CSC TECHNICAL PUBLICATION SERIES No. 154

Water Resources of Small Islands

TECHNICAL PROCEEDINGS (PART 2)
OF THE REGIONAL WORKSHOP ON
WATER RESOURCES OF SMALL ISLANDS

27 June - 9 July 1984, Suva, Fiji

WATER AND MINERAL RESOURCES PROGRAMME

COMMONWEALTH SCIENCE COUNCIL
COMMONWEALTH SECRETARIAT
Marlborough House, Pall Mall, London SW1Y 5HX

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INTRODUCTION

The main emphasis of the Workshop had been on knowledge and understanding of water resources occurrence and assessment leading to appropriate and efficient development.

In the context of this workshop, small islands were defined as less than some 5000 sq km in area and in consequence generally unfavourable to the construction of surface water storage schemes of significant size. The larger main islands of Indonesia, Papua New Guinea and Fiji were therefore excluded. The geographical region of main consideration has been the South Pacific, Micronesia and the Indian Ocean.

The Workshop was planned to have a primary training function and participants were expected to have some involvement in water resources development in small islands, whether as water engineers, hydrologists, hydrogeologists, agriculturalists, public health engineers/inspectors, environmental scientists or as managers of supply utilities. With such a wide range of background skills anticipated amongst the participants it was decided that the programme should concentrate on the understanding of source occurrence, notably groundwater, and the broader problems and issues relating to resource assessment and development. Since most of the Resource Personnel assembled for this Workshop have close associations with the region, consideration of these issues was able in most cases to be correlated with local case histories.

In addition to providing the technical review, the Workshop also planned to provide advice and comment on current country programmes of work and to identify projects or studies which would have regional value. These latter are contained in the Summary of the Discussions and Recommendations from the Workshop that formed the first part of the report. This report forms part two of the workshop and contains the technical proceedings of the main theme programme.

HON. J.B. NAISARA, MINISTER FOR LANDS, ENERGY AND MINERAL RESOURCES SPEECH AT THE OPENING OF WATER RESOURCES WORKSHOP AT USP ON 2/7/84 AT 9 P.M.

Mr Chairman, Ladies and Gentlemen,

May I, on behalf of Government, extend to you all a most warm welcome. To those of you - participants, observers and resource personnels - who are visiting our shores for the first time, I trust that your stay will be enjoyable and may this be the first of many visits.

I understand that this is a training workshop and the theme of the workshop is "Water Resources of Small Islands" with particular reference to resource assessment and its appropriate and efficient development.

The fact that this is a training workshop seems to suggest some degree of self-examination - to understand clearer what we have and where we are in terms of personnel and resources and equally as important to appreciate where we are going in relation to national policies and objectives. At meetings such as this, it is usually an opportune time to discuss and comment on the status and progress of regional or cooperative projects. But there seems to be no such programme in the field of water resources in operation in this region of the South Pacific. I am of course, not familiar with water resources activities in the Indian Ocean Region. They might have something to offer the Pacific Islanders during this workshop.

As far as Fiji is concerned, the provision and supply of water is a continuous and recurring problem, almost a night-mare. Practically every alternate year, Government had to spend a considerable amount of its limited resources to supply emergency water-supplies to rural villages and to many of its islands. A year ago, in 1983, this country experienced the worst drought in recorded history and nearly $1.0 million had to be spent on emergency water supply.

Although only a small proportion of this sum was spent for the smaller islands, the costs per unit volume delivered, were very high. Costs of $20.00 per cubic metre were not unknown for water barged to the outlying islands, involving 2 or 3 days trip from the capital, Suva. Experiences such as this should explain why we in this country are only too anxious to have the water resources on the smaller islands of our group developed.

In recent months, my Government has had serious discussions on the possibility of converting salt-water into drinkable-water. We realize, of course, that the costs of desalination plants are prohibitive; but that will not deter our efforts in this direction. When one understands that the inhabitants of some of our smaller islands have over the years been more or less subjected to the fate of the old mariner who longed: "water, water everywhere, but not a drop to drink" - one can then appreciate why water resource assessment has to be addressed and tackled. But fortunately for these people there are green coconuts around to drink from.

My Government has had an opportunity to study the various themes which you will be discussing at this workshop. And I can say that the Fiji Government considers them to be very important and relevant to our needs. It is for that reason that the Fiji Government had no hesitation in agreeing to host this training workshop. I can say, too, that when this workshop was being proposed, it was being proposed at a time when all Fiji Government hosted meetings were being subjected to detailed appraisal before approval can be granted. The fact that it was approved and the fact that I am able to stand before you today is an indication of my Government's support for the aims and objectives of this workshop.

Mr Chairman, I am also particularly impressed by the level of participants attending this Workshop. I understand that among you, you have hydrogeologists, hydrologists, water engineers, agriculturalists, health inspectors and so on. Such a group has the experience and expertise to tackle the task before this Workshop in a thorough and scientific manner.

We look forward, therefore, to the recommendations of this workshop. Be assured that when the views of this Workshop is made known, my Government will give it the most serious consideration that it deserves.

Before concluding, may I take this opportunity to thank all those Governments and Organisations who so willingly co-sponsor this training Workshop:-

1) The Commonwealth Science Council

2) UNEP

3) UNESCO

4) SPC

5) ESCAP

6) The Overseas Development Administration of UK

7) The Australian Bureau of Mineral Resources

8) The NZ Department of Scientific and Industrial Research and others that I may have been forgotten.

It is with their support and generosity that we have been able to meet here in Fiji this week. I thank them all most sincerely on behalf of us all.

It is my pleasure to declare this workshop on Water Resources of Small Islands officially open.

COMMONWEALTH SCIENCE COUNCIL

OPENING SPEECH, WATER RESOURCES OF SMALL ISLANDS WORKSHOP

Given by Ms K Gass

Ladies and Gentlemen, on behalf of the Commonwealth Secretary General and the Secretary of the Commonwealth Science Council, I would like to warmly welcome you to this workshop, the first of the Council's emphasis on water resources of small islands.

I wish to thank the government of Fiji for hosting this workshop and the Department of Mineral Resources, particularly Alf Simpson for its local organisation. I would also like to thank our resource people, particularly Dr Edmund Wright, for developing the programme for this workshop. Finally, I wish to thank our sponsors and various interested parties.

The Commonwealth Science Council is an autonomous intergovernmental body under the umbrella of the Commonwealth Secretariat. It's basic purpose is to increase the indigenous capabilities of individual nations to use science and technology for their economic, social and environmental development through promoting collaboration among the member countries of the Commonwealth. In the past, the Council has focussed its activities on technology transfer with limited success. Its emphasis has shifted since 1982 to the use of science for technology for development. This shift in emphasis has meant an expanded programme of scientific cooperation, which has been shaped by an Expert Group of eminent scientists from both the more advanced and the less advanced Commonwealth countries. This Expert Group is headed by Sir John Kendrew, Nobel Laureate, and has drawn up plans for expanding scientific cooperation in new areas of developmental significance, including high technology, over the next 10 years.

Water resources is one area of importance in view of its limiting function on agricultural production, industrialisation and population growth. The Council has six programme areas.

1. Environmental Planning

2. Mineral Resources, under which the Water Resources project falls

3. Energy

4. Renewable Natural Resources

5. Industrial Support

6. Science Policy and Organisation

These programme areas are designed to provide a strategic programme focus on integrated resource management.

The water resource project of the Council has been in existence for five years, and workshops have been held in the Caribbean and in Africa. This is the first activity in the South Pacific region. Ground water is becoming an essential source of water in many countries, and increasingly so on small islands. However, the approaches for developing water resources on these islands are necessarily different from those for large continental areas, due to physical size.

A much more integrated approach considering the relationship between surface water, ground water and sea water is needed, in small island situations. It is the problem of water development on small islands with particular reference to resource assessment and appropriate efficient development that will be the major focus of this workshop.

As a result of the Council's shift in emphasis to the use of science for technology for development, each project looks to the potential of promoting and initating appropriate research and training opportunuties, especially through regional co-operation, with the view to identifying solutions to common problems, assessing on-going studies, and sharing information and experience. We will therefore be investigating the need, scope and feasability for a research and training network in the appropriate aspects of water resources of Small Islands in this region. I would be grateful if you would keep this in mind during the workshop, and feel free to discuss any ideas or problems you have on this matter with any of the resource people.

On that point I would like to convey once again the appreciation of the CSC to the Department of Mineral Resources, the local organisers and the Government of Fiji for hosting this important workshop, and wish all participants a pleasant and fruitful stay in Fiji, and successful deliberations over the forthcoming week .

PROCEEDINGS REVIEW

by E P Wright

This introductory paper is designed as a personal review by the Workshop Technical Organiser. The Workshop Programme was planned to correspond with the normal procedure for a water resource development project commencing with considerations of geography, geology and hydrology, followed by water resource assessment and finally planning and development.

The geographical region of main consideration is the South Pacific Ocean and Micronesia but extends also to the low latitude islands of the North Pacific and Indian Ocean (Table 1).

There is justification for the distinction between large (>5000 sq. km) and small (or smaller) islands. The large islands of the region coincidentally have large populations, humid climates, more abundant and diverse water resources and commonly (but not always) a higher level of development. They include Indonesia, the Phillipines, Sri Lanka and Papua New Guinea.

The total population of the small island groups of the two regions is some three and a half million people and the islands have a very widespread geographical distribution. The economic level of the majority of the island countries is fairly low and a desire to attain the life style imported by earlier colonial powers has tended to impose a strain on basic resources.

The Theme I keynote presentation emphasised the problems of ´smaller´ islands with areas generally less than 50-100 sq. km. The water resources are constrained by a lack of potential storage, whether below or above ground level. High rise islands are commonly composed of volcanic rocks with a high runoff percentage and low groundwater storage. Smaller limestone islands are mainly of low elevation with thin freshwater lenses overlying sea water within the limestone aquifer. Rainfall occurrence, both total and seasonal will be critical factors whether in relation to rainwater catchments or groundwater recharge. The limitations of storage will most strongly affect islands with low rainfall and a high incidence of drought which includes notably those islands in the eastern Pacific (Figure 2 in Dale, Theme I). A second important factor in many of the smaller, low lying islands is a high population which creates problems both in terms of demand and in the management and protection of a freshwater lens.

Small islands with dimensions up to 5000 sq. km include notably the Solomon Islands, Hawaii, Vanuatu, New Caledonia and French Polynesia. Similar hydrological constraints to those occurring in the smaller islands also exist but to a lesser extent. Surface water storage schemes may be feasible, although of small size. Groundwater occurs in volcanic rocks, coralline limestone and alluvium. Populations tend to have a fairly widespread distribution and this dispersion constitutes a major factor in the provision of supply.

Water use in the islands of the region is discussed in Theme I. In the smaller islands, domestic supply is almost the only requirement other than the supply of groundwater for phreatophytic trees and other plants (coconut palms, babai). In the larger islands, a more varied use may existing including hydropower,

TABLE 1

Country	Number of Islands	Area sq. km.	Population
I PACIFIC REGION			
American Samoa	6	197	31,500
Cook Islands	15	240	18,500
Fiji	2 large 320 total	18,272	601,000
French Polynesia	130 islands in 5 main groups	4,000	141,000
Guam	1	549	90,000
Hawaii	8 main	16,638	887,000
Kiribati	33	719	56,452
Marshall Islands	34	171	29,670
Nauru	1	22	7,700
New Caledonia	1 large + 2 small groups	19,103	138.000
Nieu	1	258	3,578
Norfolk	1	35	1,698
Northern Marianas	16	471	15,970
Palau	1	400	14,800
Papua New Guinea	Eastern half of New Guinea + many offshore islands	461,690	3,168,700
Pitcairn	1 main	5	64
Solomon Islands	6 main	29,785	196,823
Tokelau	3	10	1,565
Tonga	3 main groups	671	92,000
Tuvalu	9	26	9,000
Vanuatu	80	11,880	112,596
Western Samoa	2 main	2,934	13,463

TABLE 1 (Cont'd)

Country	Number of Islands	Area sq. km.	Population
II INDIAN OCEAN			
Andaman/Nicobar	550	8,293	188,254
Maldives	1200+	298	149,000
Mauritius	1	1,860	936,000
Seychelles	100+	444	65,000
Sri Lanka	1	65,610	14,640,000
III SOUTH EAST ASIA			
Indonesia	5 main, many offshore	1,900,000	143,000,000
Malaysia	Continental; some offshore	336,700	13,463,000
Phillipines	2 large + many thousand others	300,000	45,000,000

industrial use and irrigation. A significant factor is the general importance of tourism, which requires both a safe and a high per capita supply including the provision for such exotic uses as swimming pools. Ensuring adequate supplies for tourism can sometimes be a strain on water resources, particularly on the smaller islands. Research is needed to reduce desalination costs and to make more effective the utilisation of alternative energy sources.

Legislation was the subject of the third presentation in Theme I. Legislation includes both written legislation and customary law and ideally should provide the essential controls required to ensure a fair and equitable distribution of a basic natural resource and the maintenance of its quality and quantity. Complications exist due to the diverse ethnological background of the populations, often within a single country, in addition to the influence of alien laws deriving from earlier colonial constitutions. In the independent small island countries, little formal legislation on water resources exists and statements of policy are generalised and do not include a Water Code. Customary law typically provides full ownership of water resources to associated landowners. With development, it is inevitable that conflicts will arise if land access is to be obtained or adequate protection of water sources to be ensured. There is an urgent need for the enactment of legislation which will be effective and acceptable. There is a tradition by which people of this region will sacrifice private ownership right for public benefits, preferably by leasing arrangements. State ownership is not favoured and emphasis should preferably be placed on natural user rights.

Theme II. The Formation of Islands.

The islands of the region may be divided into three main categories:-

(i) Continental islands which are a detached part of an adjacent land mass. Examples are Sri Lanka and the Seychelles.

(ii) Island arc islands which occur on the continental side of deep trenches and have some continental affinities. Associated volcanics are predominantly andesitic, hence the alternative classification of Andesite Province. Examples are Indonesia-New Guinea, the Phillipines, the Solomon Islands and Vanuatu.

(iii) Islands of the Oceanic Province occur on the oceanic side of trenches or subduction zones. Volcanic rocks are mostly basaltic (hence Basaltic Province and associated with intraplate volcanism. Examples are the Hawaiian islands and French Polynesia.

Some broad water resource correlations can be recognised. The volcanic sequences of the island arc andesitic province have a predominance of submarine flows and ill-sorted pyroclastics, both of poor permeability and porosity. The main aquifers are in limestones, notably raised reefs, or localised alluvial sediments. Oceanic islands with older volcanic sequences and abundant pyroclastic rocks also tend to have poor productivity in associated aquifers. In contrast, young volcanic centres have a predominance of lava flows which contain highly permeable and porous aquifers, chiefly a consequence of the abundant vesicular and fragmentary rocks in a multiple sequence of thin flows. Oceanic islands are generally submergent and may ultimately form atolls. Atolls are low lying limestone islands and water resources are effectively limited to groundwater occurring in thin freshwater lenses.

The Keynote Speaker concentrated his discussion mainly on the oceanic islands. Of the various theories of origin, he favoured one in which deformation of the lithosphere occurs as a consequence of sea floor loading by volcanic piles. The sequence which commences as an initial emergence of a volcano above sea level is followed by subsidence due to the loading of the lithosphere and is reflected in adjacent areas by emergence of other islands due to a concommitant upward bulging of the lithosphere. Although the general sequence of events fits the broad hypothesis, there are islands, such as some in Hawaii, with anomalous features. In addition to the effects of such tectonic/isostatic forces, there have also been major eustatic changes in sea level consequent on the periodic melting and freezing of polar ice caps.

The Keynote Speaker also reviewed the trend of age relations exhibited by rocks of the Oceanic Province with results summarised below.

(i)	Occurrence:	Ridges -	seamount -	guyot -	atoll -	volcano
(ii)	Average age: millions of years	89	48	37	17	5

Dates are mainly radiometric. Other methods include subsidence rates and geomorphological expression (for relative ages). Subsidence data do not generally give a good correlation with radiometric dating.

There were four ancillary speakers in this Theme who provided discussions on standard atolls, on a raised atoll (Nieu), on younger oceanic volcanic islands (Hawaii) and on the geology of an island arc group (Lau-Fiji). The theory was propounded that atolls may not have formed to any great extent until the very recent stabilisation of sea level (i.e. within the last three thousand years). The proposal does not accord with the age sequence outlined earlier, nor with the raised atoll, Nieu, which is composed mainly of Miocene limestones. Nieu also lacks the indurated sediments of the reef plate which may perhaps characterise the more modern atolls.

The value of an understanding of the geological controls must be stressed. In addition to the broad correlation of resource characteristics with age and the geochemical province, other regional controls which have caused elevation or subsidence or changes in sea level have been of critical importance in determining the hydrogeological characteristics of the limestone sequences relating either to original lithofacies or to secondary features, cementation and karstification.

Theme III. Island Hydrology and Hydrogeology.

Theme III was designed to provide the baseline hydrology and hydrogeology. Inevitably, the quantitative understanding resulted in some overlap with Theme IV, resource assessment.

The Keynote Speaker concentrated entirely on the situation of the smaller, low limestone islands and the occurrence of the freshwater lens. From the very comprehensive review which he presented, the principal conclusions are set out below.

(i) <u>Recharge</u>: Best calculated by soil moisture balance unless the soil cover is thin or absent. Factors which must be considered are set out below.

Runoff typically small to negligible but it can assume very significant proportions (up to 90% in one instance) with intensive rainfall. Sheet flow may occur which will be difficult to quantify.

Interception: 7.5% and 15% quoted for two case histories.

Instantaneous recharge: significant, 10% evaluated in one modelling study.

Evapotranspiration: monthly data, minimum requirement; Penman method recommended.

Root Constants and Maximum Soil Moisture Deficits: generally estimated.

Phreatophytic Discharge: may be a significant component of discharge.

(ii) Freshwater Lens Geometry and Response Characteristics: Influences include ground layering and groundwater head fluctuations. Latter can relate to recharge, transmissivity, storage and tidal and barometric effects. Overall response is essentially dynamic. Ground layering affects lens geometry and response to stress (i.e. abstraction, etc).

The use of a range of empirical factors to be added throughout the recharge calculations is daunting and disturbing and certainly provides encouragement to seek alternative methods such as the chloride balance (described in Theme IV). A combination of geophysical survey and drilling is essential for lens investigations, although if initial results indicate fairly uniform conditions, a simplified model can also be considered as both a predictive and management tool.

The majority of the ancillary papers continued the emphasis on the smaller, low limestone islands. In the discussion of hydrochemistry, the variability of the chemical composition of rainfall and the major control of aerosols (wave generated particles) were noted. An important factor brought out in the paper on climatology is the marked orographic effect which can occur over quite small islands, less than 100 sq. km, and moderate height. The one paper on groundwater in atolls provided an important case history, extending and developing the issues raised by the Keynote Speaker. Most notably, the effect of lateral heterogeneity (the reef flat plate) on the shape and the response of the lens is illustrated. The two main geophysical techniques most applicable to the situation in low limestone islands are seismic refraction and electrical resistivity.

The final paper discussed the ecology of islands and the relation of vegetation to water. Apart from the general correlations such as the occurrence of phreatophytes above shallow water tables and the abundance and diversity of plants which occur above the thickest part of the freshwater lens, the speaker referred to other important controls on vegetation, notably the cyclonic winds and the interference of man. This last point is significant both on low limestone islands and on the larger more variably vegetated islands. The effect on water resources is discussed of the replacement of forest by grassland.

Theme IV. Water Resources Assessment.

This Theme covers much the same topic as Theme III but with a greater emphasis on techniques of measurement and results of case studies. Appropriate surface hydrological measurement networks have been mainly evaluated for larger islands with graphs of station densities occurring for the range 100-20,000+ sq. km. It was suggested that for smaller islands, presumably less than 100 sq. km., four rain gauges and one evaporation station might suffice and for low atolls, one rain gauge and one evaporation station. In high volcanic islands with varied topography, the number of gauges would need to be higher. It should be remembered that these guide lines have been developed for analysis of total rainfall. Since the geochemistry is also important, particularly for recharge calculations, the controls to the variability of composition needs also to be taken into account in planning networks. Selection of station density should preferably be based on experimental studies. For remote areas solid state loggers attached to recording rain gauges are to be recommended. One paper discusses tests being carried out on the Solomon Islands with this type of equipment.

Surface runoff measurements may be required for safe yield estimates on surface flows, for flood studies, to evaluate hydroelectric potential or in connection with groundwater recharge. In the case histories presented at this Workshop only the last named objective was under consideration. In low limestone islands, runoff is generally considered unimportant except under very intensive rainfall conditions where water logging and sheet flow may occur. Runoff studies have been mainly undertaken on the larger volcanic islands, for water balance or for base flow analysis.

Evapotranspiration is the largest element in the hydrological cycle after precipitation. Corrected pan evaporation figures are more commonly used than Penman calculations which require extensive data.

One lecture was concerned wholly with modelling. Results of modelling studies are also referred to in a few case histories. The models used have been of the predictive type to assess probable response of the aquifer to stresses such as pumping or variations in reharge. The potential of modelling is yet to be realised and limitations of data are usually regarded as the main constraint to construction. A better understanding of regional geological sequences may allow more standardised models to be developed.

Calculated recharge rates vary from negligible to high proportions of total rainfall as shown in the listed figures below.

I Volcanic

Island	Occurrence	Method	Recharge as Percentage of Rainfall
Hawaiian Islands	Oceanic Province	Soil water balance	(i) Young volcanics 30-36% (ii) Old volcanics 16%
Babelthuap	Oceanic (Old volcanics)	Baseflow	6%
Efate	Island Arc	Baseflow	27%
Norfolk	Island Arc	Soil water balance Chloride balance	25% 18%

II Limestone

Peleliu	Limestone	Well hydrographs	20%
Male	Coral Limestone and sand	Flow net	41%
Guam	Coral atoll	(i) Various methods (ii) Chloride balance	37-62% 38%
Christmas Island	Coral atoll	Soil water balance and model	11-29% (varying with degree of cover of coconut groves)

The older oceanic volcanic sequences in Hawaii and Babelthuap show low values of recharge, 6 and 10% and this is generally attributed to weathering effects resulting in high runoff. The fairly high values of recharge for the island arc volcanics on Efate and Norfolk island are rather higher than might normally be assumed for these rock types of the Andesite Province and may perhaps be atypical.

In the limestone islands, the chloride balance tends to give lower values than the soil water balance methods. In general, errors in the former method, other than an overestimate of the rainfall chlorides, would tend to underestimate recharge and a fair consistency of the two methods may be assumed. The importance of the vegetational cover, notably coconut groves, should be noted. Recharge can be increased by reducing the cover of this tree.

Theme V. Planning and Management

The Keynote Speaker reviewed the constraints and inadequacies which are affecting planning and development in the region. These include institutional, economic, geographical/logistical, policy and legislation, and hydrological. He makes the important point that the Decade targets will be met, in many cases sooner than 1990 but quality of service needs upgrading. Urban supplies are generally adequate in the region but rural more variable.

The ancillary speakers covered a wide range of topics which included groundwater development aspects in high oceanic islands (dyke aquifers) and in atolls (galleries), rain water catchments, pollution, drilling and pump testing, desalination and surface water measurement planning for small islands.

Three papers were concerned with rainfall data processing either generally or more specifically in connection with planning storage capacity for rain water catchments. For the latter, two methods of calculation are described in detail.

Dyke aquifers had been referred to earlier in relation to Hawaii where high level aquifers have been impounded by vertical dykes and are tapped by horizontal drilling. The occurrence described in Theme V relate to an exploration drilling project in Tahiti. The results demonstrated that the aquifer geometry was more related to heterogeneities in the lava pile, mainly horizontal or shallow dipping, without apparent impoundments occurring in consequence of vertical dykes (see Figure associated with Conclusions). The aquifer head measurements were low and much less than the altitude of perched springs which are supposed to represent the overflow of the dyke aquifers. Since the dykes do not result in a significant build up in head and aquifers constitute a stratified series with restricted interconnection, horizontal boreholes will have an inflow restricted to the main layers which are intersected and drilling angles and directions could prove critical factors.

Two papers were devoted to groundwater development in atolls and the discussion of Christmas Island was particularly comprehensive on aspects of gallery design and construction. It is important to note that even with very lengthy skimming galleries, which must be adjudged the most effective way known at present to abstract from fresh water lenses, only a relatively small proportion of recharge is feasible to abstract. In the case of Kwajalein this amount is 16% of total recharge and for Christmas Island between 10 and 13%.

Two papers were concerned with pollution in small island water resources. Although a wide range of pollution occurrences have been identified overall which includes contamination of rain water (in the atmosphere or from catchment materials), contamination of other water sources including groundwater by leakage of toxic fluids from airfields or military installations, of chemicals used in the timber industry, canning and agriculture, and by domestic garbage and sewage, it is concluded that the main threat to small island water resources are the inappropriate use and handling of pesticides and inadequate sewage disposal. Monitoring of water supplies is given an obvious priority although it must be pointed out that in the case of the agrochemicals this is rather easier said than done, since there is no straightforward indicator equivalent to coliform bacteria for sewage. An emphasis is recommended on restrictions in use of dangerous chemicals which if and when used should be costed to include the expense of appropriate monitoring. Legislation is particularly critical to ensure protection of such highly vulnerable aquifers as fissured limestone or highly permeable volcanics.

The final and most important topic to be referred to in Theme V is desalination which must also include alternatives to water supply other than from localised developments of groundwater and surface water. Desalination has an obvious attraction for islands with water resource problems and a particular potential for low limestone islands with a dense population and a fresh water lens at risk due to overabstraction, high drought incidence or excessive vulnerability to sewage (or other pollution). The main constraint to desalination is cost. Of the various methods, the cheapest would appear to be reverse osmosis and this is the method discussed in three of the papers of this Theme.

Various figures of cost, either capital cost of plant, or overall cost of production are set out below as a basis for comparison. Australian and Tonga dollars (palanga) are currently equivalent at 1.5135 to the pound sterling, the Fiji dollar is 1.2814 and the US dollar 1.07. Some data has also been provided from outside sources, notably for Anguilla in a published document and from the Dupont Company. Gallons are assumed to be imperial gallons unless stated otherwise.

Christmas Island. Production requirement: 11,000 gpd (50 m^3/d)

Method of Production	Cost per m^3 (Australian $)
Gallery:	3.72
Desalination (conventional reverse osmosis):	6.41
Solar still:	4.27

Rainwater collection:	20.00 (in excess of)
Importation (tug/barge):	9.31

Note: The above costs include capital, operating, maintenance and replacement costs with a discount rate of 10 per cent.

Fiji Offshore Islands.

Method of Production	Cost in Fiji Dollars
Importation (barge):	6.00
Desalination (R/O):	20.00-40.00 (estimated)
Capital cost of small plant:	4-6 F$ per litre per day capacity

Tonga.

Estimated cost of 50,000 gpd plant (230 m^3/d): 60,000 Tonga Dollars equivalent to 0.26 T$ per litre per day of capacity.

Anguilla.*

Brackish R.O. Plant: 20,000 ≡ 75 m^3
Estimated production costs (presumed total costs): US$ 5.80 per m^3

The estimated costs of R/O production at Christmas Island and Anguilla are fairly comparable for similar size plants. The estimated rate for Fiji is much higher and appears excessive. The total estimated cost for production at Tonga is not quoted but would seem likely to be appreciably lower than for Christmas Island, perhaps as little as T$ 1 per m^3.

Three tables from the Permasep† Engineering Manual have been reproduced below. It must be emphasised that actual costs will vary significantly for different locations depending most notably on the size of the plant and the energy costs. Commercial R/O for intermediate size plants (50,000-100,000 US gpd; 190-380 m^3/d) are generally quoted at US$ 5-10 gpd of capacity for sea water treatment (US$1.3-2.6 per litre per day of capacity) which is significantly more than the estimated rate for Tonga. On the assumption of 10 US$ per gpd, the smallest plant in Table IX for a production of 36 m^3/d would include US$ 3.36 per m^3 amortisation of capital to be added to the US$ 1 per m^3 of production giving a total figure of cost of some US$ 4.36 per m^3. This is rather less than the cost quoted for Christmas Island and could relate to variance of energy costs. For larger plants and with brackish water use, costs drop appreciably (Table II from Permasep Engineering Manual, Bulletin 307) corresponding with lower energy costs and a relatively lower amortisation. These results demonstrate the potential of R/O desalination for the small limestone islands with dense populations, such as Male or Tonga.

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* Goodwin, R S Water Resources Development in Small Islands, Perspectives and Needs. Am. Soc. of Civ. Eng. Nat. Speciality Conference on Water Supply - Florida, 14-16th March 1983.

