0.01	LT 0.01
Zinc	0.29	0.14
Total Hardness (as $CaCO_3$)	457 **	426 **
Conductivity at 20 deg C (mS/m)	100.0	100.0

Analytical results relate only to the sample as received.
The letters LT in the above report mean "less than".

This sample does not comply with the following NZ Standard requirements:

* exceeds lower guideline limit
** exceeds upper guideline limit

The methods of analysis and their precision are available on request.

GLOSSARY OF TERMS

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Aquifer: An aquifer is a body of rock or sediment which contains sufficient saturated permeable material to yield significant quantities of water to drillholes, wells or springs.

Area (or zone) of influence: The area beneath which the ground water is modified by pumping

Brackish water: Fresh water with a high content of salt and other chemicals. Usually unsuitable for use other than for washing and sometimes for stock drinking water.

Capacity: The capacity of a drillhole is the maximum rate at which water has been, or could be, withdrawn from the drillhole with time.

Capillary Fringe: The zone of earth immediately above the water table in which all or most of the very fine tubes or cavities are filled with water.

Casing: A pipe which may be slotted or perforated for use in drilling operations.

Climatic cycle: The periodic fluctuation of the climate, including dry and wet years which follow one another in a more or less regular way. (Could also apply to annual wet and dry times).

Coefficient of Transmissibility: The field coefficient of permeability multiplied by the aquifer thickness.

Condensation. Gases, including water vapour, are condensed when they encounter sufficiently lower temperatures to reform as liquids (or solids such as ice)

Conductance (Specific): A measure of the ability of water to conduct an electric current. It is related to the total concentration of ionised solids in the water and is inversely proportional to electrical resistance

Cone of Water Table depression. The conical surface of the water level created in an unconfined aquifer due to pumping. Both the top (down-coning) and the bottom (up-coning) of the aquifer are effected.

Distillation:	Water heated to 100°C at normal pressure will boil and form steam. If the steam is cooled it will condense into water leaving salt and other impurities behind. The process is called distillation. Solar distillation takes place when the sun's energy is used to heat a dark surface to vaporise a thin film of water which is condensed on a cooler surface.
Drawdown:	The amount of lowering of the water level, caused by pumping. See also Residual drawdown.
Effective Porosity:	This is the portion of pore space in saturated permeable material in which movement of water takes place It is measured with satisfactory accuracy by specific yield.
Effective Seepage:	Diffuse discharge of ground water to the ground surface.
Effective Velocity:	The actual or field velocity of ground water percolating through water-bearing material. It is measured by the volume of ground water passing through a unit cross section divided by effective porosity.
Evaporation:	The reverse of condensation when water is converted to a vapour by heat.
Field capacity·	The capability of the soil to hold water in the small cavities and/or within the soil particles. Measured by the ratio of the weight of water compared with dry soil.
Ground water	Water in the zone of saturation.
Hardpan.	An impervious layer of clay or rock material.
Head:	The static head is the elevation of the water table above a reference datum.
Hydraulic conductivity:	A measure of the ease with which water, in the conditions prevailing in the aquifer, can flow through rock or soil.
Hydraulic gradient:	The change in static head per unit of distance of flow from a given point and in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Hydrological cycle: The process whereby moisture vapour produced by heat from the sun evaporates, rises into the atmosphere where it is condensed into water (or other form), is precipitated back on the earth's surface and may move down into the ground.

Infiltration: The movement of water through the ground surface into small spaces in either the saturated or unsaturated zone.

Interception: When water or condensing water vapour is caught on the foliage and other parts of vegetation it is "intercepted" from falling directly to the ground.

Log. A written record of all events experienced during the daily progress of drilling.

Perched ground water: (Perched water table) This is unconfined ground water in a saturated zone separated from, and usually higher than, the main body of ground water by a hardpan, unsaturated rock or any impervious layer.

Percolation: Similar to infiltration but at a slightly greater flow rate.

Permeability. The capacity of water-bearing rock or soil to transmit water. It is sometimes used as a synonym of hydraulic conductivity

Porosity: The property of rock or soil containing voids (spaces not occupied by solid matter) expressed as the percentage of the volume of the voids to its total volume.

Potable water Water which is chemically and biologically safe to drink.

Potentiometric surface: A surface which represents the static head of ground water as related to and defined by the levels to which water will rise in a tightly cased well within an unconfined aquifer.

Precipitation: Falling particles of water in the form of ice, snow, hail, fog or rain are collectively called precipitation.

Recharge. Recharge of ground water is the addition of water to the saturated zone, usually from rainfall.

Residual drawndown The distance the water level in a well has to rise (during recovery after a pump test) to reach the initial static water level.

Safe yield: May be defined as the maximum rate at which water can be artificially withdrawn from a ground water basin without causing depletion or deterioration of the resources to the extent that withdrawal at that rate is no longer economically feasible.

Salinity: The total content of dissolved salts in the water, commonly expressed in milligrams per litre.

Saturated zone: The zone of permeable rock or soil below the water table in which all voids, large or small, may be filled with water.

Seepage: The relatively slow flow of water at the ground surface or at the coast.

Sieve analysis: The separation of particles from a drill core to determine the relative amounts of each sized particle from an unconsolidated material. Used to determine appropriate screen selection.

Specific capacity: The rate of discharge of water from the drillhole divided by the drawdown within the drillhole.

Specific retention. The ratio of the volume of water which rock or soil, after being saturated, will retain against the pull of gravity to the volume of the rock or soil.

Specific yield· The ratio of the volume of water yielded by gravity drainage from previously saturated material, to the volume of rock or soil.

Standing level: The water level in a well which is not being pumped. If there are no other influences (other wells) then it is the static level.

Standing Water Level: S.W.L. The water level measured in a bore or well relative to ground level.

Static Water Level: See standing level The level in a non-pumped well with no outside influences.

Storage coefficient· The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head expressed as a fraction or percentage.

Surface Runoff· Water which runs off the ground surface and later into streams.

Transmissibility: The hydraulic conductivity multiplied by the thickness of the aquifer.

Transmissivity: The rate at which water is transmitted (flows) through a unit width of an aquifer under a unit hydraulic gradient.

Transpiration: Water vapour discharged by plants into the atmosphere.

Transportation: Water or water vapour is transported by atmospheric movement of clouds and other formations in the same way water flows (downhill) on land.

Tropics: The region of the globe either side of the equator lying between the Tropic of Cancer (24°N) and the Tropic of Capricorn (24°S).

Unconfined ground water: The upper surface of unconfined ground water is formed either by a body of surface water (e.g. a lake) or by a free water table, i.e. there is no capping layer of rock.

Underground water: The terms underground water and ground water are synonymous.

Voids: Open spaces within the ground or rocks which may be filled with water below the water table.

Water table: The surface in an unconfined water body at which the pressure is atmospheric. It is indicated by the levels at which water stands in drillholes or wells that penetrate the water body just far enough to hold standing water. In drillholes which penetrate the greater depths, the water level will stand above or below the water table if an upward or downward component of ground water flow exists.

Water vapour: When water is heated it evaporates to form invisible water vapour.

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