† Reg. U.S. Pat. & Tm. Off. for Du Pont's Permeators (Du Pont Company).

TABLE II
BRACKISH RO SYSTEM
TOTAL WATER COST
18,900 m /d (5 million GPD)

	Cost of Product $/m ($/1,000 gallons)
Energy 1.57 kWh/m ($0.06/kWh)	0.09 (0.36)
Chemical Cost	0.02 (0.09)
Labor Cost	0.03 (0.12)
Maintenance and Repair	0.01 (0.05)
Membrane Replacements	0.03 (0.10)
Amortization	0.13 (0.48)
Total Water Cost	0.31 (1.20)

TABLE XI
SEAWATER RO SYSTEM
TOTAL WATER COST SUMMARY
3,785 m /d (1.0 million GPD)

	Cost - $/m	($/1,000 gallons)
Energy (6.4 kWh/m)($0.06/kWh)	$ .38	$(1.45)
Chemical Cost	.01	(.05)
Labor Cost	.18	(.70)
Maintenance and Repair	.05	(.20)
Membrane Replacement	.19	(.71)
Amortization	.41	(1.55)
TOTAL	$1.22	$4.66

TABLE IX
PERMASEP* PERMEATOR SEAWATER RO SYSTEMS
ACTUAL OPERATING COSTS FOR FOUR PLANTS

	Ras Al Mishab	Cowpet Bay Condominium	Key West	Cadafe
TDS	43,000	33,000	38,000	38,000
Size	284 m³/d	36 m³/d	11,355 m³/d	3,785 m³/d
Energy	1.13 (2¢/kWh)	2.50 (10¢/kWh)	2.03 (8¢/kWh)	0.423 (4¢/kWh)
Chemicals	.15	.15	.08	0.174
Filter	.50	.20	—	0.053
Other	.03	.20	—	0.074
Labor	.22	.14	.39	0.132
Membrane Replacement	.62	.62	.03*	0.0 **
Operating Cost $/1,000 gallons of product	2.65	3.81	2.53	0.856
(/m³)	(0.70)	(1.00)	(0.67)	(0.22)

*Minimal replacements for 1st two years.
**No replacements for 1st two years.

Conclusions.

The Workshop Proceedings have extended over a wide range of issues concerning the water resources of small islands. The aspect which has been given most prominence relates to the fresh water lens which occurs on low limestone islands. There has been a very thorough review given of fresh water lens systems in relation to geology, recharge, vulnerability to pollution and methods of development. Evidence put forward would favour groundwater as the most cost-effective supply source but for the more densely populated smaller islands, such as atolls, it is possible that R-O desalination could be competitive even now and probably more so in the future. Energy costs are a critical factor and cost effectiveness would improve if cheaper, renewable energy resources can be developed.

Of the other two main types of island - continental and island arc - there has been little emphasis and the omission is perhaps most significant in the latter case since they include such important groups as the Solomon Islands and Vanuatu. Although commonly falling into the defined category of small islands (<5000 sq. km), many are of significant size and in consequence surface water, either run of river flow, or springs, constitute important supply sources. For planning purposes, it is necessary to make comparisons on the potential and cost effectiveness of development of both ground and surface water. The circumstances in Vanuatu will be described below as an example of the issues involved and because the writer has some first-hand knowledge of the country*.

The rural population of Vanuatu is some ninety one thousand out of a total of one hundred and eleven thousand and is dispersed widely throughout the island archipelago (total area of 14,800 sq. km) although often concentrated along coast lines. The recent census showed that 29,939 live in localities with less than 50 people and 77,743 (the majority) in localities with less than 200 people. A summary of water service data is shown below.

Summary of Water Service Data for the Rural Population of Vanuatu to end 1983.

		Percentage
Rural Population	93,745	100
Water service projects completed (by population)	39,572	42
Water service projects in progress (by population)	10,948	12
Residual population without basic supply	43,528	46
		100

* Wright, E P 1984. Water Resources in Vanuatu (unpublished BGS Report WD/OS/84/5).

Projects completed or in progress in relation to water source	Population	Percentage of Population with service
(i) Spring sources	15,674	37
(ii) River sources	9,079	21
(iii) Rainfall catchment	8,159	19
(iv) Wells/boreholes (locally combined with rainfall catchments	9,753	23
	42,655*	100

*includes some surveyed

These results demonstrate that some 46% of the total rural population do not have access to a basic service. They also demonstrate that of the existing supply sources, spring and river flow account for 58% of the total to date. There is a general preference for a piped distribution system from a spring or remote river source mainly because of the assumed safe quality and the lack of maintenance requirements. However in the context of planning for future development, two main factors need to be taken into account, cost and timing. For standard gravity feed systems, the costs can be demonstrated to be about 7118 Vatu per capita (110 Vt - £1) made up of 4500 Vt for materials and 2618 Vt for labour, supervision and transport. In rural water supply budget terms these costs are fairly high and reflect the significant duration of project construction. Costs are likely to remain at an equivalent level in the future or to increase because sources are dispersed and the larger sources for bigger population centres have been generally utilised already. Reservoir storage schemes have been discounted because of the high costs associated with such schemes and their unsuitability for dispersed populations.

The lengthy duration of construction of typical rural water schemes has been referred to and the current annual progress of service cover is between three and five thousand of population service annually. In the context of a residual population of over 43,000, there is clearly little hope of attaining Decade targets as set out in the National Development Plan without very large increases in project inputs, staff and materials or the use of more effective (time as well as cost) methodology. This might be obtained by integrated projects in areas of greater demand (two islands have a residual population without cover of 22,000) in which all supply options can be given appropriate consideration and which will allow a more concentrated and effective deployment of professional and technical expertise. The increasing utilisation of groundwater could prove very advantageous *in both overall time and cost terms* in comparison with development of remote surface sources of supply, even taking into account increased maintenance requirement and pumping costs. Precise costing for groundwater development for comparative purposes is not readily available, nor can the standard costs of a dispersed drilling programme using slow and cumbersome cable tool rigs be utilised to make a fair comparison. However, it could be anticipated that a figure of 2000 to 3000 Vt per capita would be a reasonable estimate and would still represent an overall lower† total cost. Groundwater development would require greater expertise in relation to siting, avoidance of pollution etc. The more effective use of professional manpower within integrated projects should ensure such an input.

† Taking account of all factors for either type of development including amortization of capital outlay.

Acknowledgements.

The assembling of such numbers of speakers with a wealth of first-hand experience of the region is not likely to occur again for some time. I should like to take this opportunity to express my appreciation to them all for their contribution to the success of the Workshop and for their generosity in giving their time throughout the days and during most evenings. This paper is published with the permission of the Director of the British Geological Survey (NERC).

THEME 1 GENERAL REVIEW

THEME I

General Review of Water Resources Development in the Region with Emphasis on Small Islands

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* The opinions expressed herein are those of the author and do not necessarily reflect the views of the United Nations

1. INTRODUCTION

The Pacific Ocean contains more than 30,000 islands. Most of these are located south of the Equator. Oceania is the generic name given by many geographers to most of the islands. Three main groupings are recognized according to geographical and ethnographical criteria, that is, Polynesia in the Central Pacific, Micronesia in the Western Pacific, North of the Equator, and Melanesia, South of Micronesia, mostly south of the Equator.

This paper deals with water resources aspects and problems in smaller inhabited islands of the Pacific. The boundaries of the area covered are: to the north, the southern maritime boundaries of Japan and its possessions, and of Hawaii (USA); to the west, the Philippines and Australia; to the south, New Zealand.

An inventory of the smaller inhabited islands of the area is presented in Table 1 (attached). "Smaller" should be understood as follows:

- area: generally less than 50 km^2; 100 km^2 at most;
- width: not exceeding 3 km (exceptionally 5 to 7 km).

These features imply that a smaller island contains a small and thin fresh ground water body surrounded by salt water.

This workshop, sponsored by the Commonwealth Science Council, follows a similar workshop which was held in co-operation with the United Nations on 6-11 October 1980 in Bridgetown (Barbados). Caribbean and Pacific islands present many similarities in terms of their dimensions and geological conditions, in that the majority are volcanic and low-rise limestone islands; their tropical oceanic-type climates, their latitude (10° to 27°N. for the Caribbean; 10° to 27°S for most of the Southern Pacific islands); and their vulnerability to tropical storms. However, there are considerable differences in terms of the ethnographic and cultural background of the populations, and also in the dimensions of the area. The Caribbean islands are mostly distributed along a relatively narrow arc which extends over 2,000 miles from the Bahamas to Trinidad. The Pacific islands are scattered over an immense area some 6,000 miles long from Palau in the N.W. to Pitcairn Island in the S.E., and 3,000 miles wide from Vanuatu in the S.W. to Honolulu in the N.E. A distinct feature of the Pacific area is the atoll-type island which is not encountered in the Caribbean.

As far as water resources are concerned, both areas have much in common in terms of occurrence of rainfall and ground water, although rainfall is in most cases more abundant in the Pacific. In both areas, extensive development of scarce water resources is required to serve the needs of densely populated areas and tourist facilities. The problems encountered, including salt water intrusion and overdraft, are similar, as are the types of technologies utilized for assessing the water resources potential and for developing the resources. It, therefore, would appear most useful to promote an exchange of information between water specialists of the two areas starting with the reports of the two workshop sessions.

2. GENERAL

While a variety of climates can be encountered in the vast Pacific area, the range of temperatures between the tropics of Cancer (Hawaii) and Capricorn (New Caledonia, Tonga) is narrow. It never gets really cold at sea level as the sun stays mainly overhead during most of the day; nor very hot, as cooling winds blow from the sea. In most inhabited islands average temperatures range from 22° to 26° C.

Winds are generally uniform in the trade wind belts. In Polynesia, hurricanes (called typhoons) are frequent. Yearly rainfall values are mostly in the range of 2 to 3 metres. In high-rise islands rainfall values vary sharply according to elevation. For example, on Ponape at an altitude of 700 to 800 m, yearly rainfall values may exceed 10 metres. Sharp contrasts can also be observed between windward and leeward exposures (for example, windward sides may receive 1 m compared to 4-5 m rainfall on leeward sides per year). In most areas humidity averages 60 to 80 per cent.

In terms of geologic origin and features the Pacific islands are quite distinct from the continents bordering the Pacific Ocean, including Australia. The islands of Polynesia correspond to the tops of volcanic mountains which rise steeply from the floor of the Pacific Ocean up to 5,000 metres and more. Some of these summits have been eroded by the movement of the sea close to sea level and have been capped by limestone reefs built by marine living organisms. These reefs have developed under water at shallow depth. Debris have accumulated over the surface forming low sandy islands.

The atolls are formed of a narrow (a few hundred metres at most) and interrupted strip of reef enclosing a shallow lagoon. Atolls are generally only a few metres above sea level, their shape varying widely from sub-circular to sub-triangular; their dimensions can be considerable, up to 120 km in length (Kwajalein). In some cases atolls have been raised up by earth forces so as to constitute massive islands. The raised lagoon has emptied and constitutes a topographic depression in the centre of the island. The largest raised atoll is oval-shaped Niue Island (15 x 20 km). Its central plateau is about 30 metres above sea level.

High-rise islands have occurred when volcanic extrusions have risen high above sea surface. The highest volcanic peak in the Pacific Islands is Mauna Kea in Hawaii (4,200 metres above sea level). In general, on high-rise islands the volcanic core, which may be active, is surrounded by a coralline platform (Rarotonga, Cook Islands), the island itself being surrounded by a lagoon and an atoll reef (Truk, Bora-Bora).

Pacific islands are mostly distributed along volcanic chains; that is the case of the Hawaiian Islands, the Society Islands and Samoa.

The atolls of the Pacific are densely populated. For example, on the three atolls of Tokelau the population is about 3,000 over a land mass of about 10 square kilometres. In high-rise islands the population is concentrated in the narrow coastal platforms.

Coconut trees are among the most valuable resources. Coconut juice is particularly important as it is the only drinking supply available when prolonged droughts occur. Copra made of dry coconut meat has traditionally been the main export of the islands. Other tree-grown staple foods are breadfruit, bananas, papaya, mango, pineapples and oranges. Small gardens have been developed close to dwellings. In atolls these gardens are developed in shallow pits dug into the coralline sand down to a few centimetres below the fresh water level. Leaves, vegetable debris and manure are deposited into the pit, allowed to rot and a fertile thin and wet soil is therefore constituted in which taro or "elephant ear", a potato-like root making starch food, is grown. Other garden crops include mainly sweet potatoes, and diverse vegetables. In major islands rice and sugar cane are grown. Small pigs and chickens, fed mainly with food scraps, and goats in high-rise islands, provide the only local meat available. Islanders are expert fishermen. Phosphate deposits are exploited on some islands (Nauru, Kiribati). They represent practically the only mineral resource of smaller islands.

A local subsistence economy still exists in islands which are not easily accessible, that is, which do not have an airport or an airstrip. A trend towards the depopulation of the smallest islands or islets, which include a few hundreds or a few scores of inhabitants, can be observed while the main centres, capitals with services, shops, airport and other facilities, are growing and eventually may absorb the entire population of an island or a cluster of islands.

There is also a growing emigration of active manpower towards industrialized countries: Australia, New Zealand, USA (via American Samoa, Hawaii), France and the United Kingdom.

Rapidly growing urbanized areas such as Colonia in Ponape and Bonriki in Tarawa (Kiribati) have created social problems. Tourism is one of the main sources of income for the Pacific island countries. The presence of several military installations, some being of major importance, especially in Micronesia, has also a major impact on the economy, the environment and society.

3. WATER NEEDS

Water is one of the major natural resources of the islands, which are poor in productive soils, minerals and energy. Water demand has been rising rapidly as a result of: concentrations of population in a small number of crowded areas, such as on the islet of Ebeye in the Marshalls, which has a population of about 5,000 and is only 1,700 m long and 150 m wide (a population density of 2000/km^2); the presence of military installations; the development of luxury hotels; and rising living standards of the population.

In the traditional way of life, water is needed for:

- Drinking: generally rain water, collected from roofs, is needed, together with ground water, if not too brackish. If these two sources are not available, coconut juice is used;

- Cooking: brackish well water can be used and also poor quality surface water;

- Bathing, cleaning utensils, washing: if no better resources available, sea water can be used for such purposes;

- Agriculture: irrigation is not commonly developed; however, surface run-off is in some cases diverted to the pits under cultivation. Water is also needed to sustain the tree (coconut, breadfruit, etc.) and bush vegetation. It has been observed in atolls that if a severe drought occurs, ground water reserves are depleted by evaporation, which is not compensated by infiltration. As a result, saline water intrudes inland from the coastline into the cultivated pits, destroying the crops. The trees also suffer: leaves turn yellowish and crops are damaged. An excessive draft on ground water resources by means of drainage or pumping so as to substantially increase the availability of domestic water would have similar effects leading to the destruction of the very food base;

- Drinking water for animals (mainly pigs): the population shows an ancestral tendency to use large quantities of water when available without restraint; this carefree attitude to "enjoy the day" results from the uncertainties of tomorrow and the permanent threat of hurricane disaster, compensated by a great resilience in times of need. For example, in Papeete (French Polynesia) water consumption, or waste, was recently estimated to be in the range of 1.5 m^3/capita/day. Moreover, it has been reported that, in another country, taps of standposts (fed by pumped ground water) are kept open by the people, who fear that water will not come back if taps are shut off. On the other hand, in some atolls, during prolonged droughts, the population live on coconut juice for drinking and 2 litres of brackish well water per day per person.

In small towns and villages where water supply systems have been developed, water consumption can be estimated at 20 to 40 litres/day; water consumption in hotels and military installations may be estimated at 100 to 200 l/day.

The concept of water demand in such areas is quite vague and extremely flexible. In Micronesia many dwellings get their supply from 50 gallon drums which receive rain water collected by roof catchments, and most, if not all of the water thus collected is used for bathing. This almost unlimited demand is matched by an erratic and limited water availability.

4. WATER RESOURCES

Five sources of water are available:

Rain water is the main resource. Its distribution in space varies widely. Total yearly rainfall can be as low as 700 mm and as high as 10 m and more in the high spots of Ponape. In most areas rainfall is in the range of 2 to 3 m per year and is sufficient to sustain vegetation, as well as to recharge the fresh ground water bodies, and to meet the needs of households and public services.

Generally, 200 to 250 rainy days may be observed per year, especially in Vanuatu and parts of Micronesia. Most of the rainfall occurs during a rainy season which can be as short as 3 months or as long as 7-8 months. In most southern Pacific islands, the rainy season ends in March/April, while it can start as early as October or as late as December. On the other hand, in Micronesia, north of the Equator, January to April are the driest months and July to November the wettest months. Some rain occurs during the so-called "dry season". Water supply conditions become dramatic in smaller islands if no significant rains occur during periods of 2 months and more.

Surface water. Runoff occurs only in high-rise volcanic islands if the volcanic rocks are not too porous; if that is the case, most runoff waters are lost to the sea. In general, topographic conditions are not favourable for storing water behind dams in sizeable quantities. The occurrence of ponds at the foot of volcanic massifs is common in Micronesia. Taro pits are developed in such areas. Under exceptionally favourable circumstances of rainfall and topography mini-hydropower development is feasible (in Ponape).

Springs. In high-rise islands springs occur either as outlets from volcanic rocks or as seepage from alluvium fills. That is the case particularly in several Micronesian islands.

Ground water is one of the major resources. A United Nations publication entitled Ground Water in the Pacific Region (Natural Resources Water Series No. 12) was issued in 1983, and provides an overlook of water resources availability in Pacific island countries. In most of the islands a fresh water lens occurs. In atolls the fresh water layer is quite thin (in many cases it does not exceed 1 metre); the water resource is not significant in terms of extraction for human consumption if the width of the island is less than 1/2 mile. However, it is sufficient to sustain the vegetation, and especially coconut groves, even if the island is narrow. In times of drought the fresh water lens evaporates to a certain extent, ground water salinity increases and the vegetation suffers.

In smaller volcanic islands ground water resources are not well known as a result of their difficult accessibility at depth. Seepages of fresh water can be observed at the contact between the volcanic core and the surrounding coralline platform.

Desalinated water. Desalinated plants, due to their high capital and operation costs, have been installed on some smaller islands mainly, if not exclusively to serve the needs of military or tourist installations. The possibility of utilizing solar energy to desalinate brackish water has been considered.

5. WATER RESOURCES INVESTIGATION AND ASSESSMENT

A certain amount of information is available on rainfall in the Pacific Region, but this information is far from being sufficient. The reasons are that: the rainfall is quite erratic in space and in time; only a few smaller islands have rain gauges, which are operated by unskilled personnel; and the rainfall data collected on large islands cannot necessarily be extrapolated to the smaller ones as the dimensions and morphology of the land mass and its exposure to winds are paramount factors in the distribution of rainfall.

It seems also that the available data have not been fully analyzed so as to determine the likely frequency and length of drought periods, a fundamental element in the knowledge of water resources in the region, including ground water.

Ground water resources have been studied in a very sophisticated manner in a number of atolls and limestone islands for community water supply or for military purposes. This has been the case in particular in the Marshalls, Cook Islands, Tuamotou, Tonga, Kiribati, Niue and Tuvalu. These investigations have included: water balance studies, delineation of the fresh water/salt water interface, by means of geophysical investigation; pumping tests. interpretation and modelling. They have shown the complexity of the interrelationships existing between fresh water bodies and their brackish or saline environment. They have also shown certain complexities in the lithology of atoll aquifers (massive coral, coral debris and sands).

The hydrogeology of volcanic islands has been studied mainly on major islands especially in Fiji, Yap, Society Islands, Vanuatu, and in lesser islands of political importance such as Moen Island in Truk. However, the investigations, mostly local in character, have indicated great variations in geological features, especially as regards the lithology. It is therefore difficult to draw conclusions which would validly apply to smaller islands, since the size of the land mass considerably affects hydrogeological conditions.

Most of the ground water investigations in the Pacific have been carried out in isolation, by a variety of firms and organizations from several industrialized countries, mainly the United States, the United Kingdom, Australia, New Zealand and France. A listing of projects carried out within the framework of the United Nations system is provided in Annex II.

The publication, Ground Water in the Pacific Region, contains listings of selected references. It would be extremely useful to establish a complete analytical bibliography of all the material dealing with water resources in Pacific islands. A similar work has been carried out in the Caribbean region by a United Nations expert.

6. DEVELOPMENT AND CONSERVATION

In small islands, and especially in atolls, most of the domestic and community water supplies originate from rainfall collection, mainly by means of roof catchments. A variety of technological, traditional and modern, are involved. Storage devices are extremely diverse; households utilize 50-gallon drums when available. Water is also stored in excavations, in ferro-cement, asbestos or aluminum tanks. A survey of the various technologies in use or usable in the area, including an evaluation of their effectiveness, operational and maintenance problems and costs, would be extremely helpful.

Large roofs such as church roofs are among the best and most economical collecting surfaces; also to be mentioned are airport runways if asphalted (Majuro), and asphalted land catchments. One of the problems is the conservation of the quality of water. Simple filtering devices using local materials have been developed and tested as pilot projects: in several cases results have proved deceptive as the installations were not maintained, abandoned or worse, vandalized.

In volcanic high-rise islands small storage and diversion dams have been built. Ponape has perennial streams, which is exceptional for islands of such modest dimensions. Springs in most cases are private property. One of the problems is the protection of the catchments against the intrusion of people and animals.

Ground water is developed mostly by means of shallow dug and drilled wells which tap the fresh water lens in its upper part. In most cases the yields have to be kept low so as to leave the fresh/brackish water lens as undisturbed as possible.

Ground water is also developed for agricultural purposes by means of the taro pits already mentioned in section 2 above.

In atolls ground water is particularly vulnerable to pollution. In order to conserve its quality, various measures have been taken such as: construction of "banjo" toilets along the shores, above the sea; restrictions on the circulation of pigs by keeping them behind enclosures, or tied to trees; disposal of refuse as far as possible from the wells.

The use of detergents, fertilizers and pesticides pose a real threat to the scarce water resources, especially in atolls.

7. POLICIES, INSTITUTIONAL ASPECTS, LEGISLATION

Two cases are to be considered. The first is the case of major islands with an airport, or a major airstrip or a political capital with government buildings, for example Moen (Truk State), Funafuti (Tuvalu), Majuro (Marshalls), Rarotonga (Cook Islands) and Tarawa (Kiribati). In such islands some kind of central water supply system does exist under the management of a water authority or a governmental technical service.

In less developed islands most water supply installations are individual, it being understood that each house with its own well or rain water collector may be occupied by several families; in addition, there are some community wells and storage reservoirs.

The World Health Organization has contributed to developing an awareness of the importance of the protection of water resources against contamination, especially in Tonga, by providing support to water boards or water authority-type organizations.

Because of the abundance of rain, water supply and sanitation have received little attention from government planners on smaller islands where human communities live in isolated and deeply-rooted traditional ways of life oriented towards day-to-day survival, and also lack resources. This is the case in most of the smaller islands, except those which have a major political, economic or strategic importance. There are, however, several fields in which the International Drinking Water Supply and Sanitation Decade's activities could most usefully develop, such as in:

- the creation of water storage facilities to alleviate water shortages during periods of drought;
- the enactment of proper rules, regulations and concrete measures including public education to prevent the contamination of water resources, especially ground water, by organic or chemical (fertilizers, pesticides, detergents) contamination;
- the organization of systems to provide water supplies during emergency periods as part of an overall contingency plan for natural disaster mitigation, especially as regards typhoons.

8. SOCIO-ECONOMIC ASPECTS

Several countries, especially in Micronesia, are now contemplating water resources development plans. It has to be borne in mind that in the recent past, a number of projects have failed to meet their objectives as they had not been sociologically and economically absorbed by the communities. As a result, installations were not maintained, or worse, were vandalized.

Sociological considerations are paramount when decisions are to be made on development projects in the Pacific region, especially in smaller islands. Traditional attitudes regarding water use, water rights, and also laws and customs regarding land, individual and collective property, skills and cultural aspects are to be taken into consideration. It has to be borne in mind that, within the same country or territory, an atoll populated with Polynesians and high-rise islands populated with Melanesians or Micronesians, may exist.

The economic factor is also extremely important, and economic conditions are extremely diverse in the Pacific area. Nauru has one of the highest per capita incomes in the world, while Samoa is among the least developed countries. Within the Trusteeship Territory certain political entities have high income from the lease of military bases while others have only an economy of subsistence based upon coconuts, taro and fish.

It is, therefore, important that the water projects be maintained within certain cost limits, especially as regards recurrent costs for maintenance and operation, so as to allow the beneficiaries to afford them with a reasonable level of external aid. Too many piping, storage, pumping, sewerage treatment and desalination installations have not worked satisfactorily or have fallen into disrepair due to excessive operation and maintenance costs.

In general, costs are high due to a number of adverse factors such as: adverse topographical or geological conditions; the small scale of projects, which results in high per capita costs; the need to import expensive industrial production from far-away countries; the high cost of expatriate expertise; and the experimental nature of some projects and related risks. An inventory and an assessment of the technologies used or usable in the region for water supply focusing upon investment, maintenance, repair and operation costs would be most useful.

9. CONCLUSION

Water resources development in the Pacific region and in particular the accomplishment of the objectives of the International Drinking Water Supply and Sanitation Decade, especially in the smaller islands, will have to overcome a great number of difficulties to be successful. These include: insulation; long distances; difficult access; lack of suitable sites for storing water above ground and underground; high cost of materials and design; small size of projects; the tendency to take water for granted, as a free commodity which is not to be paid for; the tendency to waste water; lack of local sources of energy; vulnerability of limited and fragile water resources to pollution; and exposure to typhoons.

A number of steps, however, can be taken to improve this situation. A programme of action prepared by the ESCAP Secretariat was discussed and adopted at the conclusion of the ESCAP meeting on Water Resources Development in the South Pacific, which was held in Suva (Fiji) from 15-19 March 1983.

At this meeting, a long-term plan for water resources development in the Pacific Region was adopted. The Programme and the Plan are included in the report on the Proceedings of the ESCAP meeting which was published in 1983 under No. 57 of the ESCAP Water Resources Series (ST/ESCAP/SER.F/57, United Nations Sales Publication No. E.84.II.F.7). The meeting was attended by representatives of Fiji, Niue, Samoa, Solomon Islands, Tonga and the Trust Territory of the Pacific Islands (Federated States of Micronesia, Republic of the Marshall Islands, and Commonwealth of the Northern Marianas Islands).

The recommended programme presented in Annex IV herewith dealt with various aspects for which actions (projects, investigations, training sessions, studies, drafting of legislation) were proposed, which may require the involvement of the United Nations system or some form of external assistance, especially for the following:

- water resources assessment and management, particularly in atolls;
- improvement of water supply systems;
- protection against sea water intrusion;
- determination of appropriate technologies for water collection;
- water pollution control;
- development of a water policy;
- training of water specialists;
- disaster mitigation

Regional actions in these fields could be considered for countries which express interest. The identification of such actions was the purpose of an interdisciplinary mission of ESCAP and other United Nations agencies, which was visiting the region at the time of the Suva Workshop.

ANNEX 1

Tentative inventory of smaller inhabited islands of the Pacific Region

Country or territory	Political status	Atolls	Limestone islands	High-rise volcanics
American Samoa	U.S. territory	-	-	3 smaller islands (1300, 500, 300 inhabitants)
Cook Islands	Self-governing state in free association with New Zealand since 1965	10 atolls, pop. about 2500	1 (Nassau)	3 smaller islands Mitiaro (22 km^2) Mautue (18 km^2) Aitutaki (18 km^2)
Fiji:	Independent - U.N. member (1970)			
Eastern Lau group			About 10 islands	About 20 islands
Islands off Vanua Levu				14 "
" " Viti Levu				12 "
Lomaiviti				10 "
Yasawa				16 "
Rotuma				1 "
French Polynesia:	Overseas territory of France			
Society Islands		1 atoll: Tetiaroa		3 small islands: Maiao, Bora Bora, Maupiti
Austral Islands				3 small islands: Rurutu, Tubuai, Rapa
Tuamotu		7 atolls with populations above 200		
Marquesas				7 smaller islands

Country or territory	Political status	Atolls	Limestone islands	High-rise volcanics
Kiribati: including Line Islands	Independent (1978)	15 atolls	6 single islands	-
Midway	USA (U.S. Navy)	Atoll		
Nauru	Independent state		1 raised atoll (single island 22 km^2)	
New Caledonia	Overseas territory of France	1 atoll, Ouvea		Iles Beley (3 islands) Ile Tiza
Niue	Self-governing state in free association with New Zealand		1 raised atoll (single island)	
Papua New Guinea:	Independent U.N. member			
Trobriand islands			4 coral islands	
Laughland group		1 atoll, Abomat		
D'Entrecasteaux group			1 island	1 island
Louisiade Arch		1 atoll		
Conflict group				3 islands
Witu				3 islands
Duke of York				several islands
Islands off Bougainville		Several atolls		
Takau			Small reef, pop.350	
Kilinaila		Atoll, pop. 500		
Missan			Coral islands, pop. 600	
Nuguria		2 atolls, pop. 150		
East Sepik				Coral islands and volcanic islands
Islands off Manua		Several atolls		

Country or territory	Political status	Atolls	Limestone islands	High-rise volcanics
Tokelau	Self-governing state in free association with New Zealand	3 atolls		
Tonga:	Independent		1 small island, A'tata	
Tongatapu group				15 inhabited islands
Haapai group				14 inhabited islands
Vava'u group				Tafai, Nivafoou
Trust Territory of the Pacific Islands:	U.N. Trusteeship territory			
Northern Marianas				2 small volcanic islands: Pagan, Agrihan
Marshall		4 major atolls, 6 minor atolls		
Palau		6 atolls		
Federated States of Micronesia:				
Ponape		2 atolls		
Truk		12 atolls		7 islands
Yap		9 atolls		4 islands
Tuvalu	Independent state	3 atolls	6 limestone islands	

Country or territory	Political status	Atolls	Limestone islands	High-rise volcanics
Vanuatu:	Independent state, U.N. member			
Banks Islands				7 high-rise islands, pop. 4000
Torres Islands				5 high-rise islands, pop. 200
Central Group (small islands)				5 islands, Paama, Lopevi, Epi, Tonjoa, Emal Island
Southern Group				2 small islands, Aniwa, Futuna
Wallis and Futuna	Overseas territory of France			3 volcanic islands
TOTAL (approximate)		80-90 atolls	About 40 limestone islands	About 150 volcanic islands

ANNEX 2

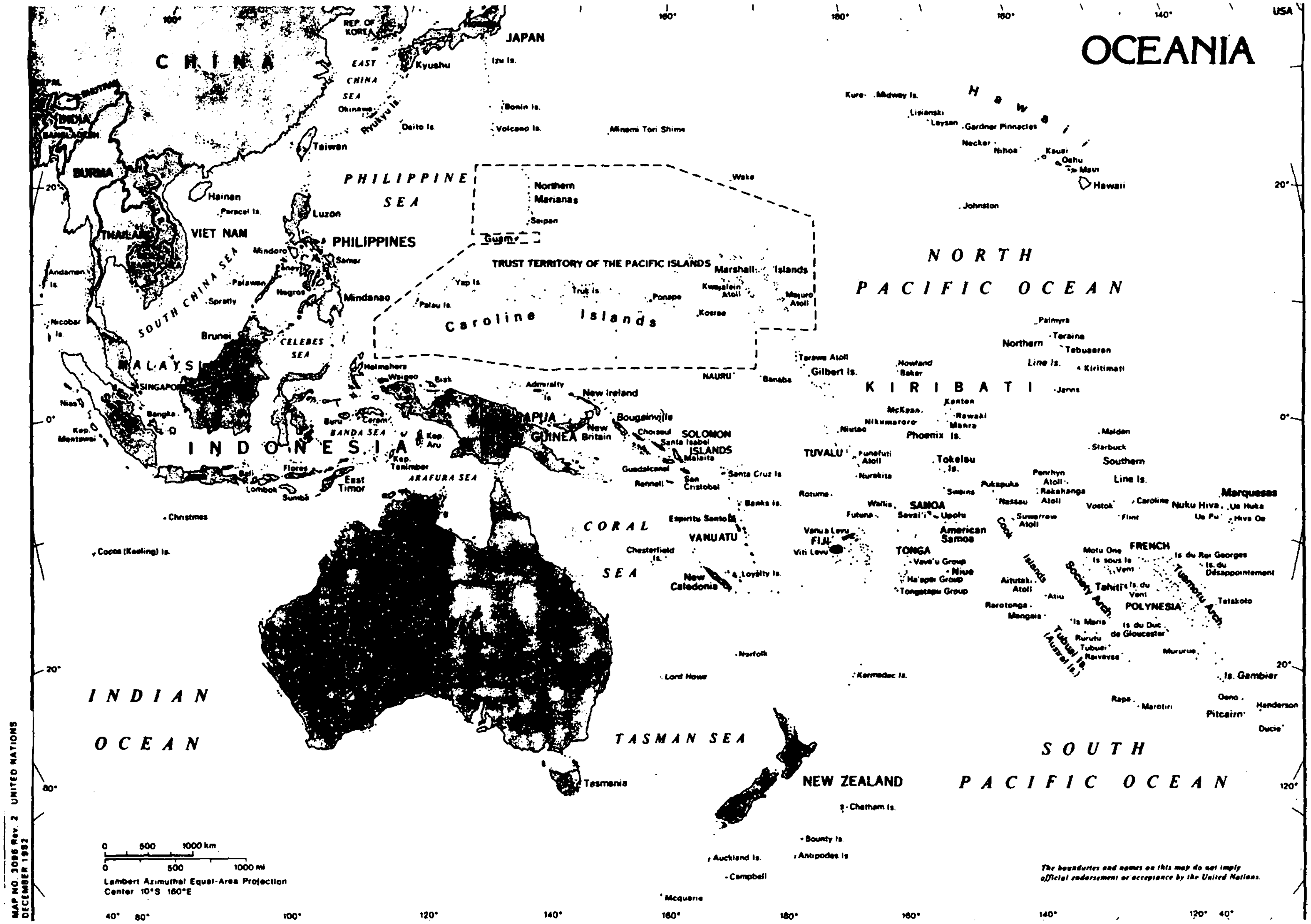
Ground water projects in the Pacific Region sponsored by the United Nations Development Programme

Country and project	Symbol	Agency	Duration	Ground water component: Exclusive or major	Substantial (30-50% of project	Minor
Cook Islands						
Environmental health engineering advisory services	CKI-73-003	WHO	1973-82			x
Fiji						
Hydrogeological survey	FIJ-69-001	U.N.	1971-73	x		
Fellowship in hydrogeology	FIJ-74-003	U.N.	1974-75	x		
Niue						
Mineral prospect- and water resources	NIU-78-006	IAEA	1979-81	x		
Papua New Guinea						
Assistance in the implementation of a water development policy	PNG-77-004	U.N.	1977-80			x
Samoa						
Hydrodata collection	SAM-74-006	U.N.	1977-82		x	
Solomon Islands						
Rural water supply and sanitation	SOI-80-002	WHO	1979-82			x
Tonga						
Tonga Water Board development	TON-75-004	WHO	1976-82		x	

The Department of Technical Co-operation for Development of the United Nations has provided advisory services in water resources development through short-term consultant missions to Kiribati, the Federated States of Micronesia (Truk, Yap, Ponape), the Northern Marianas, Marshall Islands, Cook Islands, Niue, the Solomon Islands, Tuvalu, Samoa, Fiji.

The Regional Mineral Resources Development Centre of the Economic and Social Commission for Asia and the Pacific (formerly in Bangkok, now in Bandung) has provided consultant services in hydrogeology to several Pacific countries including Tonga, Kiribati and Vanuatu.

ANNEX 3


OCEANIA
CHINA
JAPAN
REP. OF KOREA
Kyushu
EAST CHINA SEA
Okinawa
Ryukyu Is.
Daito Is.
Izu Is.
Bonin Is.
Volcano Is.
Minami Tori Shima
Taiwan
BURMA
INDIA
BANGLADESH
Hainan
Paracel Is.
VIET NAM
THAILAND
Luzon
PHILIPPINES
PHILIPPINE SEA
Mindoro
Samar
Palawan
Negros
Mindanao
Spratly
SOUTH CHINA SEA
Andaman Is.
Nicobar Is.
Brunei
CELEBES SEA
MALAYSIA
SINGAPORE
Halmahera
Waigeo
Biak
Nias
Kep. Mentawai
Bangka
INDONESIA
Buru
Ceram
BANDA SEA
Kep. Aru
Kep. Tanimbar
ARAFURA SEA
Bali
Lombok
Flores
Sumba
East Timor
Christmas
Cocos (Keeling) Is.
Northern Marianas
Saipan
Guam
Wake
TRUST TERRITORY OF THE PACIFIC ISLANDS
Marshall Islands
Kwajalein Atoll
Majuro Atoll
Yap Is.
Palau Is.
Truk Is.
Ponape
Kosrae
Caroline Islands
NAURU
Banaba
Admiralty Is.
New Ireland
PAPUA NEW GUINEA
New Britain
Bougainville
Choiseul
Santa Isabel
SOLOMON ISLANDS
Malaita
Guadalcanal
San Cristobal
Rennell
Santa Cruz Is
Banks Is.
Espiritu Santo
VANUATU
CORAL SEA
Chesterfield Is.
New Caledonia
Loyalty Is.
Norfolk
Lord Howe
Kermadec Is.
TASMAN SEA
Tasmania
NEW ZEALAND
Chatham Is.
Bounty Is.
Antipodes Is
Auckland Is.
Campbell
Macquarie
INDIAN OCEAN
Kure
Midway Is.
Hawaii
Lisianski
Laysan
Gardner Pinnacles
Necker
Nihoa
Kauai
Oahu
Maui
Hawaii
Johnston
NORTH PACIFIC OCEAN
Palmyra
Teraina
Tabuaeran
Northern Line Is.
Kiritimati
Jarvis
Tarawa Atoll
Gilbert Is.
Howland
Baker
KIRIBATI
Kanton
McKean
Rawaki
Nikumaroro
Manra
Phoenix Is.
Nui
TUVALU
Funafuti Atoll
Nukufetau
Tokelau Is.
Malden
Starbuck
Southern Line Is.
Rotuma
Wallis
Futuna
SAMOA
Savai'i
Upolu
American Samoa
Swains
Pukapuka
Nassau
Penrhyn Atoll
Rakahanga Atoll
Suwarrow Atoll
Vostok
Caroline
Flint
Marquesas
Nuku Hiva
Ua Huka
Ua Pu
Hiva Oa
Vanua Levu
FIJI
Viti Levu
TONGA
Vava'u Group
Niue
Ha'apai Group
Tongatapu Group
Cook Islands
Aitutaki Atoll
Atiu
Rarotonga
Mangaia
Society Arch.
Motu One
Is. sous le Vent
FRENCH
Tahiti
Is. du Vent
POLYNESIA
Tuamotu Arch.
Is. du Roi Georges
Is. du Désappointement
Takakoto
Is. Maria
Rurutu
Tubuai
Raivavae
Is. du Duc de Gloucester
Tubuai Is. (Austral Is.)
Mururoa
Is. Gambier
Rapa
Marotiri
Oeno
Pitcairn
Henderson
Ducie
SOUTH PACIFIC OCEAN
USA
0 500 1000 km
0 500 1000 mi
Lambert Azimuthal Equal-Area Projection
Center 10°S 160°E
The boundaries and names on this map do not imply official endorsement or acceptance by the United Nations.
MAP NO. 3096 Rev. 2 UNITED NATIONS
DECEMBER 1982

ANNEX 4

Recommended programme for water resources development in "Proceedings of the meeting on water resources development in the South Pacific" held at Suva (Fiji) from 14-19 March 1983

ESCAP - WATER RESOURCES SERIES NO. 57

III. RECOMMENDED PROGRAMME
(agenda item 6)

20. The Meeting discussed and considered measures to solve the problems identified in the discussion under the previous agenda item. It recognized that both short- and long-term measures would be required for the solution of those problems.

21. In general, the problem/project-oriented issues would require urgent and short-term measures for their resolution. Even some issues in that category, however, had certain aspects requiring long-term measures to ensure complete and satisfactory treatment.

22. The broad and long-term perspective issues required long-term measures by all concerned. In general those issues were concerned with the comprehensive and integrated approach to the development of water resources.

23. The Meeting adopted the long-term action plan shown in the annex.

24. It recommended however, that the following selected items in the comprehensive programme should be given urgent attention as they addressed the specific problems identified by the Meeting:

(a) Assessment of water resources:

(i) For each country in the Pacific region:

a. Establish an inventory of currently available water resource data;

b. Establish the minimal additional data collection system needed to meet development objectives, taking into account water quality, including sea-water intrusion of groundwater and sediment in streams, and small scale hydropower requirements;

c. Determine the areas which required the immediate assessment of water resources to satisfy their current and future needs;

(ii) At the sub-regional level:

a. Establish a project in the Pacific to determine optimum water resource availability and management on atolls (for water supply and agriculture), including water balance studies, techniques of assessment and evapotranspiration from coconuts, taro pits and natural vegetation, and develop guidelines on the above;

b. Develop guidelines for the assessment of water resources on volcanic islands or islands with surface-water potential.

(b) Conservation on water and efficiency of water use:

(i) Establish the best ways and means of educating the consumers to conserve water;

(ii) Establish a training programme for detection and repair of leakage in water supply systems and the subsequent repairs;

(iii) Establish a programme of modifications to systems to improve water supply distribution;

(iv) Establish a programme for the siting of ground-water extraction points to and the determination of withdrawal rates to avoid salt water intrusion and overpumping;

(v) Determine the priority water demands for different purposes with specific reference to the smaller atolls and communities;

(vi) Produce guidelines for the provision of water supply systems adapted for local conditions including:

a. The design of roof catchment and storage systems using appropriate materials and design methods;

b. Gravity distribution systems;

c. Hand pumps;

d. Wells.

(vii) Survey and monitoring of sources of water pollution, including microbiological, chemical, and pesticides, and the feasibility of removal thereof;

(viii) Establish guidelines for the design of waste disposal systems especially in small islands;

(ix) Establish guidelines for the security of water supplies and waste disposal systems during floods and cyclones;

(x) Coordinate activities in water pollution with the South Pacific Regional Environment Programme;

(xi) Investigate and encourage irrigated agricultural production within the constraints of other water demands;

(xii) Consider the water requirements of industries in the planning of water development projects taking into account water quality problems and the specific requirements of tourist development in the region;

(xiii) A multi-purpose approach is recommended for the development of hydroelectric power, irrigation, gravity water supplies and recreational uses when there is a perceived need;

(c) Policy, institution, legislation and technology:

(i) Establish a realistic national water policy within the framework of the economic, social and environmental conditions existing in the country;

(ii) Develop a water plan within the context of national water policy taking account of the economic, social and environmental conditions existing in the country;

(iii) Undertake evaluation of recent and/or existing water projects and base future development on those findings;

(iv) Study local communities and promote their involvement in the design, construction, financing and operation of the local water supply;

(v) Establish appropriate institutional arrangements, where possible within one organization, for the promotion and co-ordination of the assessment, development and management of water resources within each country, and wherever appropriate in outer islands, appoint trained locals to control individual island water systems;

(vi) Establish simple and enforceable legislation, using local existing legislation and relevant examples from similar island countries and territories elsewhere, e.g. the Caribbean, to cover all aspects of water resource management and, in particular, groundwater extraction, pollution and the protection of surface water sources;

(vii) Identify and promote the use of appropriate technology for water resource assessment, water-quality monitoring and water-supply system construction and operation, including appropriate use of low cost energy development (e.g. solar and wind power).

(d) Public information, education and training

(i) Develop public awareness through suitable means, including audio-visual media programmes, so as to promote the protection of water quality and the conservation of water;

(ii) Recognising the general lack of trained manpower in the field of water resource assessment, development, management, operation and maintenance, it is essential that training programmes be organized at the subregional level, taking into account the activities of the agencies in the subregional and the continuing need for participation in both basic and specialist training courses and conferences overseas. The most urgent needs are for the centralized and field training of:

a. Water managers.

b. Water supply technicians in leakage detection, pipe repairs, instrument repairs, etc.,

c. Professionals in water resource assessment and water supply design;

d. Hydrological technicians in water resources data collection and processing;

e. Villagers in the operation of water supply and waste water treatment systems;

(iii) Establish a unit in an existing university or technical agency for the collection and dissemination of water resource information/publications from within and outside the Pacific region including relevant water resource publications from United Nations agencies;

(iv) Encourage countries to produce reports on water resource problems and their solutions relevant to other countries in the region;

(v) Establish a quarterly newsletter for transmission to all relevant water agencies and departments of information on developments and incoming publications pertinent to the region;

(vi) Promote the establishment of a subregional association of water specialists to provide a direct medium for the interchange of ideas.

(e) Mitigation of damage caused by cyclones and associated floods

(i) Carry out, where appropriate, flood loss prevention and management measures, comprising both structural and non-structural measures, to prevent or minimize flood losses;

(ii) In the national disaster preparedness plan/activities include measures for the security of water supplies and water resources structures and where applicable their restoration/repairs.

25. The Meeting recommended that an interdisciplinary mission be organized and co-ordinated by ESCAP to visit the island countries of the South Pacific subregion including Micronesia to examine in depth their water problems and recommend appropriate measures for their solutions. The mission would give particular emphasis to the identification of problems shared by several countries and would formulate subregional action proposals.

26. The Mission would comprise between three and five water specialists in water resource assessment, development and management, from or appointed by member organizations of the United Nations family such as ESCAP, UNDTCD, UNICEF, ILO, FAO, UNESCO, WHO and WMO, subject to availability of resources.

27. The terms of the mission would be:

(a) To review ongoing and planned activities in water resources development and especially those related to the International Drinking Water Supply and Sanitation Decade with governmental agencies involved in water resource assessment, development and management, such as those concerned with public work, water supply, health, agriculture, hydrometeorological services and geology.

(b) To examine in depth problems encountered, such as:

(i) Lack of water resource data and of suitable data collecting system;

(ii) Lack of adequate water supplies, especially in outer areas/islands;

(iii) Environmental problems related to water resources (sea water intrusion, organic and chemical pollution of water);

(iv) Water deficiencies in agriculture;

(v) Deficiencies in technologies.(pumps, wells, roof catchments and others);

(vi) Lack of adequate legislation for the conservation and management of water resources;

(vii) Lack of technical personnel and resources especially for operation and maintenance of installations;

(viii) Lack of proper institutional arrangements;

(c) To recommend solutions and measures to maximize the use of manpower and other resources in the development and management of water resources including, inter alia

(i) Collection and utilization of water data;

(ii) Water planning, legislation and management;

(iii) Water conservation measures (both as to quantity and quality);

(iv) Training;

(v) Institutional aspects;

(vi) Water costs and financing of water projects.

28. The mission should direct special attention to low-lying limestone islands and small islands, especially atolls.

29. The mission's findings and recommendations should be drafted in co-operation and in consultation with government officials at the decision level and professional technical personnel engaged in activities related to water resources. It should take into account water resources availability; priority needs; a country's resources and the technological level and cultural background of the population concerned.

30. In order to facilitate the task of the mission, it was desirable that the relevant documentation be compiled so as to be made available upon the arrival of the mission. In addition, it was expected that a questionnaire would be circulated to the countries for completion before the arrival of the mission.

31. In this connection, the representative of ESCAP informed the Meeting that pursuant to Economic and Social Council resolution 1981/80 the UNDP resident representatives of all developing countries had been directed by the UNDP Administrator in 1982 to inform the governments that the United Nations was prepared to send on request interdisciplinary missions on water resource development to interested countries. The regional commissions were entrusted with the responsibility of playing leading roles in the organization and co-ordination of missions within their respective regions.

32. In the light of the foregoing information, the Meeting agreed that, provided the costs involved would not be charged against country IPFs taking into account General Assembly resolution 3338(XXIX) on developing island countries, the mission should be organized within the framework of the Economic and Social Council's resolution.

33. Accordingly, ESCAP was requested, as soon as possible to

(a) Inform the countries of the South Pacific subregion of the recommendation of the Meeting to organize a mission in accordance with the terms of reference adopted by the meeting and that such a mission could be organized within the framework of Economic and Social Council resolution 1981/80 concerning interdisciplinary missions;

(b) Request countries to inform ESCAP whether they would require the services of such a mission;

(c) Consult with members of the United Nations system engaged in water resources to ascertain their readiness to participate in the mission, discuss financial arrangements, etc.;

(d) Co-ordinate all arrangements for the organization of the mission.

COMMONWEALTH SCIENCE COUNCIL WORKSHOP ON

"WATER RESOURCES OF SMALL ISLANDS"

WATER UTILISATION IN THE PACIFIC ISLANDS

SUVA, 2-9 JULY 1984

W R Dale
H.O. DSIR, Wellington, NZ.

To produce a regional understanding of how water is used we need to discuss both quality and quantity of available water. I say "available" because during dry seasons and particularly during a sustained drought like 1982-83 the quantity of available water is low. As we have noted, water is the most critical of all resources on oceanic tropical islands (Dale and Waterhouse, 1984). It is the quality first and the quantity second that determines what use we make of the available water.

To put not too fine a point on it, however, under drought conditions no one is concerned if the salt or iron concentration for example exceeds the WHO recommendations (WHO, 1971). Provided the water is "acceptable" they will drink it to survive, regardless of quality. However, as a contribution to the International Drinking Water Supply and Sanitation Decade the WHO (1983) provided a minimum evaluation procedure (MEP) for water supply and sanitation projects.

What then is the fresh-water resource of the Pacific? Initially of course, it is rainfall and figure 1 sets out the rainfall regime for the region (Hessell 1981). This illustrates a very dry zone (less than 800 mm/an.) in the eastern equatorial belt increasing to under 2000 mm/an. (dry) in the region of the Cook Islands and French Polynesia. From the Tokelaus to New Britain and north to the Marshall Islands is a wet region of 2000-3000 mm/an. To the northwest lies the very wet region with rainfall exceeding 5000 mm annually - on the average. But few years are "average" years and few of us live in average places. The dry side/wet side of many larger land masses, and Viti Levu is a prime example, presents us with one of the local variants. Both the total rainfall and its periodicity are determined by large-scale solar influences with the dry-season trade winds oscillating with tropical cyclones in some areas and a monsoonal trough extending eastward over the Coral sea from northern Australia in others (Revell 1981). Figure 2 illustrates the frequency of tropical cyclones.

The basis of our water resource varies from place to place and from time to time and also in intensity. We therefore have to make the best use of the rain that falls as soon after it falls as we can. This is because it will either run off or run in. At the same time, with the prevailing temperatures, evaporation from the ground surface and from vegetation as well as the water transpired by ground cover takes place almost continuously.

Studies in many places confirm that mature broadleaf forests or conifer trees will intercept up to 50% of rainfall. But as anyone who has stood under a tree in a storm will know the longer the rainfall continues the more will reach the ground. Grasslands intercept twice as much rain as forests. On the other hand forest trees transpire more water than grain crops or pasture (Pearce and Rowe 1979).

This doesn't look good for those parts of the region which record under 800 mm of rainfall - perhaps only 400 mm has a chance of entering the ground-water system. Of course some use is made of roof collections into tanks if such a system is in place. In this way most of the rainfall can be collected from small areas. However, from a survey we conducted in 1980 (figure 3) we know the roof catchment areas on most small islands are themselves quite small and often not matched with sufficient tank storage (Dale 1981). This is one way in which substantial improvement can be made to increasing available water - by increasing tank storage.

Otherwise there is a dependence on wells, galleries, streams and dammed water courses supplemented by tanks and a mains storage/supply systems particularly on the higher islands and drilled or dug wells on the lower islands.

Once the rain water enters the terrestial system its chemical characteristics change (Dale and Waterhouse 1984) and this influences the uses which may be made of the ground water. It also starts running out to sea. In a recent study on a small sandy cay we found a thin skin of water, much purer than the underlying fresh water, a week or two after substantial rainfall. It is worth exploiting this fresh rain water by pumping to storage rather than letting it flow away to the ocean. Despite some lag, that's where most of it is heading anyway. This lag, especially on the high islands, acts as a temporary reservoir just as stream-course galleries do. Unfortunately in the Pacific much of the rock structure is porous volcanic material which, although it allows the ground water to move freely down slope, is commonly structurally unsuitable for storage reserviors. Indeed lava tubes have been exploited in Hawaii for the development of water supplies (Takasaki and Mink, 1983).

Kassas (1983) noted that on a global scale only 3 per cent of water is fresh water (42 million km 3). Of this, no more than 23% is contained in ground waters, lakes and rivers. It is the careful exploitation of these groundwater resources and the effective use of the available waters which is the main thrust of the discussion.

In 1642 Abel Janszoon Tasman made a journal entry regarding water supplies on Tongatapu (Tonga). Two Dutch longboats went ashore "but returned without water: for the inhabitants themselves had to dig holes from which [they] scooped water." He later records returning to the ship with "nine casks of dug water" (Sharp, 1968). So the principle to tapping the potable ground water in the Pacific is as old as settlement in the region. Today we have mechanised the process with drills, pumps, reticulation and treatment systems but you still have a finite resource to exploit.

By today's reckoning there are four main uses:

- Personal needs: for drinking, cooking and other domestic purposes.

- Agricultural needs: for private gardens or commercial crops.

- Industrial needs: for washing, cleaning, raising steam and the like.

- Tourist needs: for personal use, swimming pools, and the related industrial services.

In Tasman's day, and even today in some places, the typical consumption is 10 to 20 litres per person per day where the water has to be carried considerable distances. Where water is more easily available the consumption is nearer 50 litres per person each day and rural water supply schemes in developing countries are often designed for 40 to 60 litres per head for their daily production (Halcrow, 1983). Compare this with a value of 600 litres per person per day for some industrialised water-rich countries. It is a matter, then, of comparing the volume of water available with the proposed consumption to determine the daily use for basic necessities. Some supplementation using brackish ponds or shoreline springs for personal washing and laundry is certainly the practice in parts of our region.

If a society wishes to practice agriculture then further water may be required. At the simplest level water is ladled by hand on individual plants or trees during the drier parts of the year. This labour-intensive work means other activities have to be neglected. Given adequate water resources trickle irrigation is an effective way to supply water to individual trees, bushes or vines but is of course capital intensive.

Our experience at Totokoitu (Cook Islands) is that the yields of oranges in a drought season can be halved when water supplies are limiting. Flowering may be aborted but a second flowering in the same year may partly compensate for loss of yield. So if agriculture is to be considered so is the need for water by the crop up to maturity. Additional water is required for pest and disease control through foliar sprays. Coconuts which are major subsistance and commercial crop in the region, are also significant users of water with the ability to draw some of their requirements from brackish or seawater as well as fresh water. Drinking nuts are, however, and important traditional source of water for humans and pigs. As livestock farming is established the requirement for stock water makes a futher demand on the resource. Each milking dairy cow can consume upwards of 5 litres of water per day. Paddy rice is of course a special case restricted to only a few countries in the Pacific.

As the rural agricultural industry develops the need for processing plants increases. Canning factories, fish packhouses, abattoirs and oil mills need steam and washing water. Even small juice-freezing or juice-concentration plants will require water. Health and hygiene regulations, which seem necessary for the safe running of these operations, require high quality water in increased quantitites. Suddenly we find water treatment is needed to remove some of the 400 ppm or so of total hardness (as calcium carbonate) before water from underground sources on coral islands can be used in industrial boilers. Treatment for bacterial contamination is equally important where water is needed in any food industry. Modern sterilisation systems, however, may provide an easy solution to this problem.

Having established a modest agricultural industry we need a tourist industry to pay for it. For example 1977 Fiji earned around $70M from tourism. This requires water (again of a quality standard acceptable to the visitor) and in greater quantity than local people expect for showers, baths, swimming pools (and ice for their drinks). This is what they are accustomed to in their own (usually) water-rich countries and they expect it too on holiday. All the support services; hospitals, laundries, food production and preservation, flush toilets and so on will also be expected. This competition for limited water resources increases as the number of users increase (Dijon 1983). There is a good side to this story, however. The water lens - either as a fresh-water body within the sands or rocks of smaller islands or flowing down from the peaks of the high islands - may produce more water if a proper development programme is followed.

Ad hoc (wild cat) drilling without the benefit of geophysical and hydrogeological information is disastrous. So is pumping without monitoring. Serious understanding of the shape and volume of the aquifer is needed to determine correct drill sites and safe pumping rates. Appropriate forward planning should include the desired storage reticulation and the treatment facilities for the designed purpose. In other words a systems approach based on agreed objectives.

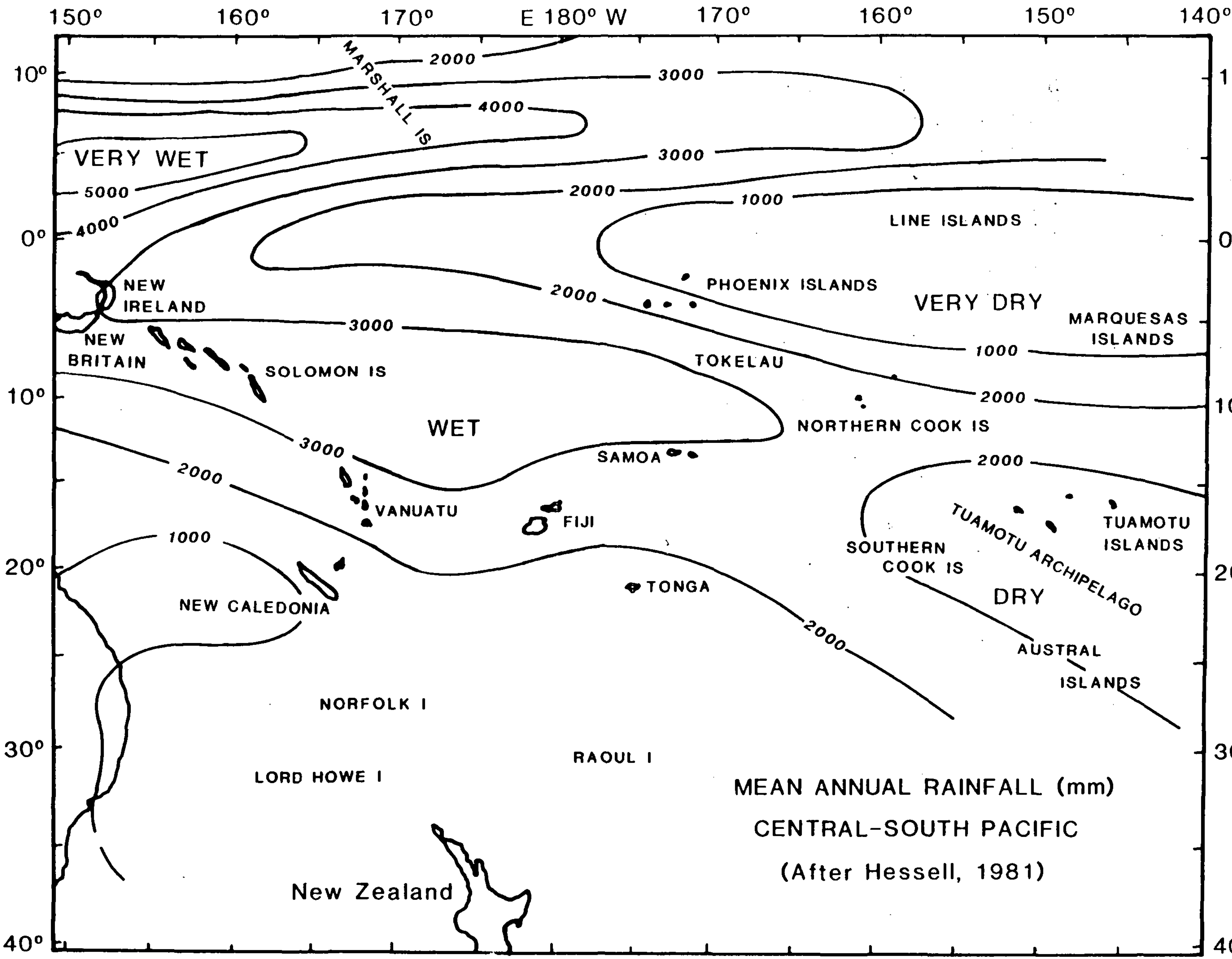
Studies like those of Jacobson and Hill (1980) for Niue, Hunt and Peterson (1980), Ayres and Clayshulte (1983) in Micronesia and Waterhouse and Petty (1984) for the Southern Cook Islands are important. In some of these studies they have identified the rainfall, determined the interception and evapotranspiration losses and calculated the ground-water recharge. Without this basic information the risk of overpumping is high and salinity of the ground water will increase. Naturally the sound practitioners have set correct pump heights and identified safe pumping rates. But all this data hinges on knowing the absolute datum for sea levels. Now this basis is likely to prove a stumbling block for the more isolated islands unless authorities have taken the precaution of establishing such datum points in advance.

We use the water but are casual about its disposal. Some studies in the region (Lynch, 1984) suggest that contamination of the cavenous limestone water lens by harmful bacteria is widespread. We know that waste water from factories, hospitals and domestic septic tanks can infiltrate into the ground water and with the dynamic movement of water through gravity and also stimulated by bore pumps, waste fluids can easily distributed within the ground-water system.

There is some support for this argument from the occasional outbreak of water-bourne diseases in the region. Septic waste discharges are often too close to someone's "fresh-water" borehole! In addition there are discharges of agricultural chemicals (washings from mobile spray plant and fungicide dip-tank wastes). Soluble fertilisers, including heavy metals like zinc, are applied to pastures, animal wastes are leached and modern washing powders and detergents add soluable phosphates to the ground water (Ayres and Clayshulte, 1983).

In conclusion then we have a responsibility to use the limited freshwater resource carefully and ensure we do not recontaminate the groundwater by discharging untreated wastes so that they contaminate the hydrological system. This workshop is an important occasion for use to encourage all countries in the region to identify then adopt appropriate practical planning and monitoring steps for the effective use of each small island's limited water resources.

Figure 1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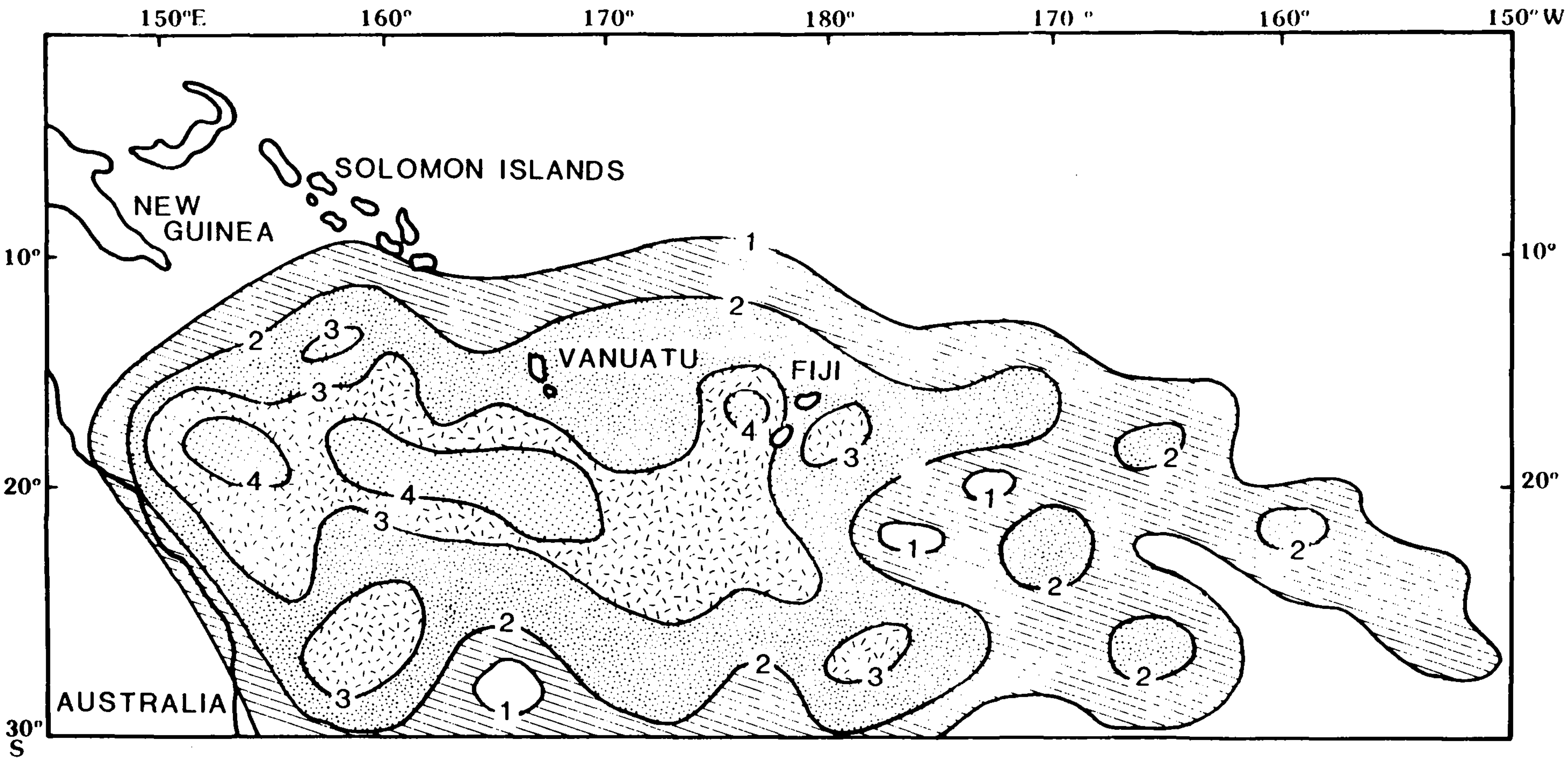
LINE ISLANDS
NEW IRELAND
NEW BRITAIN
PHOENIX ISLANDS
VERY DRY
MARQUESAS ISLANDS
SOLOMON IS
TOKELAU
WET
NORTHERN COOK IS
SAMOA
VANUATU
FIJI
TUAMOTU ARCHIPELAGO
TUAMOTU ISLANDS
SOUTHERN COOK IS
TONGA
NEW CALEDONIA
DRY
AUSTRAL ISLANDS
NORFOLK I
RAOUL I
LORD HOWE I
MEAN ANNUAL RAINFALL (mm)
CENTRAL-SOUTH PACIFIC
(After Hessell, 1981)
New Zealand

TROPICAL CYCLONE FREQUENCY



Average frequency per decade of tropical cyclone centers passing within 40 miles
(after Gabites 1976 and Revell 1981).

Figure 2

Figure 3 ROOF CATCHMENT AREAS

	Population ('000)	Roof Area (m^2)	Land Area (km^2)	Rainfall (mm/a)
Niue	3.6	52000	258	2200
Tokelau	1.5	51000	10	2050–2360
Tonga	90.1	11700	448	1780 – 2300
Wallis / Futuna	6.0	60	76	3000–4000

Figure 4 CHEMICAL CHANGES TO RAINWATER

	pH	Ca	Cl	Tot. Hard	Heavy Metals(g/m^3)
Roof	6.5	3.0	8	11.0	all 0.01 (low)
High Is.	6.2	3.0	13	(40.0)	all low
Margins	7.2	66.0	107	215	all low
Atoll	7.5	107	35	390	all low

all g/m^3 except pH.

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WATER LAW

E P Wright*

Introduction.

This paper is written from the viewpoint of a hydrogeologist concerned with understanding the basic processes of law in relation to the development of a natural resource. The time is clearly apposite for a consideration of this issue. There is much current and planned development of water resources throughout the region, as elsewhere in the world, stimulated in some part by the UN Decade of Water Supply and Sanitation. The discussion is relates primarily to the circumstances of the island countries of the Pacific and Indian oceans, many of which have recently gained their independence, or are beginning to question the controls of remaining external authorities, mainly France and the United States. Inevitably legislative changes are occurring which in this region are being strongly influenced by traditional customs.

The objectives of law in relation to water resources may seem fairly self evident and along the following lines.

(i) To ensure an adequate distribution of water to supply basic needs for everyone.

(ii) To promote the optimum utilisation of water resources and to plan for the future; to protect existing user rights within this context.

(iii) To ensure an appropriate role for government in the management of the resources.

There will be obvious differences in precise interpretation of these objectives in accordance with the political and socio-economic fabric of individual countries. Nonetheless, it is reasonable to assume that these broad concepts would be generally acceptable.

Water Law has a long history, as long as that of man himself, and even written legislation goes back more than 2000 years. Despite this lengthy period of development, it is fair to say that water law in all countries tends to be a somewhat unsatisfactory blend of traditional rules and subsequent legislation. This statement applies even in the most advanced and developed countries. Water is a complex and pervasive resource for which there is often much competition and diverse usage. It is inevitable that legislation which is predominantly use-oriented should be fragmented and often overly complex. It has to take account of a host of considerations, economic, environmental and social as well as technological. Hydrologists, geologists or engineers cannot be expected to have special knowledge of all these aspects but are or should be in a position to recognise the unified nature of the resource and to provide planners and politicians with a proper perspective on which to base policy and planning.

Essential Definitions.

There are two main categories of law, unwritten and statutory. Unwritten law includes the traditional or customary law and also the so-called Common Law in

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which the legal principles are derived from the previous decisions of the judiciary. It is the basis of the law of England. Statutory law is written legislation enacted by the State Legislature or by empowered Committees, e.g. Acts, Statutes, Decrees and Bylaws.

Historical Development.

There are four historical societies which have made major contributions to the initiation and development of water law. They include the so-called hydraulic civilisations of ancient China with legal codes concerned mainly with irrigation rights; the Hebrew and Moslem systems which by virtue of the arid environment placed emphasis on groundwater; and Roman Law which has been more broadly concerned with overall water resources within a generally humid environment.

The Chinese civilisation which developed more than 2000 years ago in the vicinity of the Hwang Ho River had an elaborate unwritten code which placed great emphasis on individual flexibility but sought an equitable distribution of water resources. The system was sustained by a belief in harmonious and accepted rules of conduct which would ensure the solution of private disputes without recourse to the procedures of external justice or arbitration. The flexibility of human judgement was preferred to rigid legislation and water was regarded in the category of 'things common' which could be used but not owned. The unwritten code lasted throughout the land development stage. Written legislation first commenced in the Ch'in dynasty (c. 250 BC), concomittantly with modifications of the natural river systems by diversions etc. and with increasing competition. There was initially resistance both to the concept of written legislation as imposing too rigid an interpretation and to the central role of government.

The Hebrew peoples produced the Bible and the Talmud (400-200 BC) both of which contain legal doctrines and injunctions relating to water and in particular groundwater. The Moslem laws of later date bore close similarities. Both systems stressed community ownership of this essential scarce resource although with important private use rights and priorities in use. The right of thirst was over-riding. Control was also exercised by restricting development around existing sources.

Roman Law has given rise to the two major legal systems of the western world: Common Law which is the basis of English Law, and the Civil Code represented most notably by the legal systems of France and Spain. Roman Law classified matters in relation to concepts of ownership. Air or flowing water were not susceptible to ownership as such but could be used. They fell into the category of 'res nullus or res communes', belonging to no one or common to all*. The Common Law has maintained this concept in respect to flowing water in defined channels, whether surface or underground; the Civil Code departed from the concept by declaring that all things, including such intangible elements as water itself, can be owned, whether by private individuals or the State. In both systems, groundwater could be owned, either as part of the land in the Common Law System or in the Civil Code as an individual commodity.

Modern developments in Water Law in advanced countries have tended towards limiting the privileges of private ownership or user rights and to increase the power of the State. Such changes have been progressive. The riparian doctrine in Common Law which provided initially almost unrestricted usage by riparian land owners, became constrained by doctrines of natural flow and reasonable or beneficial use. A second important development in Common Law was the

* Justinian (AD 534): By natural law, these things are common to all; air, running water, the sea and as a consequence the shores of the area.

'Correlative Rights Doctrine' whereby owners of land above a common reservoir (groundwater) had co-equal or correlative rights. Another variant of user rights is that resulting from prior appropriation "A prior appropriation of either (wood or water) to steady individual purpose establishes a quasi-private proprietorship which entitles the holder to be protected in its quiet enjoyment against all the world but the true owner[1]. The constraints and additions to Common Law rights were introduced in consequence of increasing demand on existing supplies as were the laws applied in regions with less abundant resources, such as the Western United States. The modifications to riparian doctrine were designed to offset the advantages obtained by upstream owners by controls which required that each user should return the flow to the common channel substantially undiminished in quantity or unimpaired in quality.

Modern Legal Systems.

Modifications of traditional legal practices have now been made in virtually all countries, mainly designed to increase public control over water resources. Degree of control varies and the methods may range from incorporation of the resource into full State control (the public domain) or more commonly by licensing of use. The prior appropriation doctrine, referred to earlier, is a forerunner of the modern licence system. Although the concept of equitable use is still fundamental to most modern legal systems, the importance of land ownership or the seniority of existing water use rights are progressively being superseded by use criteria with State control by licence. This is essentially a recognition of the nature of water as inconsistent with normal ownership concepts, the need to ensure equitable distribution in accordance with defined use criteria and the essential role of the State in ensuring that such objectives are attained.

Water Code.

During the course of the Workshop participants were asked to comment on existing Water Law in the countries which they represented. Many of the Pacific Islands apparently had no water legislation as such (e.g. Tuvalu, Maldives, Vanuatu, Micronesia); others had legislation which was either not enforced or generally disregarded (e.g. Solomon Islands, West Samoa). The island groups affiliated to or controlled by foreign powers, notably France and the USA (e.g. New Caledonia, French Polynesia, Guam/Marianas, Hawaii) had legal systems based on those of the controlling power, although with some resistance from indigenous people and with customary law prevailing in remoter areas. The apparent lack or disregard of existing legislation is not surprising in view of recent political events in which many of the Pacific Island groups have gained their independence. To some extent it may be assumed that inherited legislation from a previous Colonial power was likely to be inappropriate, at least in the context of customary law towards which there are general reversionary trends. At the same time, the degree of technological development which has been obtained or which is currently being provided by international/bilateral aid agreements, and the common occurrence of significant plans for further development require that effective and appropriate legislation should exist. The first requirement in progress to this end is the formulation of a Water Code.

A Water Code is defined as 'a basic legislative document which establishes the broad general principles and patterns for administrative action but leaves the regulation of matters of detail up to subsequent ancillary legislation'*. Although a legislative document, it is not conceived as a synthesis of existing legislation, which in any case would be inappropriate in the present context,

1 A decision of the California Supreme Court in 1855 quoted by H E Thomas in 'Water Laws and Concepts', Trans.Am.Geophys. Union, 1969, V. 50, No. 2, pp 40-50.

* Guidelines for the Drafting of Water Codes. Water Resources Series, No. 43, United Nations.

but as the basis for more effective legislation than already exists. The Code should be concerned primarily with fundamental issues, policies, principles and rights. It should hopefully command enduring assent so as to avoid continual alteration or addition. A Code has to be socially and politically acceptable as well as effective and will therefore tend to be country or regionally specific. As far as possible, it is desirable that the Code should be consistent or reconcilable with what already exists in a country's constitution or customs. In drawing up a Code, it is as well to be aware of inherent deficiencies in existing legislation, whether imposed or traditional. Most existing water legislation tends to be use-oriented and therefore fragmentary. An understanding of the unified nature of water resources, including all forms of surface and groundwater, will lead to more efficient overall use, and better coordination among the various administrative groups dealing with particular use variations, e.g. domestic supply, agriculture, energy, etc. Making full use of the potential of technological achievement requires concerted planning. The exercise of constructing a Water Code which will contain basic principles will have considerable educative value and compel close association of all relevant circumstances, social, political, economic and technological. It is an approach which should be followed in relation to the use of any basic resource.

A Water Code essentially confers administrative powers on central or local government authorities and restricts private rights. The four main policy issues which need to be detailed in a Water Code are set out below and discussed separately.

(i) Rights in natural waters

(ii) Power relating to land

(iii) Registration and licensing

(iv) Administrative structure

Rights in natural waters:

In this first section the Water Code must define in appropriate legal terms, the manner of the State's title to natural waters, the nature of equivalent private rights if any, and those waters to which the Code applies. The State may wish to own or to control a water source. As noted earlier, in the Common Law legal system, flowing water in defined channels cannot be owned, either by the State or private individuals. The right to use would be in accordance with the riparian doctrine with such modifications and additions as may exist. In such circumstances, the State could gain equivalent rights by purchasing the land adjacent to the water courses in question. In those countries whose legal systems operate according to the Civil Code, the State may own water occurrences outright, irrespective of the type. A second formula of ownership available in the Civil Code is that based on the concept of the *public domain*. The State in effect is caretaker for the public and has complete user rights in perpetuity but is unable to sell or dispose of such rights, nor do they lapse by virtue of lack of use. State ownership rights in accordance with the first concept in the Civil Code and that based on Common Law principles, where these apply, are identical with the rights of private citizens, and ownership may be sold or transferred.

Alternatively, as a more modern approach the State may elect to control usage rather than to own water sources, particularly in Common Law countries where ownership of water rights is legally constrained.

It is important that the Code should specify the different sources of water to which it applies - surface water in channels, ground water, distributed surface water etc. The latter for example is important for drainage or irrigation. The modern tendency is to make provision for potential administrative control over all sources of water. In view of the continuity and interaction between water sources, there is logic in the approach.

Private rights in respect to water form a subject on which existing legal systems generally give full and detailed consideration. The main concern is for adjustment of disputes between individuals. Such private rights are mainly exercised without prior administrative concession. It is a matter of debate whether a re-statement of private rights should appear in the Code or whether the Code should be concerned mainly to ensure that the State possesses adequate administrative control. There are obvious advantages if the concept of ownership of waters can be played down since ownership has an implication of absolute rights.

Ownership of water rights in the Pacific Islands has been most clearly defined in terms of the ecosystem products, fish, coral, seaweed, etc. In several Melanesian countries, such as Vanuatu, the Solomons and Papua New Guinea, ownership of rights to harvest such products is restricted to certain groups. Ownership of the water itself tends not be defined in traditional Pacific Island law with occasional exceptions in areas where water supplies are scarce. It is in association with land that the concept takes on more critical importance and will be referred to later.

Rights over land:

Successful management of water resources inevitably requires that certain controls be exercised over adjacent or associated land in addition to those concerned directly with the water source. The Water Code should contain a declaration of the interests and objectives of the State in this respect and the limitation of any claimed powers. These rights may be needed to construct or undertake works, to gain access or to control the activities of private persons. Such administrative rights may be so comprehensive and long term that either ownership or perpetual supervening administrative rights may be required. Alternatively more limited administrative rights may suffice. Purchase may need to be carried out on compulsory terms or by negotiation. The Code will need to acknowledge that the State is liable to pay compensation for damage or for expropriation, whether it be complete or limited. The State will also need to assert its right to carry out remedial actions required in consequence of unauthorised activities of private individuals and to obtain from the offending individuals the full costs. Some discussion on private rights over neighbours land may also be appropriate.

The State's title to land can be couched in the variety of ways discussed as for water, whether by ownership, incorporation into the *public domain* or by a declaration of supervening administrative control.

The issue of land rights and land ownership is likely to represent one of the most difficult problems to resolve satisfactorily. The Pacific island people's preoccupation with land goes to extreme lengths. Customary man sees land as a reality with which he and his successors have an eternal link. The affinity may transcend all other loyalties whether to tribal group or to the nation state. There is a general reluctance to sell land and a resistance to compulsory purchase.

Although all governments in the region have legal powers in their constitutions which will allow them to make compulsory purchase of land, there is generally a reluctance to do so, especially of customary land. Alternative preferred procedures include leasing and the creation of communal lands which can involve legislation to ensure adequate control but without change of title. A full definition of public purposes, objectives and constraints is more likely to obtain public consent and facilitate land transfer, whether by purchase or by leasing. There are precedents which indicate a willingness to allow customary land to be used for specific public purposes provided that utilisation is not changed without the customary owners consent and that compensation is paid. In view of the typical reluctance against State ownership in many island countries, a policy allowing flexible administrative control seems the most appropriate method. Water reserves in South Tarawa are leased and controlled by a public utility. Although no livestock or additional agriculture (babai pits) is allowed, the landowners retain the rights to use tree crops and existing babai pits and have been paid compensation for the loss of normal rights to the land.

Registration and leasing:

These legislative procedures provide powers to control and regulate water usage or other relevant acts by private persons or organisations. Registration is a declaration of private rights which are usually of traditional origin; licensing is the seal of official permission. Registration does not confer rights but is official recognition of a claim and may be ratified by licensing.

The system helps ensure proper and equitable use of available resources and facilitates planning and monitoring of development. Flexibility is incorporated since licensing covers limited periods only and may not necessarily be renewed. The use of such administrative procedures will tend to prevent private disputes and costly litigation. A wide range of activities should be included, relating to both consumptive and non-consumptive water uses, in addition to those which could affect the flow or quality of the water.

The Water Code should also introduce the concept of payments and penalties and confer special powers on administrative bodies or agencies to grant permits or levy charges. Even where water usage costs are subsidised, e.g. rural water schemes, the use of nominal charges will pave the way for acceptance of the procedure and increases may follow when the recipients of the supply are better able to pay. Payments, for example, could cover the cost of leasing land needed for proper control and protection of a water source or access for a distribution system.

The concept of penalties will also need to be included for acts, e.g. pollution, which will have adverse effects on the water source or supply.

Administrative framework:

Water resources are utilised in a variety of ways and there is inevitably a proliferation of government agencies. Although it may seem desirable to keep all administrative functions within one agency, there are practical and economic difficulties in doing so, not least because of the cost of providing specialist staff with the wide range of expertise required to cover all fields of work. Additionally it is generally considered advisable to separate the responsibility of supplying water from the assessment, allocation and use-licensing of resources in order to avoid any conflict of interests. In smaller, lesser developed countries, a compromise may be obtained by using the organisation responsible for the most important development option as the main executive agency required to undertake overall resource assessments and empowered to allocate resources.

The functions of a national water administration may be summarised as follows:

(i) Inventory of water resources and current usage.

(ii) Recommendations of policies and plans for development, conservation and protection.

(iii) Development by government agencies and co-ordination of programmes.

(iv) Allocation, administration and supervision of private development and usage.

The government agency or agencies should be granted adequate powers to carry out these functions. Specific and detailed listings are not normally included in the Water Code but are contained in ancillary provisions. Specific and relevant examples or broader groupings may be included in the Code to illustrate the principle.

Case History: Vanuatu.

Prior to independence in July 1980, Vanuatu (New Hebrides) was controlled jointly by Britain and France, an arrangement inherently complex and particularly so, it may be assumed, in legislative matters since it would require a combination of the French Civil Code and English Common Law. Legislation of this period in respect to water was minor and mainly concerned town planning in Vila and Luganville, the two main urban centres. But even on such local issues, unnecessary and inefficient complications resulted from the joint control system.

Since independence, no legislation specifically related to water supply has been passed but new land regulations will have an important bearing on water supply matters. These include Land Acts by which all land reverts to the indigenous customary owners and a prohibition of land ownership by non Ni-Vanuatu. Other important acts relate to negotiations for purchase of the Municipal Areas of Vila and Luganville. The implications of this major reversion to customary law now need to be assessed in relation to water supply.

Physical features and population

Vanuatu is an archipelago stretching north-southwards in a chain over 800 km in length and comprising 12 main islands and islets. The range of size of the islands, their geology, climate and population type and distribution, is representative of the Pacific Islands generally. None of the main 12 islands exceeds 5000 km and only 2 exceed 2000 km . The majority are less than 1000 km and include high islands dominated by volcanic rocks and low coral islands and atolls. The larger high islands have a more complex geology which includes volcanic sequences, coral limestones of various ages and valley alluvium. Rainfall decreases from north to south and at four spaced sites with long term records, the range of mean annual rainfall is from 1596-4103 mm. The rainfall is seasonal and a rain shadow exists in the westerly coasts of high islands. There are five perennial rivers of moderate size.

The indigenous people are of Melanesian stock; the total population is 111,251 (1984) of which 94,470 live in rural areas. The population per unit area varies considerably from larger islands which may have less than one person per km area to over 70 on some small coral islands. The population on the larger islands tends to concentrate in coastal areas with the vast majority in localities containing less than 500 people (Table 1).

Water demand and supply

The urban centres of Luganville and Vila have piped distribution which meet minimum service levels or higher. Circumstances of source occurrence and distribution design render the systems vulnerable to pollution and attention to this risk is needed.

Of the total rural population of 93,752 some 42,665 are said to be provided with design service levels of 25 litres/c/day (lower for rainfall catchment supply) in existing, under construction or planned schemes (1984). Table 2 shows the percentage of such numbers related to supply source.

Spring flow systems mainly utilised a gravity-feed piped distribution. In general, spring sources are in remote areas and therefore have good natural protection. Arrangements need to be made to obtain permission from customary land owners and this apparently presents little problem if the owner lives in the community which is to be provided with a supply. Problems do occur in obtaining rights of access to lay lengthy distribution systems and difficulties also arise when developing sources adequate to supply several communities. Similar problems arise with riverflow sources and the latter lack the natural protection afforded by springs.

Groundwater from wells/boreholes provides for only a moderate percentage as yet (22%) but this number could increase substantially in the future, mainly as a response to more favourable economics of development and improved pumping systems. The main advantage of the nearness of the source location is to some extent offset by the vulnerability to pollution (aquifers mainly phreatic and in limestone) and the need to exercise control over the areas of influence to well sources.

The two urban centres of Vila and Luganville have groundwater sources from well fields in limestone aquifers on the margins of the planned 'municipal areas' which are under negotiations for purchase. The sources of supply are clearly vulnerable to pollution over areas which extend within and outside the municipal areas. The distribution system is also at risk. The main pollution risk in both cases in the built-up areas is from septic tanks for which land conditions are far from ideal. Additional pollution may also exist in outlying areas still within the groundwater catchment and could include cattle, agricultural practices, minor industry etc.

Close administrative control of water source and supply systems is clearly required in the municipal and adjacent areas and in the more densly populated limestone islands which are largely reliant on groundwater. Despite the inherent resistance to State ownership concepts, there would seem to be little alternative option to ownership unless an indefinite supervening administrative control can be acceptable and effective.

A lower degree of control would be acceptable in rural areas mainly in relation to associated land areas for access or to prevent actions which could have deleterious effects on the water supply. Leasing arrangements would seem to be most appropriate. Such costs might be met by a charge levied on the service and justification would be apparent.

Recommended organisation structure for Vanuatu

The present arrangement in Vanuatu corresponds fairly closely to the recommended structure following recent administrative changes which have given more overall responsibility for water resources to the Department of Geology, Mines and Water Supplies within the Ministry of Lands and Natural Resources. Some modifications to the existing systems are recommended and are embodied in the schematic framework shown in Table 3. Main changes are as follows:

(i) The formation of a Water Resources Board whose members could include senior representatives from government departments concerned with water use or economic planning in addition to representatives from the private sector.

(ii) The Public Works Department to retain authority for urban water supply, maintenance and charging of fees. An extension of service to include sewage facilities could also be envisaged, whether mains sewage or non-sewered sanitation. Proper maintenance and design of the latter could be undertaken by PWD with charges levied comparable in concept to water service charges.

Although legislation is assumed to exist which will guarantee private rights, a system which allows an appeal against administrative decisions is desirable. This facility could be incorporated within a special judicial review body with special knowledge of water law and legal representation or alternatively able to provide access to the ordinary courts as required.

	Size of Locality											
	<10		10-49		50-99		100-199		200-499		500+	
	Loc.	Pers	Loc.	Pers	Loc.	Pers	Loc.	Pers	Loc.	Pers	Loc.	Pers
Total Vanuatu	566	3216	1077	26,889	360	25,191	182	24,702	101	29,331	3	1922
Urban												
Port Vila Centre	-	-	1	45	2	75	4	581	26	8,539	1	63
Port Vila Rural	-	-	-	-	3	244	1	180	11	3,573	1	630
Luganville Centre	1	4	3	117	4	321	4	588	15	4,153	-	-
Total Urban	1	4	4	162	9	740	9	1,349	52	16,265	2	693
Rural (by difference)	565	3212	1073	26,727	351	24,451	173	23,353	49	13,060	1	1229

Table 1. Distribution of Population in Vanuatu: Basic Statistics from 1979 Census.

Table 2. Population served by different sources (in existing, under construction or planned schemes, 1984)

Source Type	%
Springs	37
Riverflow	21
Rainfall Catchments	20
Wells/Boreholes	22
	100

WATER RESOURCES BOARD (within Central Planning Office)

(a) Policy interpretation and drafting - Coordinate work programmes

JUDICIAL REVIEW BODY

(a) Ensure administrative agencies acting within law

(b) Protect private rights

(c) Establish liability and impose penalties or compensation

MINISTRY OF LANDS AND NATURAL RESOURCES
Department of Geology, Mines and Water Supplies

Main Executive Agency on Water Resources

(a) Rural water supply development (planning priorities by CPO and Local Government)

(b) Urban water supply : within items (c)-(e)

(c) Data storage - resource evaluation - Master Planning

(d) Allocation of resources - Use License - Levy charges as required

(e) Water quality/abstraction : monitoring and surveillance

(f) Provide advice on overall legislative provisions; enforce specific legislation in accordance with Water Code

Private Users

(a) Basic rights without license

(b) Basic rights with license

(c) Obligations to provide information, allow legalised administrative intervention and required pay levies

Public Works Department (Ministry of Works)

(a) Urban water supply

(b) Construction, metering, maintenance and surveillance

(c) As empowered : levy charges and enforce legislative provisions

Municipality

(a) Urban sewage

(b) Environmental pollution control and general licensing

Environmental Health Unit (Ministry of Health)

(a) Rural water supply development (rural sanitation)

(b) As empowered : levy charges and enforce legislative provisions

Water in Agriculture (Ministry of Agriculture)

(a) Drainage, irrigation, flood control

(b) Construction. metering, maintenance and surveillance

(c) As empowered : levy charges and enforce legislative provisions

Table 3. Schematic Administrative Framework and Functions.

THEME II FORMATION OF SMALL ISLANDS

Page

GEOLOGIC CONSTRUCTION OF ATOLLS

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INTRODUCTION

Atolls are common throughout the tropical Indo-Pacific ocean and provide a habitat for a significant portion of the population within the equatorial region. The atoll is a unique end product of a continuous series of geologic and biologic processes that have been at work for perhaps tens of millions of years. The purpose of this paper is to briefly describe these atoll-building processes, their geologic products, and how they relate to island hydrogeology.

As viewed from sea level, the atoll is characterized by a ring-like structure consisting of a barrier reef system totally or partially enclosing a central lagoon. Maximum lagoon depths between atolls range from a few to several hundred feet. Often, but not necessarily, islands primarily composed of unconsolidated carbonate sediment form on top of the reef platform. These islands are variable in size and shape, low lying, and usually vegetated with numerous species of plants (depending on the availability of fresh groundwater). Below sea level and out of view, the atoll pedestal, composed of sediments and volcanic rocks, may extend upward from the ocean floor for several thousand feet.

GEOLOGICAL HISTORY OF AN ATOLL

Most atolls begin as submarine volcanoes which develop over so-called hotspots or near ocean-floor spreading centers (such as the East Pacific Rise). Outpourings of basaltic lava build a mountain on the sea floor that may eventually reach sea level or, with continued volcanism, will build high islands. Contemporaneous with the formation of these high islands is the development of fringing reefs along the newly formed shoreline.

As discussed in the paper by Barry Waterhouse (this volume) oceanic volcanic islands tend to subside with time due to tectonic processes of plate motions and localized factors (including loading). If subsidence is slow enough such that coral growth keeps up with the relative changes in sea level, then thick sequences of reef and reef-associated sediment will accumulate. Eventually, with continued subsidence, the familiar ring-like reef structure of the atoll will develop.

A set of diagrams depicting the series of events that leads to the formation of an atoll is shown in Figure 1. Examples of islands demonstrating the various stages cartooned in the figure are readily found throughout the Pacific region. Referring to the diagrams, during the early stages of volcanic island subsidence and reef development the reef tract is narrow and few if any islands form upon its surface. As subsidence continues and the volcanic core slowly submerges, the reef tract increases in width by progradation and more islands form on its surface. Eventually a few of the islands coalesce and increase in size as the reef tract expands lagoonward. The whole process of reef development, sediment production, transportation, and deposition is directly related to the relative position of the land to the level of the surrounding sea.

During the past few million years, eustatic sea-level fluctuations related to global episodes of glaciation have affected reef growth and carbonate sedimentation across the Indo-Pacific region. Rapid lowering of sea level during glacial advances exposed reef structures to subareal conditions which relocated coral growth and subjected the carbonate platform to erosion and karstification. Fringing reefs began to develop once again adjacent to newly formed emergent shorelines. With subsequent melting of alpine and continental glaciers a large volume of water was added to the world's ocean causing a eustatic rise in sea level. Previously emergent platforms were submerged and coral growth was again displaced. With advances and retreats of glaciation, this cycle of falling and rising sea level was repeated numerous times during the Pleistocene; each cycle left an imprint on the geological makeup of the atolls.

GEOLOGICAL COMPONENTS OF AN ATOLL

Deep drilling and seismic studies primarily in the Marshall Islands (Dobrin and Perkins, 1954; Raitt, 1954; Raitt, 1957; Ladd and Schlanger, 1960) and Funafuti Atoll (Royal Society of London, 1904) have revealed information on the subsurface geology of atolls. In general, the atoll complex is composed of several thousand feet of mainly reef and reef-associated sediment overlying and partially draping an older volcanic basement. The basement is composed of basaltic lava similar in composition to that of the oceanic lithosphere itself. Numerous facies indicative of specific depositional environments have been identified within the various carbonate units. These facies represent previous deposition within the fore-reef, reef, back-reef, and lagoon environments.

It is noteworthy that little evidence has been found to indicate the pre-existence of atoll islands. This lack of evidence may be due to one of three factors: (1) sediments comprising atoll islands are similar to sediments comprising the substrate upon which the islands sit and therefore cannot be distinguished in samples collected from the subsurface; (2) prior to burial, the unconsolidated sediments of the atoll island may have been removed by waves and currents; or (3) atoll islands simply did not form prior to the latest high sea-level stand. With regard to point number three, the interpretation of observations made on numerous atolls in Micronesia suggests that islands seem to form when a hard substrate is present prior to the deposition of their reef-associated sediments. In addition, results from drilling on atoll platforms indicates that within Holocene sediments, only the present-day reef flat depositional environment exhibits a significant thickness of well-indurated material. Sediments underlying the reef flat are, for the most part, poorly cemented to unconsolidated except for the occasional thin well-cemented zone or layer. If a substantial hard substrate did not develop prior to the present and the interpretation of the observations is correct, then atoll islands would not have formed to any great extent until the very recent stablization of sea level (i.e., within the last three thousand years).

Although the overall geology of an atoll is interesting from the geologist viewpoint, it is of little practical value to the hydrogeologist. What is of interest, however, is the upper couple of hundred feet of the carbonate pile near sea level. This is the geologic package within which fresh groundwater will occur. Therefore attention is turned to taking a closer look at the various components that comprise this important zone.

Numerous atolls within Micronesia, and probably elsewhere, appear to have very similar geological characteristics. This is not particularly surprising since the same physical and biological processes are at work shaping each atoll and all islands have gone through about the same history (at least during the Pleistocene). The picture that is unfolding is an interesting one in terms of the hydrogeologic framework of atoll islands and may eventually lead to a general model which can be applied to many previously unstudied island cases.

Based on work conducted on Enewetok (Ladd and Schlanger, 1960), Bikini (Emery et al., 1954), Tarawa (Jacobson and Taylor, 1981), and Nukuoro (Ayers and Clayshulte, 1983), it is known that reefs and reef-associated sediments of recent age rest upon an older Pleistocene karstified surface. Carbonates of Pleistocene-age units usually differ greatly in their hydraulic properties when compared to their Holocene counterparts; higher permeability due to the development of secondary or solutional porosity is the most significant difference. Although depth is variable, the Pleistocene contact is often located between 40 and 80 feet below sea level. Recent carbonate sediments overlying the Pleistocene units are mostly unconsolidated to poorly consolidated with occasional thin hard layers of either coralline algae or well-cemented sands and rubble. Numerous facies may be present and usually exhibit unique hydraulic properties.

As an example of what might be encountered in the subsurface of a typical atoll-island aquifer system, the results from field work conducted on Deke Island, Pingelap Atoll (Ayers et al., 1984), are briefly presented. Field work on Deke included core drilling, seismic-refraction surveys, and surficial geologic mapping in an effort to collect information related to the hydrogeologic makeup of the island's lens system. Figure 2 shows a representative geologic cross section of Deke; all relevant field data was used to construct the diagram. Table 1 is the symbol legend for Figure 2.

Referring to Figure 2, sediments comprising the island (unit 1) rest partly upon the reef-flat plate (unit 3) and partly upon sands deposited lagoonward of the reef flat (unit 5). Unit 3 extends beneath the island to variable distances and forms a continuous plate from the reef margin to wherever it grades into sediments of the sand apron. Beneath the reef-flat plate, and apparently associated with it, are sand- and gravel-size sediments derived from the reef environment. A notable characteristic within unit 4 (observed as a drilling response) is alternating hard and soft zones. Based on the analysis of cores, these zones are associated with well-cemented sections and unconsolidated layers of rubble. This alternation of cemented and non-cemented zones would certainly produce a strong horizontal component to the groundwater-flow regime (anisotropy). Another point that is noteworthy is the close affiliation between the reef-flat plate and this unit. Constituent particles comprising both units are the same; the difference is the abundance of cement. As readily observed in core samples, the amount of cement binding the sediment decreases with increasing depth. The reef-flat plate forms a wedge-shaped plate with the thickest portion oriented toward the reef. Where the plate grades into the lagoonward unit (unit 5), the lithologic character of both units 3 and 4 change; the matrix cement is absent and the sediments are mainly unconsolidated and finer grained. All of this seems to indicate that the process of cementation is somehow linked to sea-water circulation along the ocean shoreline. Further, since the unit below the reef-flat plate is similar in particle composition but lacks thick zones of well-cemented sediment with depth (i.e., prior development of well-cemented reef-flat deposits), the process of reef-flat cementation is probably controlled by the present-day sea-level stand. Hopefully, as more field data become available, the origins of the reef flat will be explained. Because of the important role it plays in the occurrence and movement of fresh groundwater, the endeavor is an important one.

The presence of a Halimeda facies (unit 6), similar to that described for Enewetok (Ladd and Schlanger, 1960), underlying the reef-flat plate, its associated sediments, and the sand apron was confirmed by drilling and its contact was mapped by seismic shooting. Field data indicates that the top of the Halimeda facies is highly irregular and occurs at variable depths below sea level. Based on velocity data there seems to be a transverse change in either density or composition near the lagoon shoreline where velocities tended to be somewhat lower. The best explanation for the velocity contrast would be a change in composition associated with disparate depositional environments. That is, the Halimeda facies probably grades into an environment more closely related to lagoon deposition.

Each of the above described units is an important component of the hydrogeologic framework of Deke Island. The various units exhibit unique hydraulic properties that influence, to some extent, the occurrence and movement of fresh groundwater within the lens system.

The main hydrological function of the island (unit 1) is simply to catch rainwater and transfer it to the subsurface units, that is, to the units which comprise the reef-tract complex. Numerous processes are involved with the transmittal of water. A portion of the rainfall is intercepted by plants and may be returned to the atmosphere by direct evaporation. After rainwater reaches the ground surface, some is used by plants and transpired back to the atmosphere, some is retained in the soil and sediments of the unsaturated zone, some is evaporated back to the atmosphere, and the remainder eventually percolates downward intc the saturated zone. All of these processes, of course, are part of the hydrological cycle and are important factors to be considered when dealing with the overall water budget.

As documented by water-level observations in standpipe-piezometer pairs during the course of the Deke study, the reef-flat plate functions as a confining bed beneath which fresh groundwater is under hydraulic pressure. The presence of the plate greatly affects the configuration and behavior of the fresh-water lens as well as previously held views of how groundwater occurs beneath atoll islands. A simple Ghyben-Herzberg lens model does not apply to the flow system of Deke and to similar islands. The picture is greatly complicated by (1) partial confinement of the flow system, (2) leaky behavior of the reef-flat plate, (3) impedence of direct recharge to the subsurface, and (4) extension of the discharge area past the ocean shoreline of the island. Details of these points are addressed in another paper of these proceedings; however, the second point is worth pursuing since it reflects the hydrogeologic properties of the unit. As documented by data collected during water-level observations, the reef-flat plate is not totally impermeable as its well-cemented character might suggest. It was observed that on rising tides, groundwater was pumped upward through the plate, possibly via fractures (observed on the exposed reef flat) or via the small degree of interparticle porosity not affected by the cementation process. The tidal pumping response was delayed and its amplitude was dampened as compared to the unimpeded responses observed in piezometers which penetrated the plate. On falling tides, infiltrating rainwater and residual groundwater (that is, water left standing over the plate after a rising tide) tended to gravity drain downward into the lens flow system.

There is a sharp contrast in permeability between the reef-flat plate and the underlying unit. Low abundance of fabric cement and numerous unconsolidated zones, in addition to the wide sediment size range, contribute to the relatively high permeability of unit 4. The permeability of unit 4 is about 1500 ft/day or equivalent to an aquifer composed of sand and fine gravel. As a testimony to this high permeability, the following was experienced after the completion of a borehole which penetrated unit 4. Seawater was used as the drilling fluid. After drilling was completed, salinity profiles were measured within the borehole for several days. Measurements indicated that the borehole had cleared well within a 24-hour period.

Based on available information, unit 5 is composed of unconsolidated sand derived from both the lagoon and the reef environments. The portion of the unit of interest underlies the island between the reef-flat plate and the lagoon shoreline. Because the plate is missing, recharge water infilrating island sediments enters the flow system unimpeded. Of greater interest is the apparent disparate permeability between this unit and unit 4. Although no direct measurement of permeability was made for this unit, considering the type of sediment comprising unit 5 and its more uniform size distribution (measured from samples) and from the greater dampening of the tidal signal, it can be deduced that the permeability of unit 5 is probably an order of magnitude less than that of its neighbor. Generally, clean sands in the size range that comprises unit 5 have a measured permeability of around 150 ft/day.

Permeability values were not determined for the two deeper units because little material was recovered during drilling. It is assumed, however, that the permeability of units 6 and 7 are probably close to that described for units 4 and 5 since they appear to occupy the same relative depositional position as overlying units.

CONCLUSION

Atolls are unique geological structures. Their development is linked to tectonic processes within the oceanic lithosphere, to biological processes of reef building, and to numerous other factors that produce, transport, deposit, and consolidate carbonate sediments. Because many atolls are inhabited, it is important that the practicing hydrogeologist understand their complex history (particularly during Pleistocene and Holocene times) and numerous the processes that have contributed to the development of atolls, if realistic and sound approaches are to be applied to solving the numerous water problems experienced by atoll island communities.

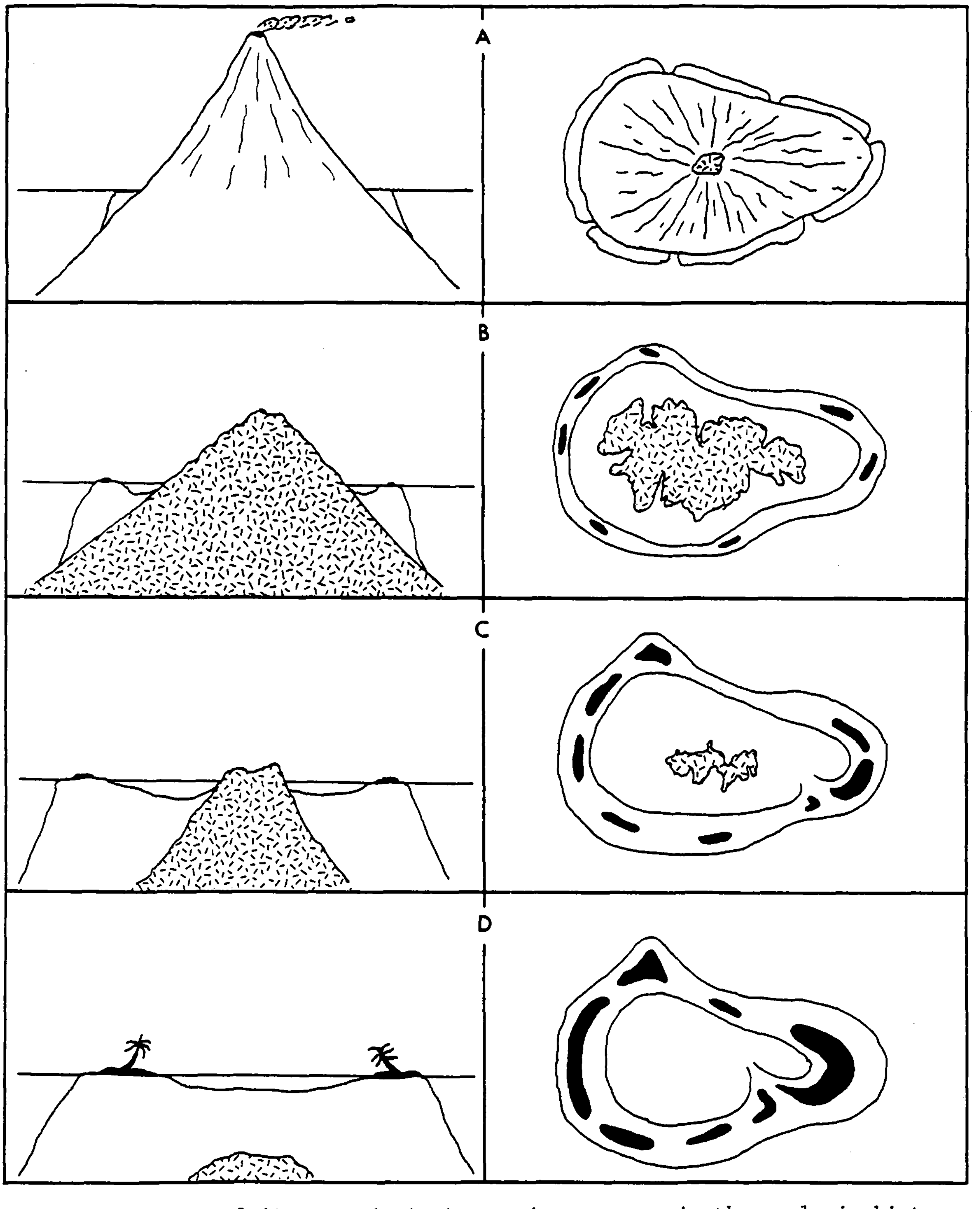


Figure 1. Series of diagrams depicting various stages in the geologic history of an atoll. An emergent high volcanic island (A) forms as the initial stage. After cessation of volcanism, the volcanic core begins to subside (B) until little is above sea level (C). The final stage is the familiar ring-like structure that characterizes most atolls (D).

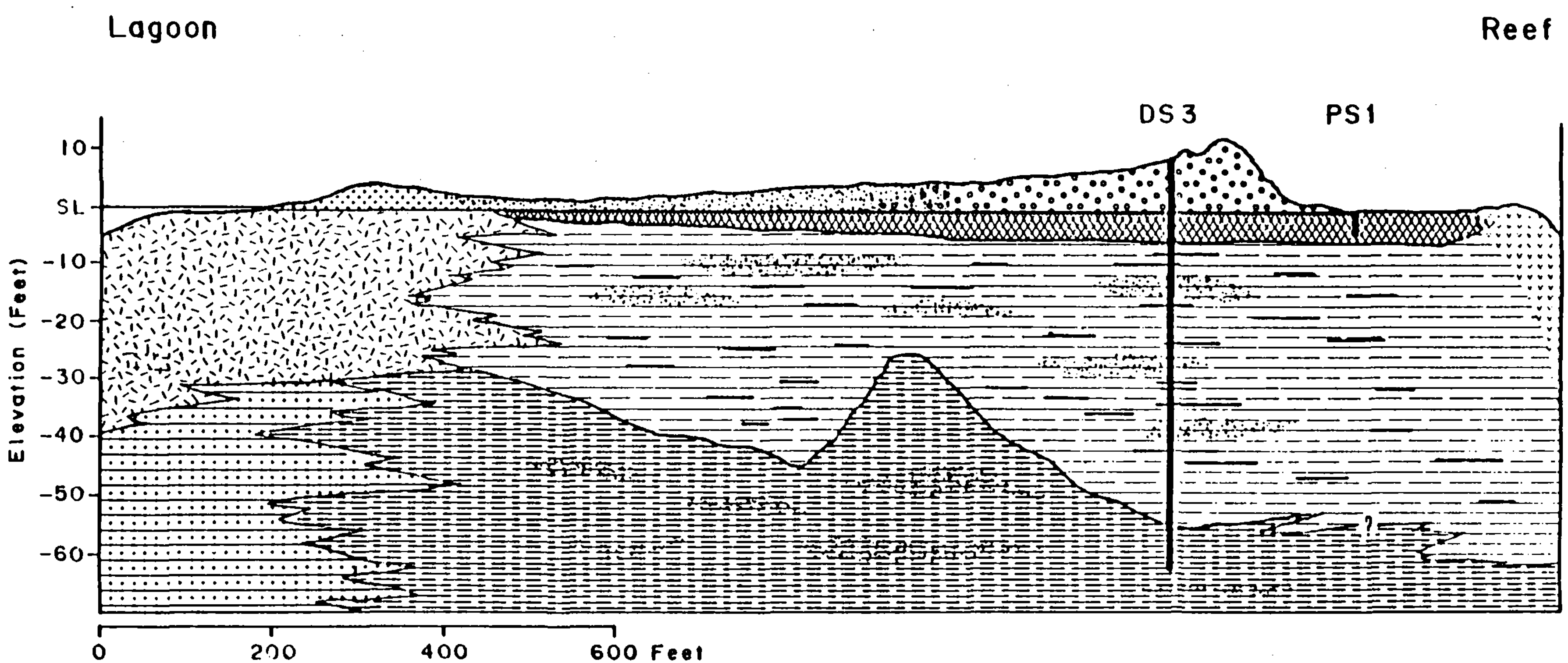
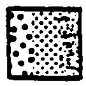
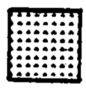
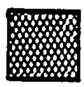
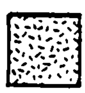
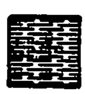
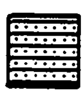


Figure 2. Geologic cross section of Deke Island, Pingelap Atoll. Six stratigraphic units comprise the hydrogeologic framework of the island's groundwater-flow system. Table 1 gives the legend and a brief description of each unit.

Table 1. Legend and brief description for the stratigraphic units shown in the geologic cross section of Figure 2.

Unit No.	Symbol	Description
1		Unconsolidated sediment comprising Deke Island.
2		Reef strucure.
3		Well indurated sediments of the hard layer (reef flat); Permeability is very low.
4		Unconsolidated to poorly consolidated sediments probably associated with back-reef deposition; Permeability is very high.
5		Mostly unconsolidated sand-size sediments probably deposited in the sand apron behind the reef flat; Permeability is high.
6		<u>Halimeda</u> facies composed of poorly consolidated sand- and gravel-sized reef rubble; Permeability is very high.
7		Unit composition is unknown, may be associated with lagoon deposition; Permeability is probably similar to that of unit 5.
		Unit contact established by measurement.
		Hypothetical unit contact; represents a gradation between units.

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Workshop on Water Resources of Small Islands, Fiji, 1984

NIUE ISLAND: AN EXAMPLE OF A RAISED ATOLL

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Abstract

Niue Island, in the south Pacific Ocean, is a raised coral atoll with an area of 259 km^2. The original atoll rim is preserved as a peripheral ridge about 60 m above sea level, and the original lagoon floor now forms an internal basin about 35 m above sea level. Drilling has proved limestone of Miocene age to a depth of more than 200 m. Gravity and magnetic surveys indicate that the limestone probably overlies volcanic bedrock at a depth of about 300 m below sea level. The classical Ghyben-Herzberg freshwater lens does not exist on Niue island. Results of electrical resistivity surveys indicate that in the centre of Niue the freshwater layer is 40-80 m thick and beneath the former atoll rim it is 50-170 m thick. It decreases to zero close to the coast, where mixing with salt water occurs along fissures in the limestone. The irregular configuration of the freshwater layer is ascribed to permeability differences in the limestone.

NIUE ISLAND: AN EXAMPLE OF A RAISED ATOLL

Niue Island in the South Pacific Ocean (Fig.1) is a raised coral atoll comprising limestone and coral sand. The original atoll topography is substantially preserved (Fig.2). The former lagoon floor, the Mutalau Lagoon (Schofield, 1959), is now a flat-bottomed internal basin at an elevation of about 35 m above present sea level. The former atoll rim, the Mutalau Reef, is now a narrow peripheral ridge which extends around the island at an elevation of about 60 m. The former lagoon passage is now a dry valley to the south of Alofi (Fig 2) at an elevation of about 42 m.

A narrow terrace, the Alofi Terrace, extends along the west and south coasts, at an elevation of 25 m; steep cliffs descend from the terrace to the sea. Younger coral terraces, 2-4 m above sea level, fringe parts of the east and south coasts, and a fringing coral reef about 100 m wide encircles the island at sea level. Concentric lineaments are apparent in the southwest of the island, and probably represent strandlines of the former lagoon.

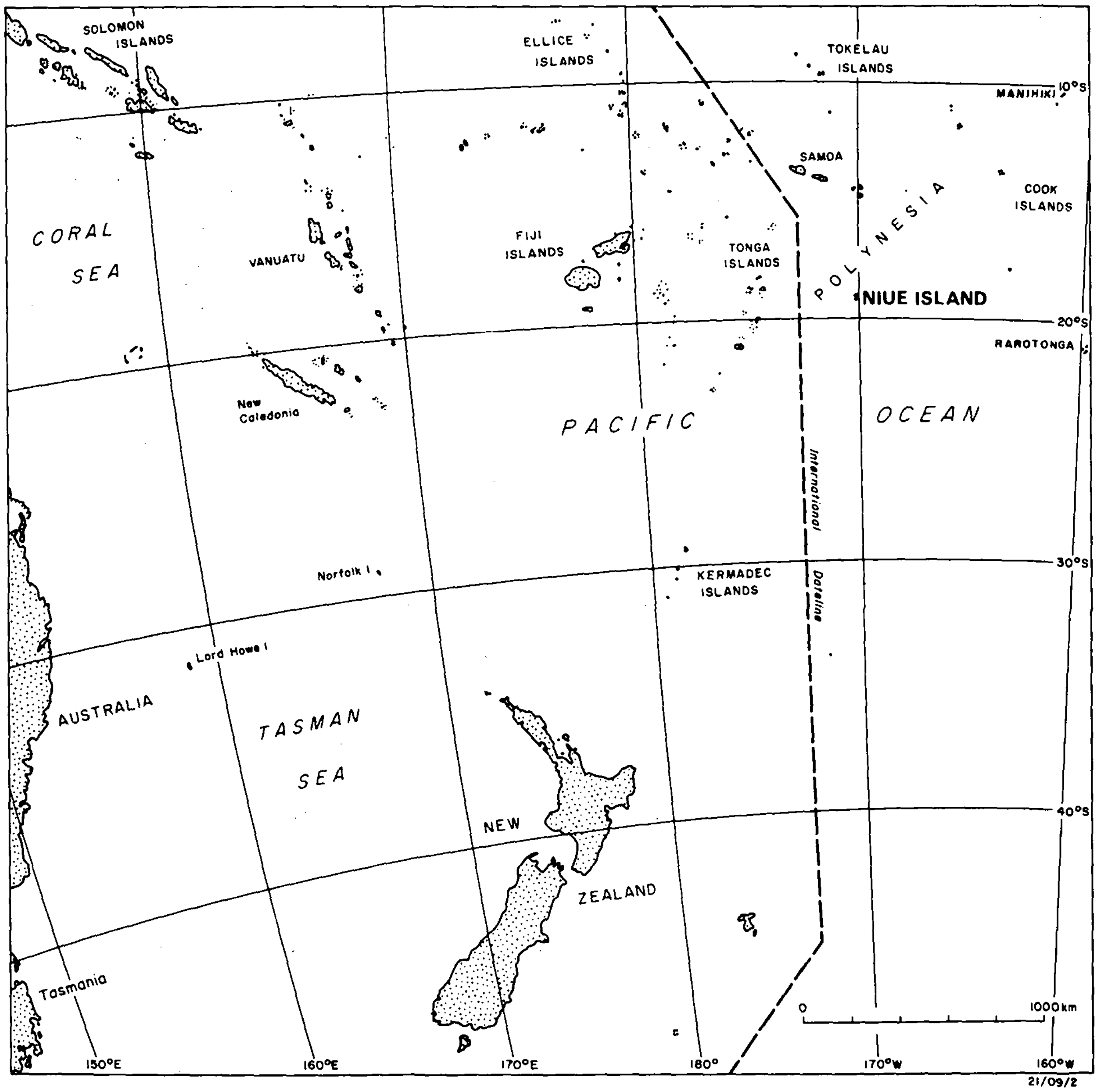

Figure 1 Location Map

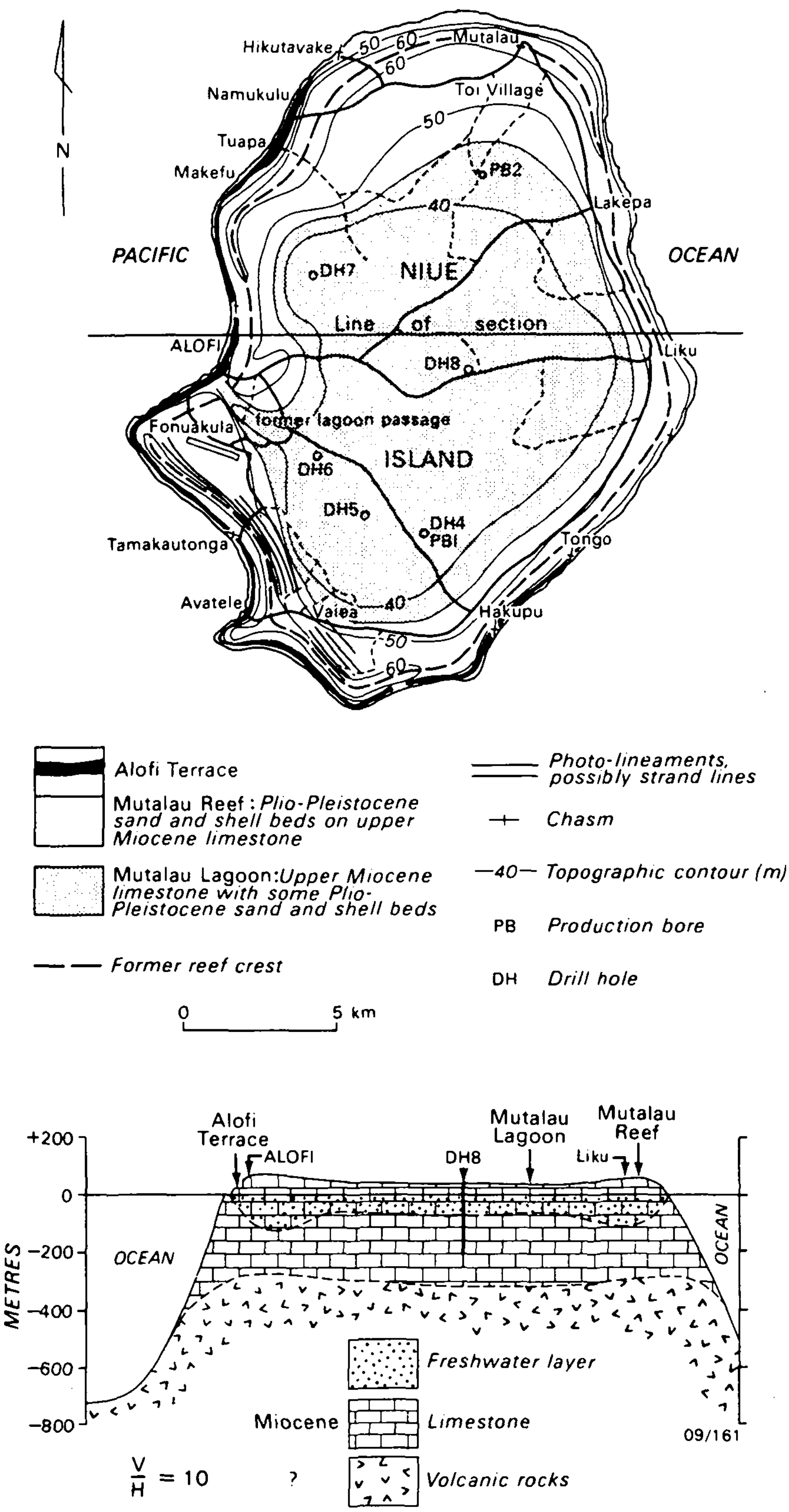

Figure 2

Geology and Geomorphology of Niue Island

Drilling has proved limestone to a depth of more than 200 m in central Niue. The limestone varies in texture from hard and dense to soft and chalky or sugary; the sequence also includes beds of unconsolidated sand and hard, recrystallised dolomite. The limestone is jointed and cavernous to great depths, and most of the sequence to a depth of 170 m below sea level is Middle to Late Miocene (Jacobson & Hill, 1980). Fossils from surface localities in the interior of Niue have been dated as Plio-Pleistocene (Schofield , 1959); they were probably taken from a thin veneer of younger sediments in parts of the former lagoon.

The island is underlain by a seamount that rises 4000 m from the floor of the Pacific Ocean. Gravity and magnetic surveys indicate that Niue has a dense, reversely magnetised, volcanic core centred in the south of the island (Fig. 3) and that the volcanic rock is at an average depth of about 300 m below sea level (Hill,1983).

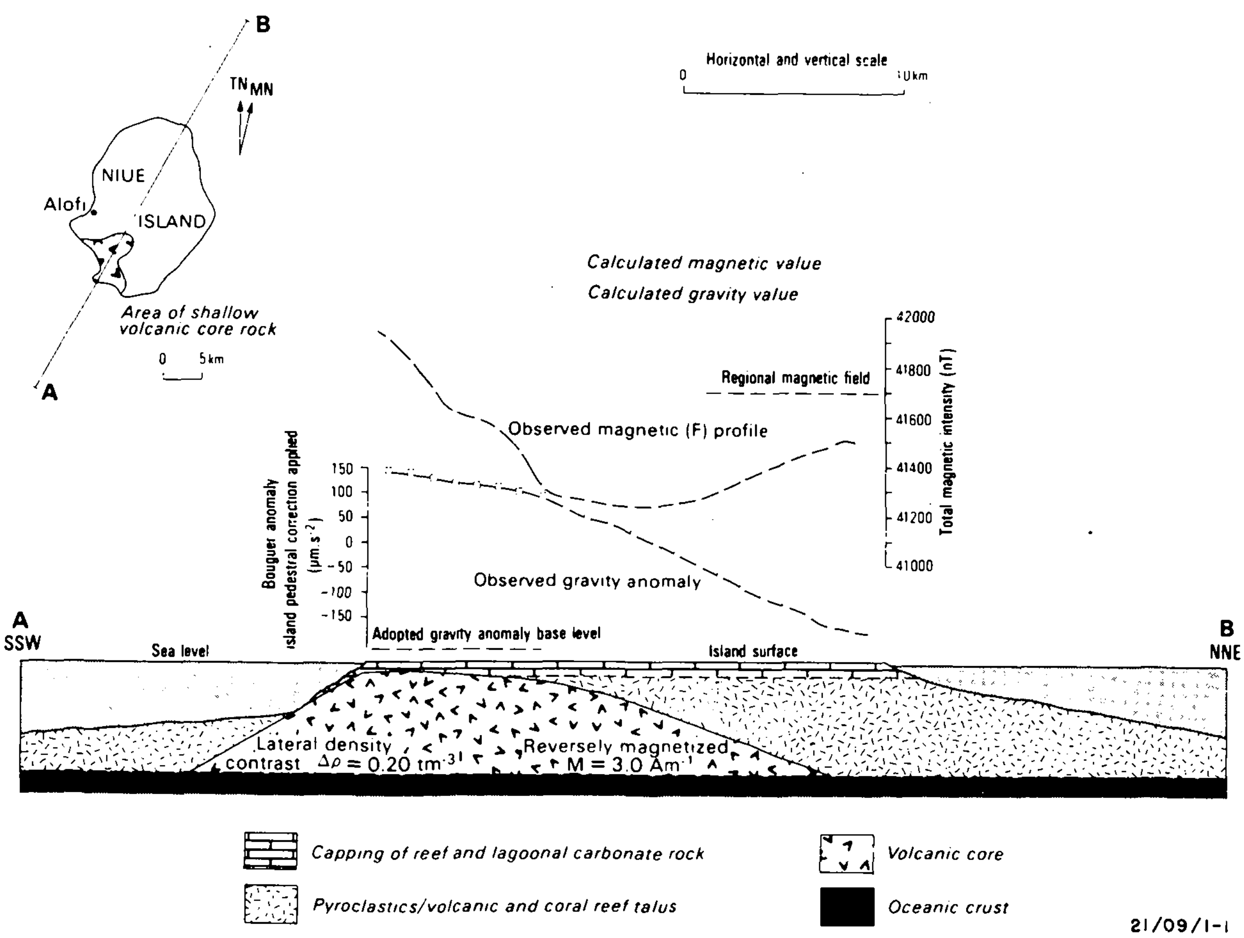

Figure 3

Interpreted volcanic substructure of Niue Island (after Hill,1983)

Niue Island has been affected by a complex history of sea-level changes, the "yo-yo oscillations" of sea-level so graphically described by Friedman (1975). Local tectonic effects have been superimposed on these changes - the "yo-yo tectonics" of the seafloor. This has given rise to the coastal terraces and to the extensive dolomitisation of the sedimentary sequence (Schofield & Nelson, 1978). The most recent uplift to form the present raised atoll may be due to the upwards bulge of the Pacific lithospheric plate before its subduction in the Tonga Trench (Dubois and others, 1975).

The thickness of the freshwater layer has been inferred from electrical resistivity depth probes (Jacobson & Hill, 1980). It ranges from 40-80 m beneath the centre of Niue (Fig. 4), to 50-170 m beneath the former atoll rim, and declines to 0 close to the coast. Thus the freshwater layer is approximately doughnut-shaped, and does not have the characteristic lens shape of small oceanic islands with an homogenous permeability distribution. The irregular shape of the freshwater layer is probably due to a variation of permeability within the limestone, with less permeable material underlying the rim of the island. This could be the case if the former lagoonal sediments are porous calcarenites while the former atoll rim is underlain by recrystallised or cemented reef limestone or dolomite.

Some geomorphological features of the Niue Island coastline are shown in Figure 5. A transition zone of brackish water extends inland for up to one kilometre due to mixing along fissures in the limestone. Several types of caves are developed; deep fissures near the coast described as "chasms" by Schofield (1959), are water-table windows. Groundwater is developed through a number of bores on Niue, and the freshwater resources are substantial enough for the foreseeable agricultural and industrial development.

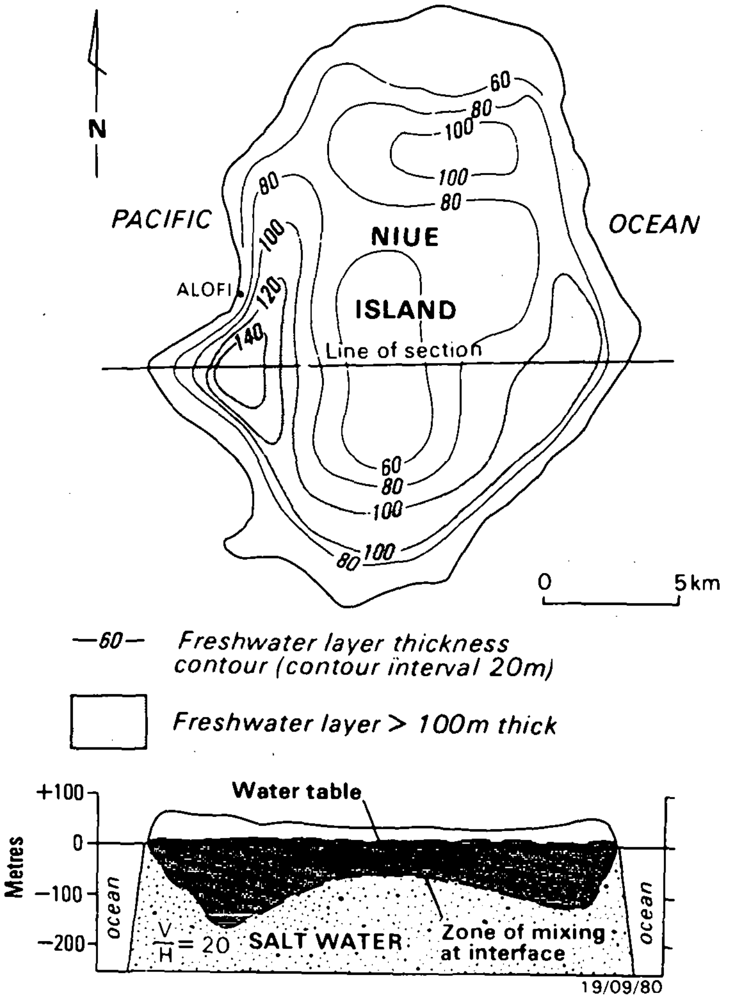

Figure 4

Niue Island: Thickness of the freshwater layer inferred from resistivity data

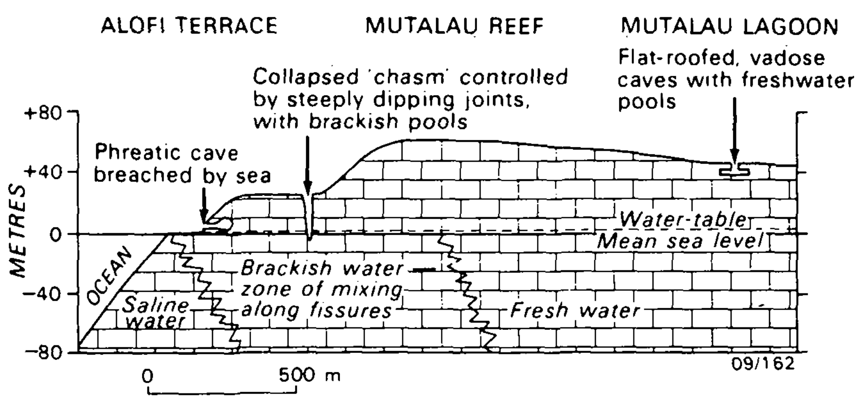

Figure 5 Cross-section showing geomorphological features, west coast of Niue Island

Acknowledgements

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GEOLOGICAL AND GEOMORPHOLOGICAL EVOLUTION OF SMALL ISLANDS, PACIFIC REGION

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Abstract

A review of the evolution of small oceanic island in the Pacific region is given. The islands are volcanic in origin and rise from the deep sea floor to heights in excess of 4200 m asl (Hawaii). Sea floor loading by volcanoes on an elastic lithosphere is considered a mechanism for elevating or depressing nearby volcanic islands.

The growth of islands dating back to the pre-Oligocene, and the formation of a coral cap when the volcano is at or near sea level is described.

Five bathymetric features of the sea floor are recognised. They are (oldest to youngest average ages) ridges 87 M, seamounts 57 M, guyots 35 M, atolls 11 M, and volcanoes 8 M years. Dating is by radiometric methods, assumed subsidence rates, or geomorphological criteria. Eustatic fluctuation of sea level, and the effect on some islands is noted.

The geology, size, and topographic features of an island determines water supply potential. Three types are described (youngest to oldest); high islands (volcanic), raised atolls, and atolls.

Keywords Pacific islands; evolution; volcanic; sea floor deformation; age; water supply.

Introduction

'Small Islands' are defined as being less than 5000^{2}km in area located within the central Pacific region. For convenience the islands are classified into high volcanic islands, raised atolls, and atolls. The geological and geomorphological evolution of each 'type' is discussed. Most of the evolutionary processes are related to the theory of plate tectonics, which explains earthquake and volcano distribution, continental drift, seafloor spreading, and mountain building.

The geological age and geomorphology of the islands provides a rough guide to their water resource potential e.g. the younger islands (the high volcanic islands) have better prospects.

Theoretical Development

Many theories have been suggested for the formation of island chains, a common feature in the Pacific. These include the relative motion between the lithosphere (the earth's crust and upper mantle) and a partially melting (hot) spot in the mantle (the part of the earth's interior extending between the outer core and the base of the crust) (Wilson 1963a, 1963b), propogation of volcanism along fractures (Betz & Hess 1942, Batiza 1982), diapiric upwelling (a domed structure ruptured by the squeezing out of plastic core material) (McDougall 1971), melting caused by shearing beneath the lithosphere (Shaw & Jackson 1973), heating of the lithospheric plate during volcanism and consequent regional uplift (Schlanger et al. 1981), or deformation of the lithospere by sea floor loading (McNutt & Menard 1978).

All of these mechanisms have their proponents and equally there are probably as many opponents to theories as supporters. The model adopted here provides a simple and acceptable mechanism for the formation of oceanic islands.

Sea Floor Deformation

The model is that proposed by McNutt and Menard (1978). Although it provides a simple explanation for some observed geological and geophysical features common to many Pacific islands and island chains, it can be questioned in some details which do not neatly fit the picture in all cases. McNutt and Menard present an argument for sea floor deformation by modelling the oceanic lithosphere as an elastic plate overlying a fluid asthenosphere, a shell of weakness underlying the lithosphere. Their model (Fig. 1), which can be likened to a modern day water bed, illustrates the isostatic effects of a young growing volcano on nearby islands or atolls formerly at sea level but now up to 70 m above sea level. McNutt and Menard (ibid) argue that the weight of volcanic material accumulating on the sea floor compresses the lithosphere in that region, and the consequent thinning of the lithospheric plate is compensated by a thickening nearby. This is demonstrated by the presence of moats and arches revealed by topographic profiles in the ocean bathymetry. That the weight of volcanic material is probably significant in sea floor topography can be judged by the volume of lava extruded from an estimated 22000 to 55000 seamounts and 1500 to 200 active volcanoes on the Pacific lithospheric plate (Batiza 1982). McNutt and Menard's (1978) hypothesis that islands may have been uplifted by deformation of the lithosphere seems logical.

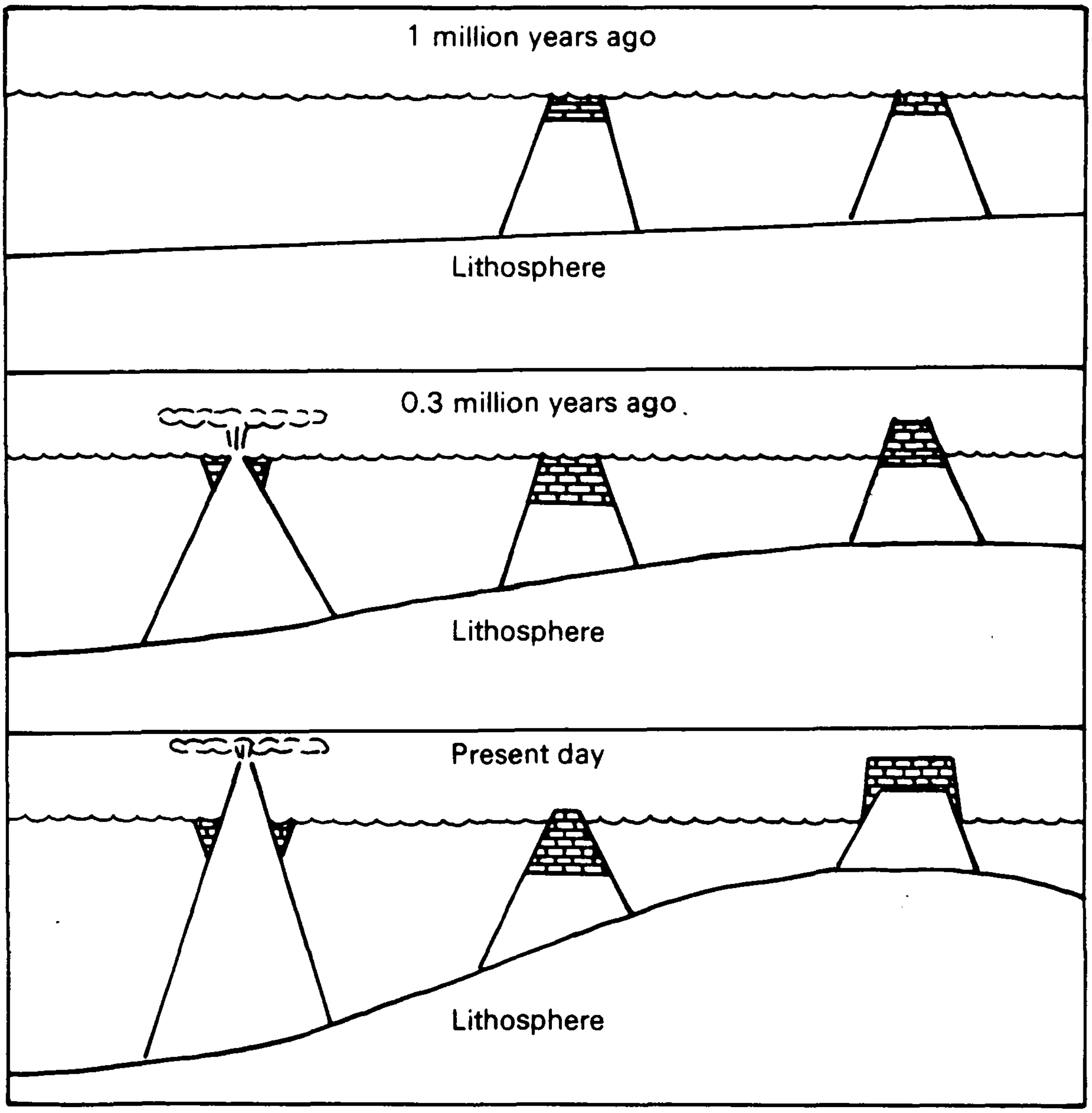

FIGURE 1 Model of apparent sea level change on coral atolls caused by volcanic loading on an elastic lithosphere (after McNutt & Meñard 1978).

Growth of an Oceanic Island

The observations from emergent islands in the Pacific allows, to some extent, a deduction of their geological history.

Yonekura (1984) classifies three types of islands in and around the Pacific. They comprise:

1. Continental islands belonging to any continental mass such as Asia, America, and Australia.
2. Island arcs associated with oceanic trenches, active volcanoes on islands, and back-arc basins.
3. Oceanic islands, either volcanic or coral reef, standing from deep ocean floors far from any continent.

The present discussion is restricted to oceanic islands of which Scott and Rotondo (1983) distinguish eleven distinct types. They comprise (Fig. 2)

a. Volcanic island with no fringing reef
b. Volcanic island with fringing reef
c. Raised volcanic island with fringing reef
d. Almost-atoll
e. Raised almost-atoll
f. Atoll
g. Inundated atoll
h. Part raised atoll with open lagoon
i. Part raised atoll with enclosed lagoon
j. Raised atoll with dried out lagoon
k. Raised atoll with typical form lost

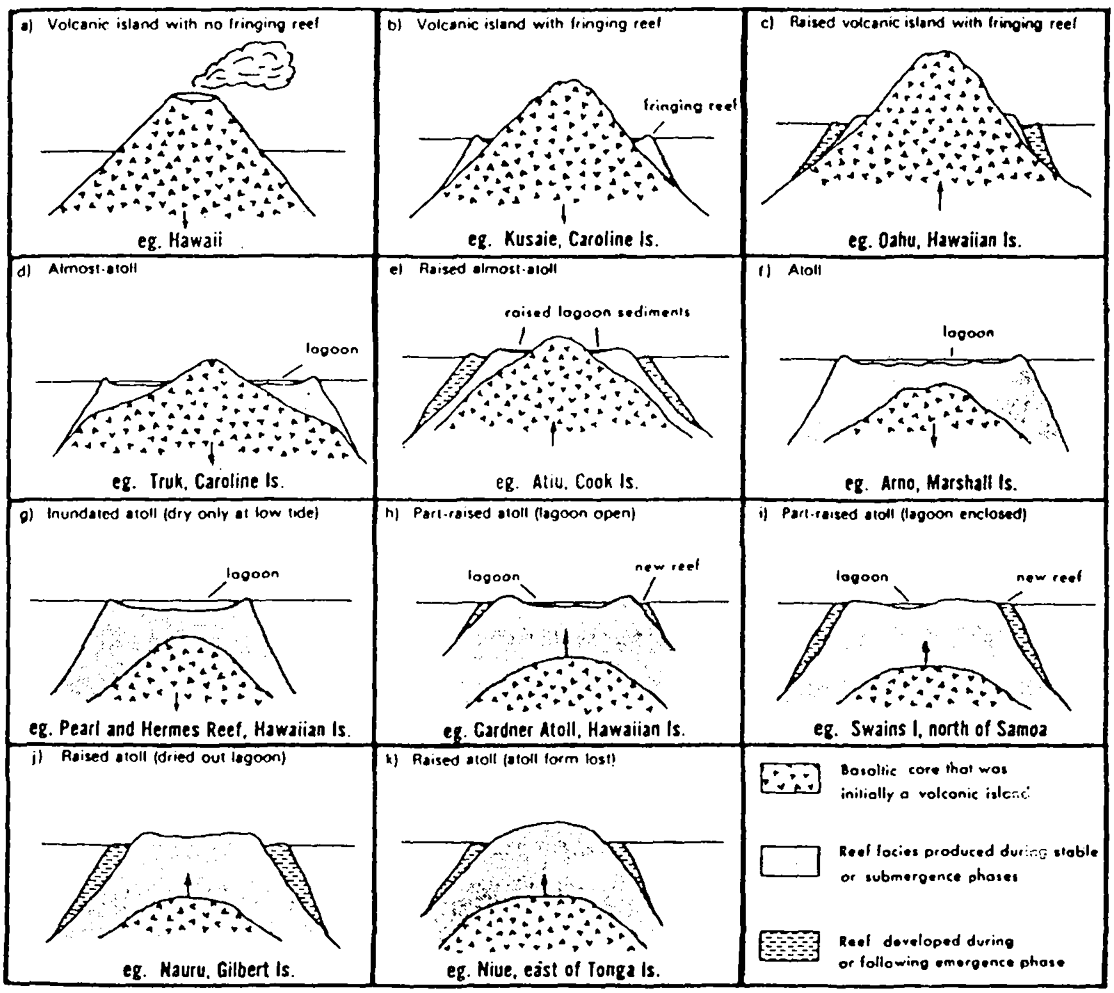

FIGURE 2 Island–atoll types on the Pacific lithospheric plate (Scott & Rontondo 1983).

The formation of each oceanic island type is controlled by episodes of dilation or contraction of the lithospheric plate, and in their model Scott and Rotondo show five subsidence and six elevation cycles (Fig. 2). It is suspected that some of these would be eustatic rather than tectonic events as depicted.

At least two of Scott & Rotondo's illustrations are in error. Atiu (e) is a volcanic island, or raised island with fringing reef, not a raised 'almost atoll' although this description has been applied to Aitutaki also in the Cook Group (Wood & Hay 1970; Waterhouse & Petty in press). Niue (k), a raised coral atoll, displays the original atoll rim as a peripheral ridge about 60 m asl, and the original lagoon floor now forms an internal basin about 35 m asl (Jacobson 1980).

In the following discussion, a simplified history of events shows two phases of island construction i.e., initial elevation followed by a continuing period of subsidence (Fig. 3).

During periods of intermittent volcanic activity, it has been suggested that the ocean floor in the vicinity of the volcanic island swelled upwards as a result of increased lithospheric pressure associated with the fusion processes which generated the lava to form the island. In the dying stage of eruptive activity the volcanic edifice would then start sinking under its own weight at a rate which may have been between 2 mm to 10 mm per hundred years (Detrick & Crough 1978; Baillard 1981). Fig. 3 illustrates the possible history of elevation and subsidence of a volcano from its initial eruption in the pre-Oligocene (pre 37 m.y.) to the present day; (1) coral reef forms when volcano rises to within -45 m or above sea level, (2) continued emergence of volcano forms high island and elevates coral reef (makatea), (3) intermittent volcanic activity, and subsidence as a result of sea floor loading, (4) dying stages of volcanism and continued subsidence of volcanic edifice,

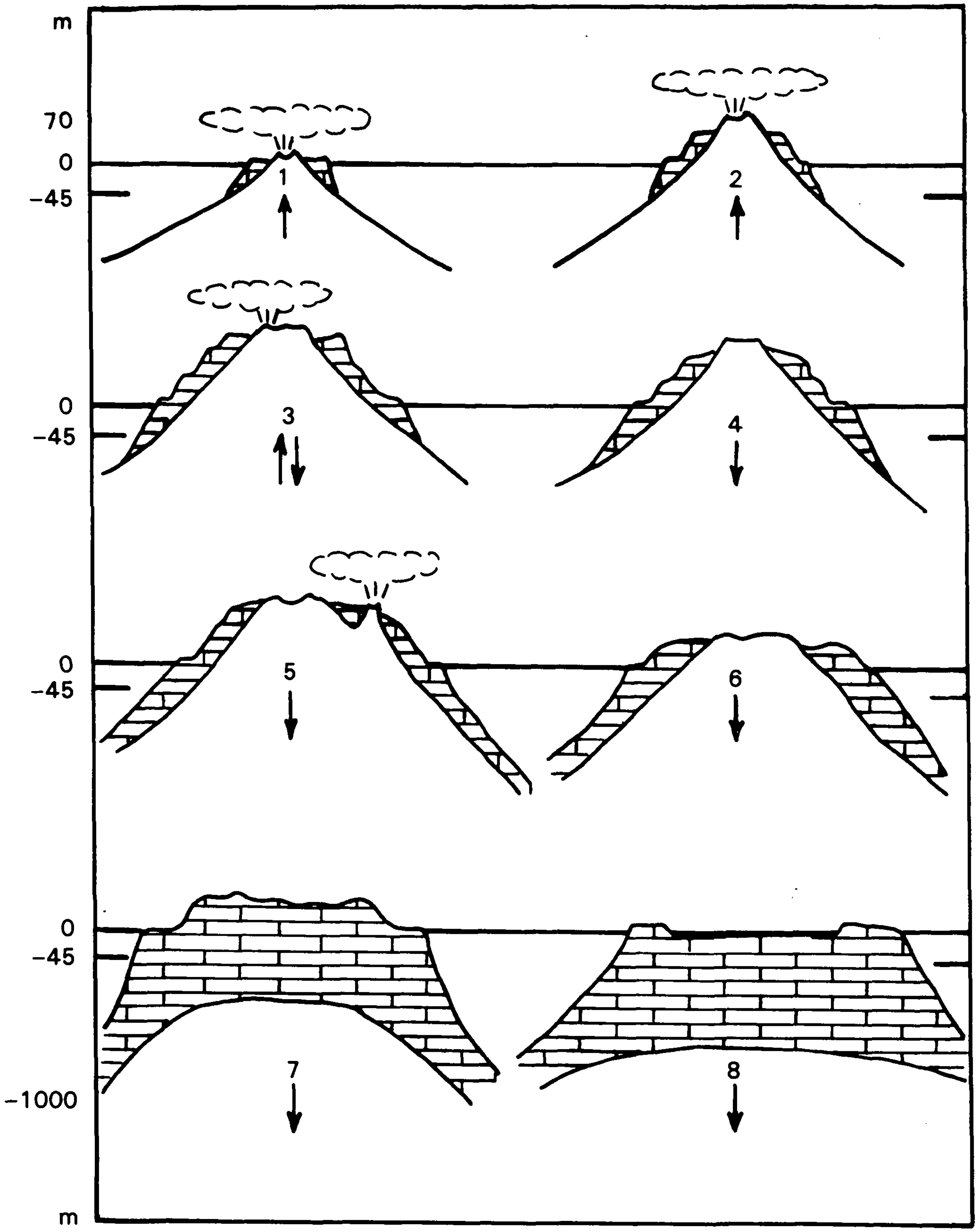

FIGURE 3 Diagrammatic sketch (not to scale) to illustrate elevation and subsidence of a volcano in the Pacific. The events 1–8 are described in the text. Coral from sea level to–45m is greatly exagerated to illustrate the zone of maximum depth to which coral can live .

(5-6) spasmodic inner parasitic eruptions as volcano sinks to greater depths, (7-8) volcano erodes and continues to sink forming "raised" atoll (7) and atoll (8) while coral continues to grow upwards. Eustatic fluctuation of sea level probably occurred contemporaneously during both growth and subsidence stages, and earlier coral reefs are now preserved at various levels down to about 1000 m below sea level.

During the long periods between volcanic eruptions, and when sea water depths, temperatures, food, and oxygen supply were favourable, coral colonies became established around the islands. Subsequent fluctuations of water depths in response to both sea floor loading on the lithosphere and the melting and freezing of the polar ice caps contributed to the death of the polyps, but their calcareous skeletons remained to form the prominent reef system that now surround the islands. Both volcanism and reef building proceeded contemporaneously, as shown by interbedded makatea limestone and volcanics in drillholes on Mangaia (Waterhouse & Petty in press) and by abundant coral fragments in tuff and agglomerate on Aitutaki in the Cook Group (Wood & Hay 1970).

Irrespective of the mechanism, whether it be isostasy, eustatism, or tectonism, apparent or real sea level fluctuations relative to present day level, have been recorded at -66, -44, -23, -11 and 12 m in the Pacific generally (Baillard, 1981), -33 to -37, and -11 to -15 m on Niue (Schofield 1959), and -120 m and -37 m in the Southern Cook Group (Wood & Hay 1970). There is also good evidence for stillstands at various levels from 3 m up to 70 m and possibly 240 m asl (Wood & Hay 1970; Schofield 1971).

The maximum depth to which coral can grow is considered to be -45 m (Fairbridge, 1968) which, when added to the net sea level fluctuation range of 360 m, (-120 to +240 m) gives a potential <u>in situ</u> coral thickness of some 400 m. Thus, the thickness of coral resulting from eustatism alone may be of this order, but it is known that it is greatly in excess of 400 m in places i.e. 600 m on Hao and 1000 m on Rangiroa in the Tuamotus (Baillard 1981), 500 m on Manihiki in the Northern Cook Group (Wood and Hay 1970), possibly 1000 m on Home Island in the Cocos Group (Jacobson 1976), 1400 on Eniwetok in the Marshall Islands and probably 900-1000 m on Funafuti in the Tuvalu (formerly Ellice) Islands (Menard 1964).

Eustatism alone cannot account for these considerable thicknesses of coral and some other explanation is required. It is suggested that the volcanic edifice itself plays a role in the development of the coral reef. During the growth stage of the volcano, as soon as the summit rises above -45 m bsl, coral becomes established and forms a crown. This may have occurred as early as the middle Oligocene or Miocene for fully developed atolls judging by the age of the makatea limestone on Mangaia (Wood and Hay, 1970). Returning to the "water bed effect" model of McNutt and Menard (1978), continued uplift as a result of adjacent sea floor loading would also elevate the coral cap to different heights between different islands. When the volcanic mass exceeds the lithospheric strength, its own weight on the lithosphere would result in gradual sinking of the entire edifice. In accordance with the Darwinian theory advanced in the mid nineteenth century the coral would continue to grow upwards, as the bases on which the reefs first became attached slowly sank below the level of the sea.

The detail and time scale of these complex series of events involving periodic emergence and submergence by volcanic activity, possibly contemporaneously with eustatism, and crustal warping, remain to be solved.

Alignment of Volcanics Arcs

It is accepted that many volcanoes in the central Pacific region are along alignments that show up on bathymetric charts as plateau like features, commonly with a broadly NW SE orientation. The emergent peaks of the volcanoes, or their coral caps, form island chains and submerged ridges, examples of which are the Hawaiian Islands, the Marquesas, the Tuamotu Ridge, Austral Ridge, Line Islands, and Southern Cook Group.

Age of Volcanics: Radiometric

Volcanic activity in one form or another has extended over much of the geological time scale and was widespread in the mid Cretaceous epoch (100 m.y.) (Schlanger et al. 1981). An unreliable potassium argon (K-Ar) date of 156 m.y. from Tahiti, given by Jarrard and Clague (1977) indicated a mid Jurassic age for a dredge sample, but most of their dredged or outcrop samples were much younger. An analysis of Jarrard and Clague (ibid) radiometric age data from Pacific linear island chains shows some broad trends (Table 1, Fig. 4). For this paper, 181 reliable or probably reliable ages have been selected from a total of 250 samples, and grouped by origin into volcanoes, atolls, guyots (a flat topped seamount), seamounts, (a mountain rising from the sea floor but not reaching the surface), and ridges. There are obviously many more determinations for volcanoes than for the others, but the trend for volcanoes shows an age range from active to about 25 m y and an average of around 5 m y; atolls are averaged at 17 m y; guyots at 37 m y; seamounts 48 m y; and ridges 89 m y.

Age of Islands: Subsidence

A more indirect dating method for island structures relates an assumed rate of subsidence to depth of burial of the volcanic edifice. Drillholes

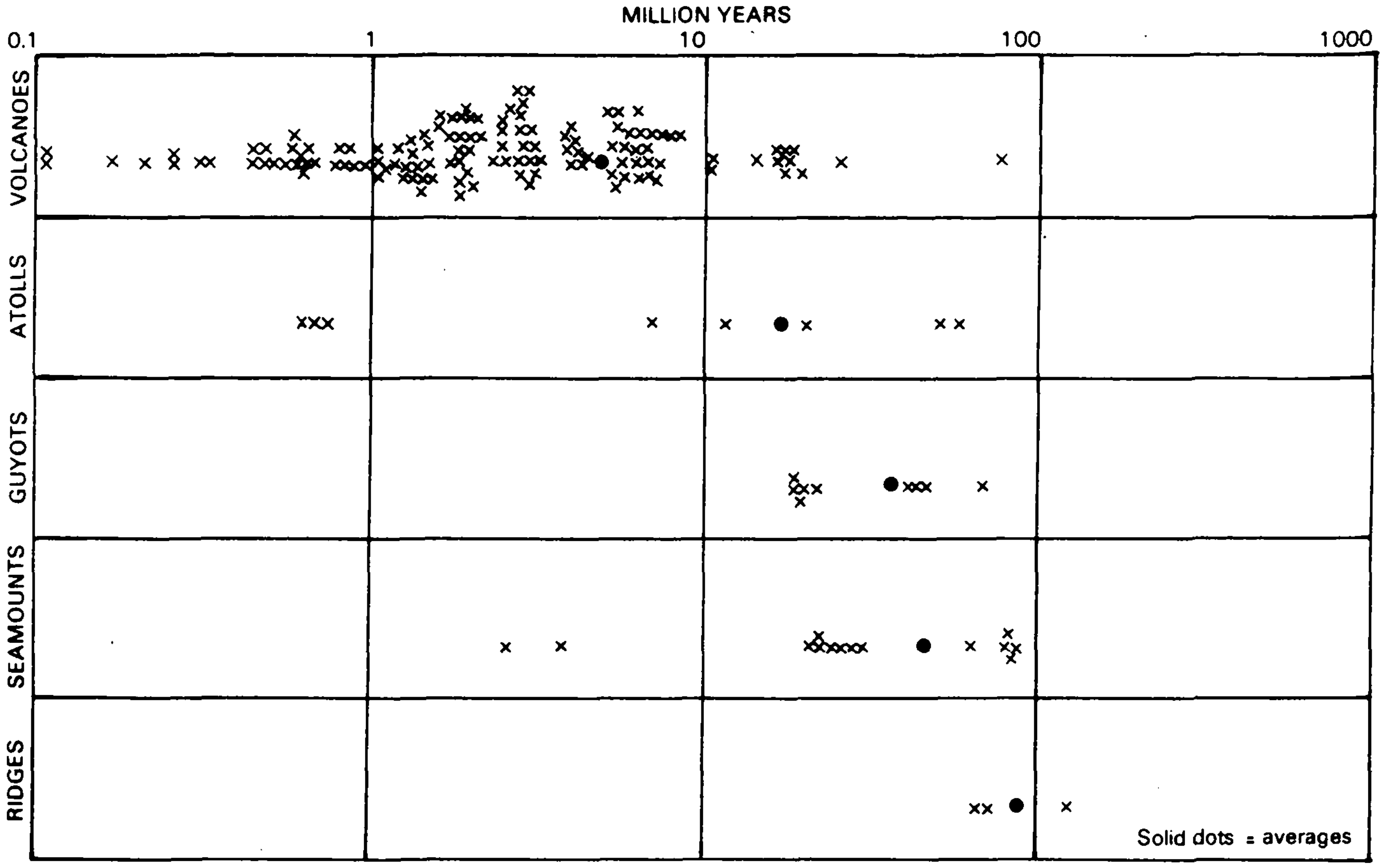

FIGURE 4 Log plot of age determinations from Pacific island chains (calculated from Jarrard & Clague 1977).

	Number of dates	Youngest (my)	Oldest (my)	Average (my	<average (%)
Volcanoes	143	active	77	5	75
Atolls	11	0.7	59	17	55
Guyots	11	19.3	74	37	46
Seamounts	13	21	88	48	53
Ridges	3	69.7	126	89	67

Table 1 Summary of radiometric age data of 181 reliable or probably reliable determinations from Pacific linear island chains. *(calculated from Jarrard & Clague 1977)*

penetrating the coral cap on the atolls of Eniwetok and Bikini in the Marshall Island and Midway in the Hawaiian Islands indicate that they have subsided 1.4 km, 0.78 km, and 0.38 km respectively (Menard and Ladd 1963). From 60 m y of dated stratigraphic horizons, Menard & Ladd (1963) calculated the islands had subsided an average 20 m/m y (2 mm/100 yrs). At this rate of subsidence volcanism became extinct, or nearly extinct 70 m y years ago on Eniwetok, 40 m y ago on Bikini, and 20 m y ago on Midway (Table 2).

Seismic data suggests that Funafuti atoll has a coral cap about 1 km thick and at an assumed 2 mm/100 yr subsidence rate it would have taken 50 m y to have sunk to this depth. However, Baillard (1981) in discussing Pacific atolls on a regional basis, assumed a subsidence rate of 10 mm/100 yrs, a rate five times faster than Detrick et al's figure, and if Baillard's 10 mm rate is applied the ages are significantly different (Table 2).

Age of Islands: Geomorphology

Kear (1957) in discussing the connection between age and degree of erosion of volcanoes, defined four stages in cone dissection. They were, in order of increasing age;

Volcano Stage e.g. Hawaii. Cones that are essentially similar to those of active volcanoes. Holocene.

Planeze Stage e.g. Rarotonga (Dalrymple et al. 1975). Dwindling sectors of the constructional surfaces (planezes) survive on the ridges between deeply eroded consequent valleys. Craters do not survive to the latter part of this stage unless enlarged by erosion. Mid Pleistocene to Holocene.

Residual Mountain Stage e.g. Rapa (ibid) Continued erosion causes the planezes to dwindle and then virtually disappear. The residual

	Subsidence (m)	Age (my) at subsidence rate of 0.2 cm/100 yrs (2)	Age (my) at subsidence rate of 1 cm/100 yrs (3)
Eniwetok (4)	1400	70	14
Bikini (5)	780	40	14
Funafuti (6)	1000	50	10
Aitutaki (7)	1000	50	10
Rangiroa (8)	1000	50	10
Hao (9)	600	30	6
Manihiki (10)	500	25	5
Midway (11)	380	20	4

Table 2 Minimum age of atolls based on subsidence rates. Notes (1) Eniwetok and Midway drilled to basalt; remainder from seismic calculations.

(2) Detrick & Crough, 1978 (3) Baillard 1981

(4) Ladd & Schlanger 1960 (5) Raitt 1954

(6) Menard 1963 (7) Hochstein 1967

(8,9) Baillard 1981 (10) Wood & Hay 1970

(11) Ladd et al. 1967.

hill or mountain no longer exhibits any recognizable original cone surface except possibly at its base. Lower Pliocene to mid Pleistocene. Skeleton Stage e.g. Mangaia (ibid) Only the most resistant internal parts of the cone remain eg stocks, necks, dykes. Upper Miocene to upper Pliocene.

Stages of erosion that extend beyond the Skeleton Stage are not specifically defined, however islands older than the Skeleton Stage would be represented by gently domed or flat topped surfaces, deeply weathered and eroded in their emergent form, or capped by coral. Atolls, guyots, seamounts and ridges are grouped together for the purpose of this discussion, and their age is considered simply as Miocene or older.

Kear's geomorphological method and criteria can be applied to the volcanic 'high islands' (defined below), on the understanding that more than one stage may be represented on the same island i.e. Upolu in Western Samoa exhibits three stages of erosion (D. Kear pers. comm).

Discussion on Age of Islands

In applying the various methods discussed above, it becomes apparent that there is no completely accurate criteria for determining the exact age of an island. Darwin's evolutionary principles for the formation of small islands seems universally accepted. The precise dating of evolutionary geological events however are less reliable because of their dependence on largely assumed criteria.

There is little correlation between the radiometric dates obtained for atolls (Table 1; Fig. 4) and those calculated on the basis of rates of subsidence (Table 2). The major constructional phase of island volcanism is claimed to be short (0.5 - 1.5 m y; Jackson et al. 1972) but it is apparent that even a long life span from birth to extinction would be inadequate to accommodate the ranges presented in Tables 1 and 2.

It is clear that volcanic activity at any one centre is not restricted to one period of time, and that spasmodic eruptions have occurred at a much later date than that of the main edifice building stage on at least some of the islands in the Pacific (Waterhouse & Petty in press). Radiometric dating recorded by Dalrymple et al. (1975) of lava from Atiu (7.2 m y), Rarotonga (1.19 - 2.8 m y). and Aitutaki (0.66 - 0.77 m y) in the Southern Cook Group indicate later stages of activity than any suggested from the assumed subsidence rates, and it is conceivable that still younger eruptions, the products of which have not been identified, also occurred on these islands.

The ages indicated by geomorphic criteria are also inconsistent with the K-Ar dates of Dalrymple et al. (1975) who remarked that the assertion that the Cook Islands chain increases in age to the NW was not supported by the K-Ar results, and that the volcanic rocks of Rarotonga and Aitutaki are much younger than predicted. This is well demonstrated on Aitutaki which could be Eocene, Miocene, or Pliocene on geomorphic evidence (Wood & Hay 1970), Eocene to Late Miocene on the subsidence theory, or mid Pleistocene on K-Ar dating.

Water Resources

The age, geology, and geomorphology of an island governs to a large degree its water resources potential. In the following elementary hydrogeological discussion, three distinct 'types' of island commonly encountered in the Pacific are 'high islands' (volcanic), 'raised atolls', and 'atolls'. Each have distinctive hydrogeological characteristics, as discussed by Dale & Waterhouse (in press).

The high volcanic islands (Fig. 5) generally yield good quality water from a number of sources which include drillholes, dug wells, springs, maui 'skimming' tunnels, infiltration galleries and streams.

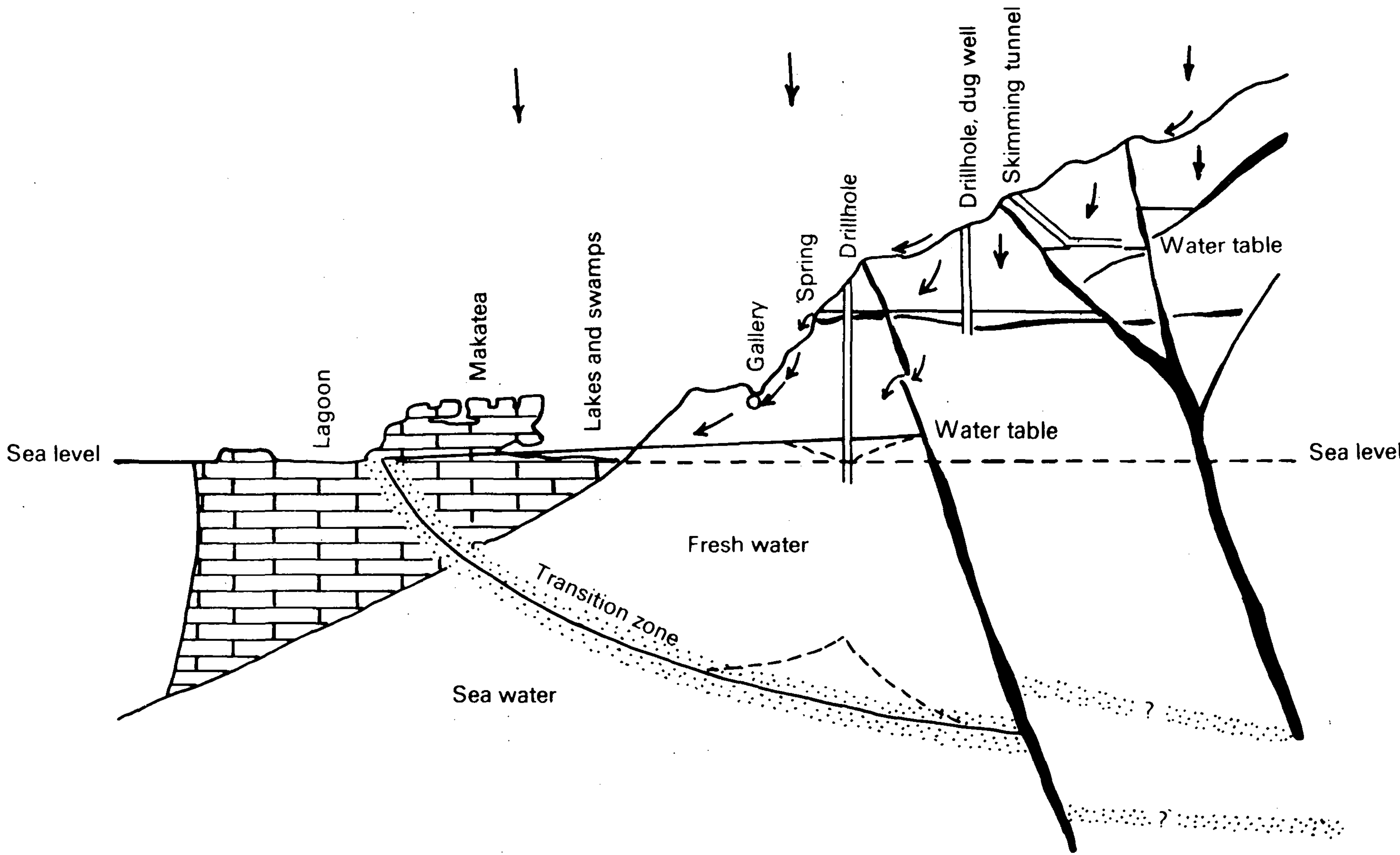

FIGURE 5 High island (half width) showing emergent volcano with feeder dykes and sills, and flanking coral reef. Rainwater is shed by direct runoff, or percolates to water compartments in the volcanics or to freshwater lens.

In geologically young volcanoes the 'fresh' surface rocks allow rainwater to penetrate readily to the groundwater reservoir. Conversely, prolonged exposure to the elements (weathering) reduces the volcanic material to impermeable clay which impedes rainwater absorption and increases surface runoff. As a general rule, the younger the volcano the better the prospects as a water resource.

In raised atolls (Fig. 6) the limestone surface usually includes fractures and solution channels through which rainwater can penetrate to the groundwater reservoir above or close to sea level. Streams are generally absent but adequate supplies may be obtained from drillholes, dug wells, or brackish ponds. If the water resource is close to sea level care must be taken to ensure that prolonged abstraction does not lower the fresh water level to below the sea level, in which event salt water contamination would ultimately occur.

In a coral atoll, (Fig. 7) a limited amount of fresh water might be obtained from the fresh water (Ghyben-Herzburg) lens close to sea level. The delicate hydraulic balance between the fresh and salt water must be maintained if this resource is exploited.

Acknowledgements

The author thanks his colleagues G. D. Mansergh, D. N. B. Skinner, L. J. Brown, and D. R. Petty for their comments and suggestions, and to the Director, New Zealand Geological Survey for permission to publish. He also thanks Mrs. A. Willoughby for typing the draft and fine manuscript.

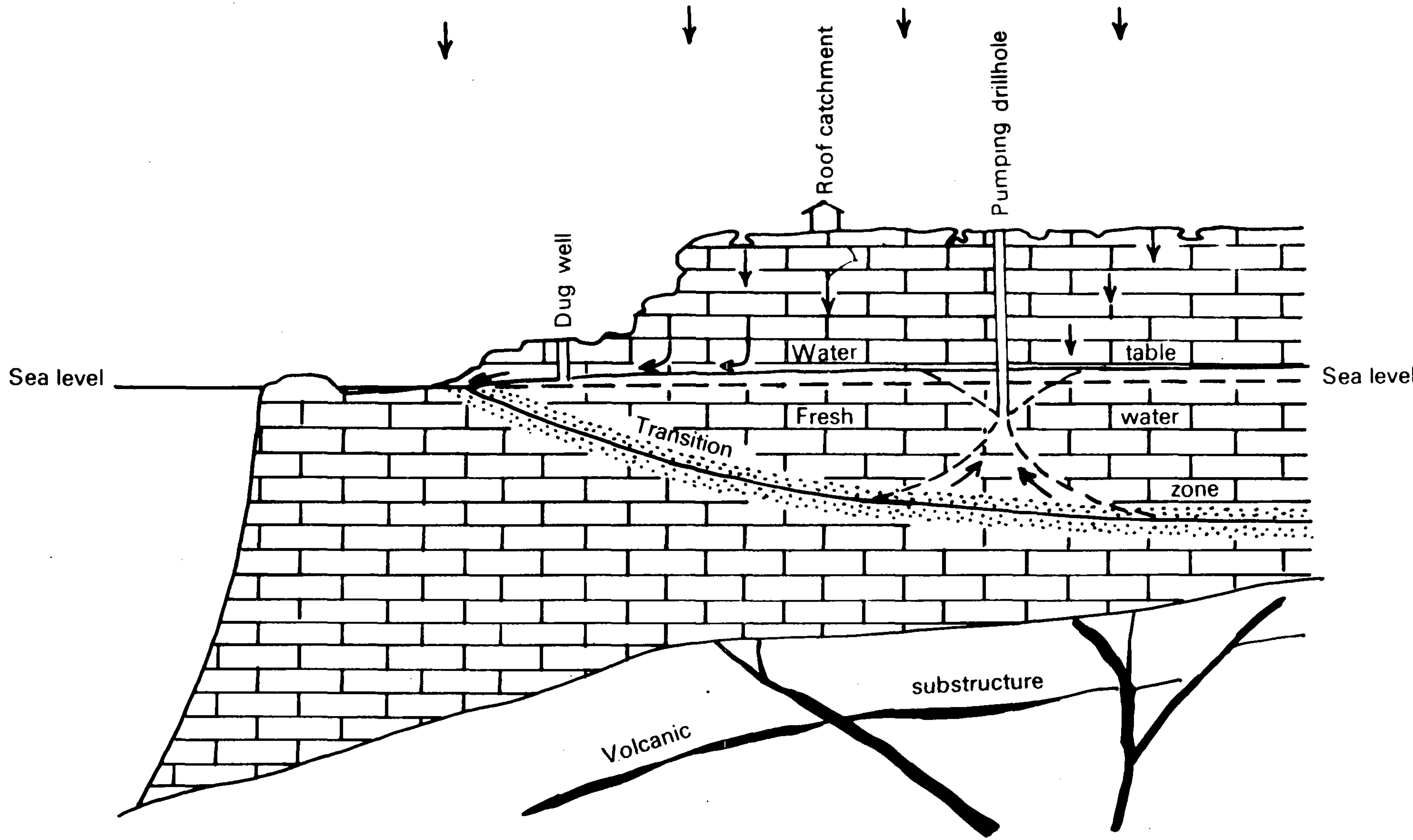

FIGURE 6 Raised coral atoll (half width). Submerged volcanic core capped by coral limestone many hundreds of metres thick . No streams are present and water penetrates rapidly to the freshwater lens. Overpumping, with consequent lowering of the lens surface to or below sea level , will yield salt water .

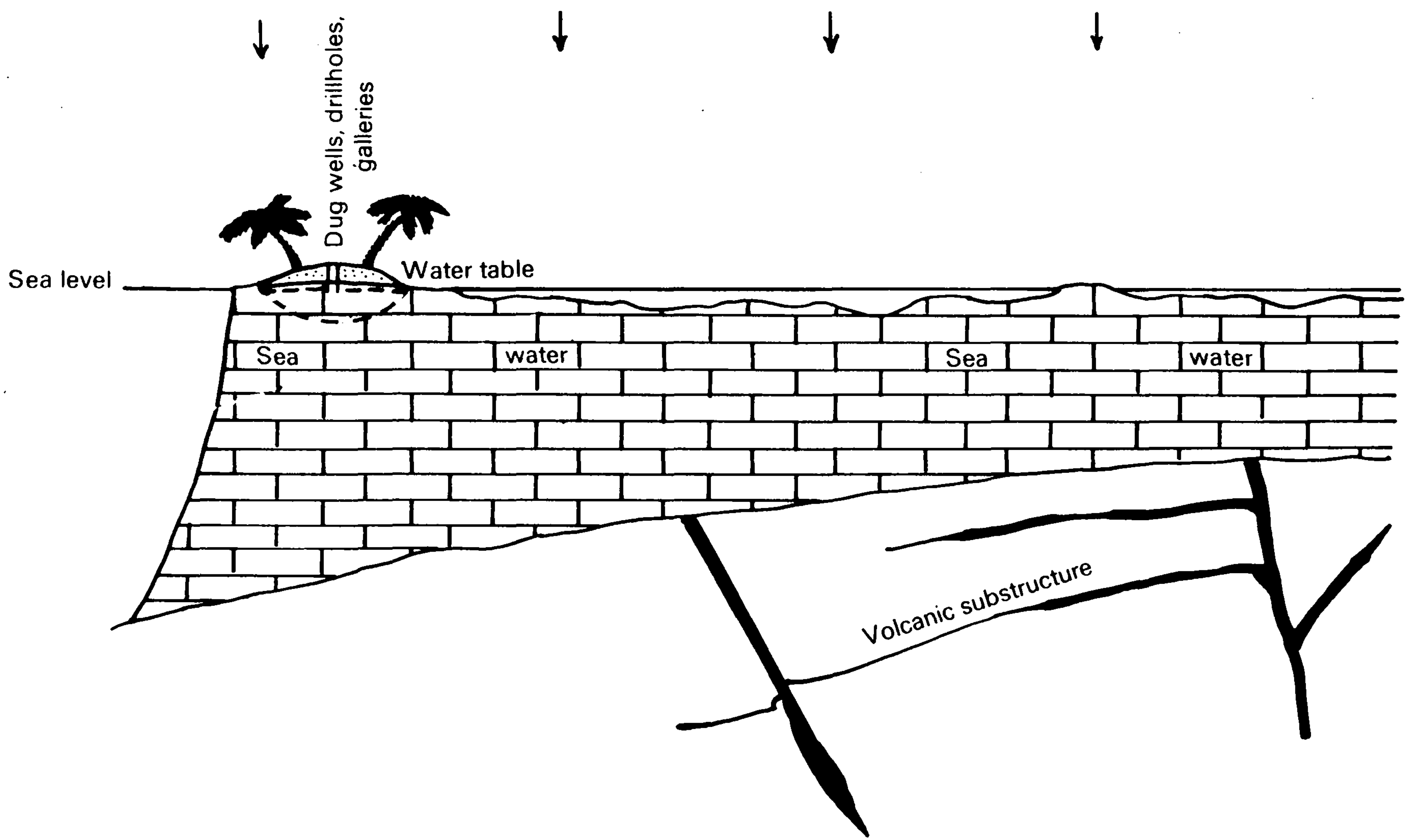

FIGURE 7 Coral atoll (half width). Original island almost completely submerged. The peripheral rim rises to a few metres above sea level and comprises of cemented beach rock, coral, sand, conglomerates, and storm debris. Thin soil and sparse vegetation is usually present.

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THE GEOLOGICAL HISTORY OF THE LAU GROUP, FIJI

by

D. Woodhall

The islands (39) and atoll reefs (31) of the Lau group form the eastern part of the Fiji islands. The islands are surrounded by barrier and/or fringing coral reefs, but the atoll reefs are so called because they have no associated islands. More detailed descriptions of the geology of the Lau group have been given elsewhere (Woodhall, 1984 & in press).

Many of the islands are deeply eroded volcanic cones formed of basaltic, andesitic, and occasionally dacitic and rhyolitic, lava flows and volcaniclastic rocks. The majority of these volcanoes are of late Miocence age, but some formed during the middle Miocene and early Pliocene. The activity of each Miocene volcano was followed by erosion and submergence, and there is stratigraphic evidence which indicates that the submergence was rapid and in many cases entire volcanoes were submerged. Following this submergence coral reefs became established on and around the islands and they probably resembled the present day barrier and atoll reefs in the Lau group. Growth of these reefs continued during a lull in volcanism that occurred between that of the late Miocene and early Pliocene. The early Pliocene volcanism was much less widespread, and the products more basaltic, than that of the Miocene. Although none of the Miocene volcanoes appear to have been reactivated during the early Pliocene, some of the Pliocene volcanoes formed either within or adjacent to pre-existing reef systems of Miocene-early Pliocene age.

Regional uplift and associated block faulting, which has strongly influenced the present day configurations of the barrier and atoll reefs, may have occurred during as well as after the early Pliocene volcanism. The uplift of the Miocene-early Pliocene coral reef systems was intermittent and as a result the newly emergent reef and lagoonal limestones were terraced. The limestones were intensely recrystallized following their emergence. The greatest amount of uplift took place in central and northern Lau, and because of this, the underlying Miocene volcanic basement beneath the Limestone has been exposed by erosion on many islands, but in southern Lau, where there was less uplift, no volcanic basement has been exposed and therefore most of the islands in this part of the Lau group are formed entirely of limestone.

Renewed coral reef development, following the uplift of the earlier reefs, commenced during the late Pliocene and continues at the present day.

Renewed volcanism took place during the late Pliocene and Pleistocene from small centres situated on pre-existing eroded Miocene volcanoes and limestone terraces. The products of this volcanism were lava flows and pyroclastic deposits of alkali basalt composition, and these basalts are quite distinct from those erupted during the Miocene and early Pliocene. Small volcanic cones which formed during the Pleistocene have undergone very little erosion.

During the sea level lowstands of the Pleistocene glacial periods the present day coral reefs, and their associated lagoons, were emergent features and consequently must have undergone erosion. Following the submergence of the reefs as a result of the interglacial and post glacial sea level rises, coral growth was re-established on topographic highs that remained after the erosion which took place during the glacial periods. Slight regional uplift, probably in combination with the glacio-eustatic changes in sea level, brought about the emergence of what are now the present day reef systems. Evidence for this emergence is limited to scattered occurrences of limestone which form the erosional remnants of a very low lying terrace. Only rarely is more than one terrace apparent. The limestone has been much less recrystallized than that of the Miocene-early Pliocene.

The superficial deposits that occur on most islands, and which form various sand cays, were deposited within the last few thousand years, after the present day sea level was attained following the lowstand of the last glaciation, but before the first human settlements were established on the islands. Many of the sand cays are the only islands associated with reef systems that would otherwise be atoll reefs.

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Discussion - Theme II

Q. How does the age of geological structures assist in developing ground water supplies?

(Keynote Speaker) The younger volcanic rocks (say 3000 years old) are usually more permeable and therefore have greater potential for holding and supplying water. Older volcanics (say 50 million years) have undergone weathering and these changes usually mean that impermable clay minerals are formed which reduce the permeability of the rocks.

(Simpson) Radiometric age determinations need expensive equipment which we don't have. It is nice to have these sophisticated data but in our region we need to use simpler evidence, such as geomorphology, from field observations.

Q. Could you clarify the terms porosity, effective porosity and permeability?

(Chairman) You may have high porosity without permeability - if the pores are not connected you do not have any permeability. Could someone explain effective porosity please?

(Barker) Effective porosity can be determined by allowing saturated rocks to drain and measuring the water running out. Within the rock structures other water is held on the surface (specific retention). The total porosity is the sum of the effective porosity and the specific retention.

Q. Could you expand on the "yoyo" movement of islands in relation to the flexibility of the lithosphere?

(Jacobson) There have been some (isolated) research studies but no general theories seem available. Perhaps some of the internal research reports could add to this knowledge if a regional research programme could be developed. An on-going project is by the HIPAC team, basically a group of workers from Kobe University (Japan), with members from NZ and Fiji. One report, giving data from Micronesia, Fiji, Samoa and Cook Islands, has recently appeared, and further studies will be made beginning later this month.

THEME III ISLAND HYDROLOGY AND HYDROGEOLOGY

AQUIFER PROPERTIES AND PUMPING TESTS: An Introduction

J A Barker
(British Geological Survey)

1. INTRODUCTION

An aquifer is a geological formation that has the ability both to store and to transmit water in significant quantities. This paper introduces the physical parameters characterising these two properties, and then pumping tests, which are used to determine the values of these parameters in the field. The significance for such tests of some of the special conditions encountered on oceanic islands is also discussed.

Much of this material is presented in greater detail in standard hydrogeological textbooks (.e.g Bear, 1979; Todd, 1980; Walton, 1970). However, it is hoped that this brief exposition will serve both as an introduction for readers who intend to undertake hydrogeological investigations, and as an adequate survey for those whose main interest lies outside hydrogeology. A selected bibliography is provided as an aid to further study.

2. AQUIFER PARAMETERS

2.1 Storage

There are two distinct mechanisms by which water can be stored in (or yielded by) an aquifer, and it will be convenient to introduce these by considering first a confined aquifer and then an unconfined aquifer. (Although the former case will be of limited interest in relation to small islands).

Figure 1a depicts a confined aquifer of thickness b. Suppose there is a net flow of water, of volume ΔW, into a section of the aquifer of area A, this will be accompanied by an increase in head, Δh. It will normally be found that these quantities are related through the equation:

$$\Delta W = S \cdot A \cdot \Delta h$$

The constant S is a dimensionless parameter which characterises the storage capacity of the aquifer and is known as the *storage coefficient* or *storativity* of a confined aquifer. Another quantity of interest is the *specific storage*, S_s, which is given by:

$$S_s = S/b$$

and represents the volumetric change in storage per unit volume of the aquifer per unit change in head.

A typical value of S_s might be 5×10^{-6} m^{-1}, which represents a change in storage of only five cubic centimetres in one cubic metre of aquifer for a one metre change in head. The reason for such small values is that the storage and release of water is due to the small amount of elastic compression and expansion of the water and rock matrix.

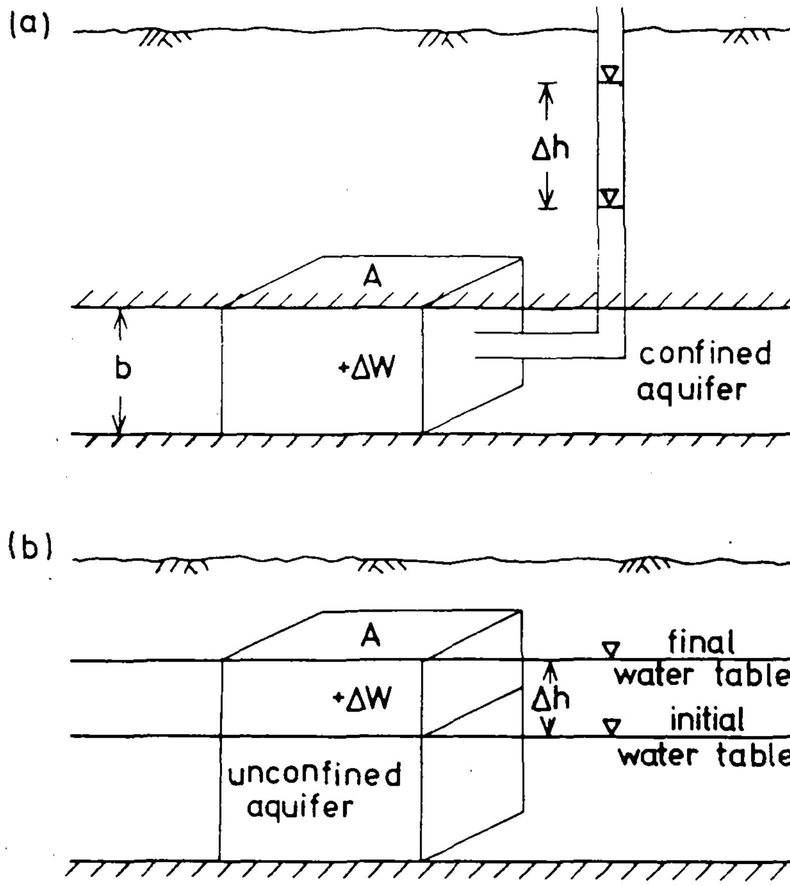

Figure 1. Definition sketch for the relationship between change in storage and change in head. (a) A confined aquifer. (b) An unconfined aquifer.

Figure 1b depcits an unconfined aquifer where an increase in storage of ΔW within area A is accompanied by a rise Δh in the water table. As before:

$$\Delta W = S \cdot A \cdot \Delta h$$

where S is now the storage coefficient or storativity of an unconfined aquifer. In this case the storage capacity provided by the elasticity of the water and rock matrix is almost completely negligible in comparison with that due to the pore space above the initial water table. This pore-space storage is referred to as *specific yield*, S_y, and for all practical purposes is equal to S.

It might be expected that the specific yield is equal to the aquifer porosity, n, and this would indeed be true for a water table rising into an initially dry rock (provided no entrapment of air took place). In practice, however, the rock above the water table retains a certain amount of water in intimate contact with the rock matrix due to molecular forces. This quantity is characterised by a parameter known as the *specific retention*, S_r, which is given by the difference between porosity and specific yield. Therefore:

$$S_y = n - S_r$$

and it becomes clear why the specific yield is also often referred to as the *effective porosity*.

2.2 Conduction

Figure 2 represents uniform groundwater flow through saturated rock as a result of a head difference Δh over a distance $\Delta \ell$. If the volume of water that flows through area A_p, perpendicular to the flow direction, in unit time is q then it is normally observed that these quantities are related by:

$$q/A_p = K \cdot \Delta h/\Delta \ell$$

which is known as Darcy's Law. The constant K is known as the *hydraulic conductivity* of the rock (the term *coefficient of permeability* is also used).

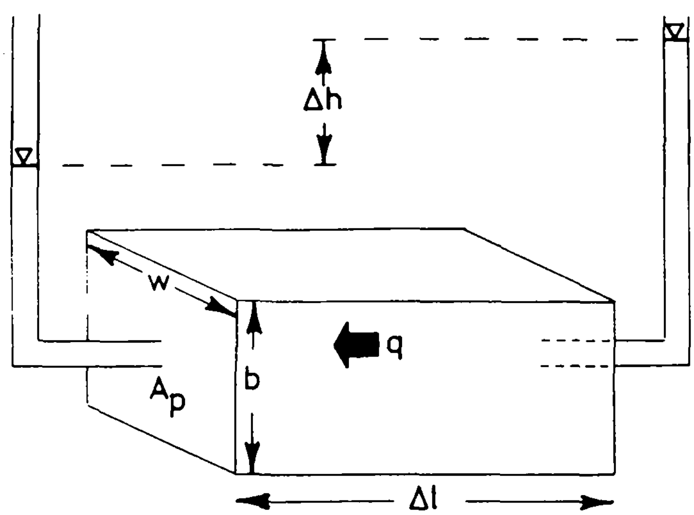

Figure 2. Definition sketch for flow through an element of aquifer under a uniform head gradient.

Suppose now that the area A_p penetrates the whole aquifer thickness, b, over a width w; then the above equation can be written:

$$q/w = K \cdot b \cdot \Delta h/\Delta \ell = T \cdot \Delta h/\Delta \ell$$

where the quantity T (= K·b) is known as the *transmissivity* of the aquifer.

The quantities K and T are most frequently expressed in units of m/day and m^2/day respectively.

2.3 Heterogeneity

In the above discussion it has been assumed that the aquifer material is homogeneous; however, it is often found that aquifer parameters vary significantly from place to place. Hydraulic conductivity, in particular, can vary by several orders of magnitude within a single aquifer unit. Often the parameter of interest is an average over a large areal extent since this will determine the regional flow behaviour. But local heterogeneities can also be important; for example, in relation to the performance of individual wells.

3. PUMPING TESTS

Pumping tests are performed for two (often related) reasons: (i) to determine the hydraulic parameters of an aquifer, and (ii) to determine the production characteristics of a given well. Frequently, wells are constructed specifically for the former task and are never used for production.

In its most general sense a pumping test can be described as an experiment in which a known hydraulic stress is applied to an aquifer (normally, but not always, using a pump) and the response of the aquifer (changes in pressure or head) observed.

3.1 A typical pumping test

Figure 3a represents what is probably the most commonly applied form of pumping test; namely, a constant rate interference test in a confined aquifer. Water is pumped at a constant rate, Q_w, from one borehole or well while the reduction in water level, s (the *drawdown*), is observed in a second borehole. When the data is plotted as drawdown against the logarithm of time, t, since the start of pumping (Figure 3b) it is often observed that for large times there is a relation:

$$s = m \ln t/t_o$$

An analysis of the data can be effected by estimating the constants m and t_o, graphical methods are usually of sufficient accuracy, and then estimating the aquifer transmissivity and storage coefficient from:

$$T = Q_w/(4\cdot\pi\cdot m)$$

$$S = 2.25\cdot t_o\cdot T/r^2$$

The mathematical theory on which these formulae are based will be found in most hydrogeological textbooks and will not be repeated here. They are only valid under certain circumstances; most importantly, it is necessary that the aquifer is homogeneous over a significant region.

It must be emphasised that this is only one of several possible methods for analysing the same data. Perhaps more commonly, the analysis would be carried out with the aid of *type curves*.

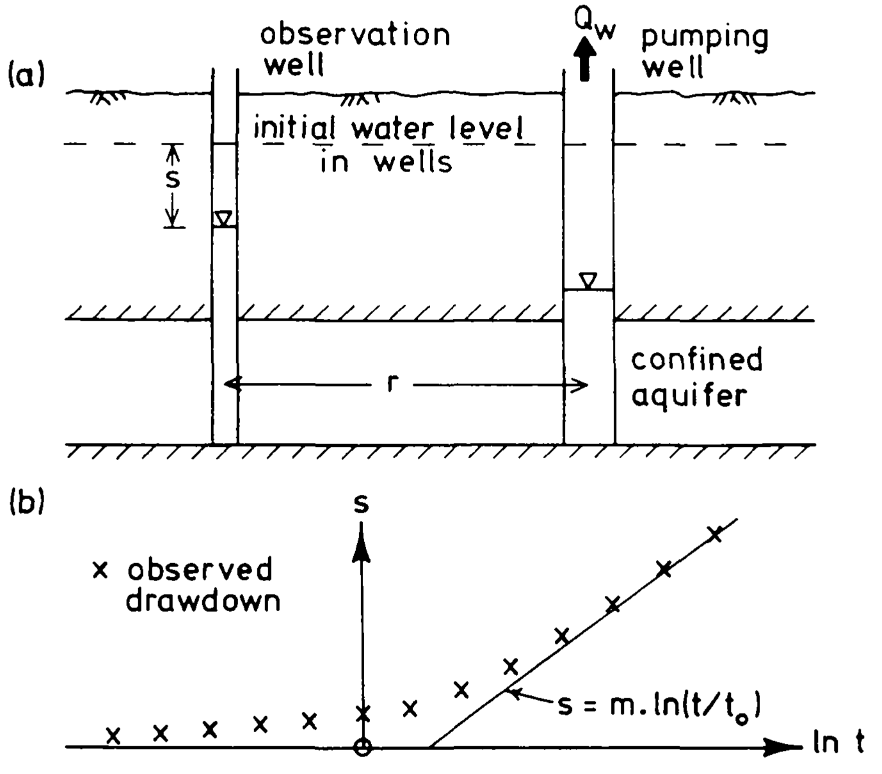

Figure 3. Constant rate pumping test in a confined aquifer.
(a) Section through pumping well and observation well.
(b) Typical drawdown data.

3.2 Types of pumping test

In Table I an attempt has been made to classify pumping tests according to a number of features. Brackets are used to group alternative possibilities, although not quite all combinations can be realised in practice.

The hydrological context of the test, naturally, has a major influence on the test procedure (form and duration of pumping, number and placing of observation wells, frequency of data collection) and on the method of data analysis.

Confined and unconfined aquifers have very different storage coefficients (Section 2.1) and this will significantly effect the length of the test. Also, data analysis for an unconfined aquifer can be very difficult, especially if the drawdown at the pumping well is large. Leaky aquifers, where water can seep through a semi-pervious stratum, have quite different long-term responses to pumping.

During a pumping test the region of the aquifer influenced will expand with time. If this region includes significant geological changes (such as a fault which might act as an impermeable boundary) these will influence the drawdowns. Recharge boundaries, such as rivers, lakes and the coast, will tend to cause the long-term drawdowns to be limited.

TABLE I
A Classification of Pumping Tests

AQUIFER	confined unconfined leaky	unbounded no-flow boundaries recharge boundaries coastal boundaries	homogeneous layered fissured	isotropic anisotropic
PUMPING	constant rate constant head multiple rate slug test			
RESPONSE	steady state transient			
WELL(S)	fully penetrating partially penetrating	small diameter large diameter		
DRAWDOWN OBSERVED IN:	pumping well only observation well(s) only both			

Layering and fissuring can have a very complicated effect on the drawdowns. This makes data analysis particularly difficult, and sometimes computer models have to be employed.

The rate of abstraction of water can be varied considerably. Most commonly, a constant rate test is employed, and this has the advantage of relatively easy data analysis and producing parameters which are characteristic of a significant region of the aquifer. Constant head tests are rarely employed by choice but are convenient under certain circumstances, such as in testing an artesian aquifer. When the hydraulic characteristics of a well are of particular interest the rate of pumping is often changed in discrete steps and the drawdown in the well observed; this is called a *step test*. A test that can often be very convenient is the *slug test*, where water is extracted from or injected into a borehole as fast as possible and the subsequent return of the water level to its original position monitored. Slug tests only yield parameter values characteristic of the aquifer in the immediate vicinity of the borehole.

3.3 Special considerations for small islands

3.3.1 Where an aquifer outcrops in the ocean it is subject to a tidal variation in head, the effect of which propagates through the aquifer. In so far as the resulting head variations in boreholes interfere with pumping tests, this is an unwanted phenomenon for which correction needs to be made. Such a correction involves monitoring the water level fluctuations in the pumping test boreholes before the test and correlating them with tide levels or, preferably, with fluctuations in neighbouring boreholes which are unlikely to be affected by the pumping test. Then the tidal component of drawdown variation can be predicted for each borehole during the test, and subtracted from the total observed drawdown.

3.3.2 From a different point of view, the tidal fluctuation constitutes a measurable stress on the aquifer which can be regarded as a natural form of pumping. From the resulting response of the water level in a borehole it is possible to obtain an estimate of the ratio of the transmissivity to the storage coefficient of an aquifer, T/S, which is known as the *diffusivity* (e.g. Todd, 1980, pg 242). When the aquifer is unconfined this method is only effective when the mean saturated thickness is large in comparison to fluctuations in that thickness.

3.3.3 Rocks of very high hydraulic conductivity are not uncommon on oceanic islands (e.g. many rocks of coral and volcanic origin). Pumping tests in such material tend to a steady state so quickly that normal methods of transient analysis become ineffective. The results of such tests can reveal reasonably accurate conduction parameters (transmissivity, hydraulic conductivity), but only very inaccurate, if any, values for storage coefficients. This may not be a severe problem because, if the aquifer responds very rapidly, its behaviour can be predicted by assuming steady-state conditions at any instant. However, if the storage coefficient is of interest then the complementary use of tidal response data (Section 3.3.2) may sometimes prove effective.

Formulae useful in the analysis of steady-state borehole tests are given by Hvorslev (1951).

3.3.4 Most methods of pumping test analysis are formulated in terms of the aquifer transmissivity. However, on small islands the aquifer will often be of large unknown thickness. Under these conditions, with relatively shallow boreholes, a transmissivity value is difficult to determine. It will then often be sensible to analyse the data by a method which is formulated in terms of hydraulic conductivity (e.g. Hantush, 1962; Kruseman and de Ridder, 1979, pg 162).

3.3.5 Since the salinity, and therefore the density and viscosity, of groundwater varies near the coast it may seem necessary to take account of this when analysing data from pumping tests. However, in relation to all the other uncertainties and approximations involved in pumping-test analysis, such variations are unlikely to have any significant effect: probably less than 3% error in the derived transmissivity or storage coefficient.

3.4 General remarks

3.4.1 The analysis of pumping-test data is far from being a routine matter. Frequently the aquifer fails to respond as anticipated, which often reflects the presence of unexpected aquifer heterogeneity or recharge mechanisms. Even when the behaviour of the aquifer is well understood quantatively, the analysis can be mathematically complex, sometimes to the extent that a computer model has to be employed. In consequence it can prove worthwhile, on balance, to perform a technically complex and expensive test (e.g. using deep boreholes and pumping for long periods) so that the data analysis becomes relatively straightforward.

3.4.2 Thought should always be given to the exact use to which parameters derived from pumping tests are to be put. For example, there is no point in going to a great deal of trouble to obtain an estimate of the storage coefficient of an aquifer, as well as the transmissivity, if the results are only to be used in a steady-state model, which requires only the latter parameter.

3.4.3 If the intention is to put the pumping-test derived parameters into a numerical aquifer model, which will normally require average regional values, it may be more appropriate to obtain these values by calibrating the model. Pumping test data might be used in the calibration procedure, but it will probably be more valid to use head variations in response to natural stresses such as rainfall and tides.

4. SELECTED BIBLIOGRAPHY

Listed below are some standard hydrogeological textbooks, all of which provide an introduction to pumping tests, along with more specialised works on the execution and analysis of pumping tests. The monograph by Kruseman and de Ridder is particularly recommended for its comprehensive coverage of methods for analysing pumping test data.

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FRESHWATER - SALTWATER RELATIONS

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(British Geological Survey)

1. INTRODUCTION

The purpose of this paper is to introduce the basic concepts that are used in describing the relationship between the freshwater and saltwater in a coastal aquifer. The emphasis will be on a qualitative description although the powerful Ghyben-Herzberg approximation, which is the basis of most quantitative investigations, is also introduced.

Since this presentation is necessarily of very limited scope and detail, an annotated bibliography is provided as an aid to further study.

2. GENESIS OF A FRESHWATER LENS AND TRANSITION ZONE

Figure 1 represents a section through an oceanic island (this and subsequent figures are highly distorted for clarity). The freshwater lens is a dynamic system, maintained by recharge, with flow from the water table towards the coast. Where the freshwater meets the saltwater there is a *transition zone* through which the salinity increases with depth as suggested for the vertical line XY in Figure 1.

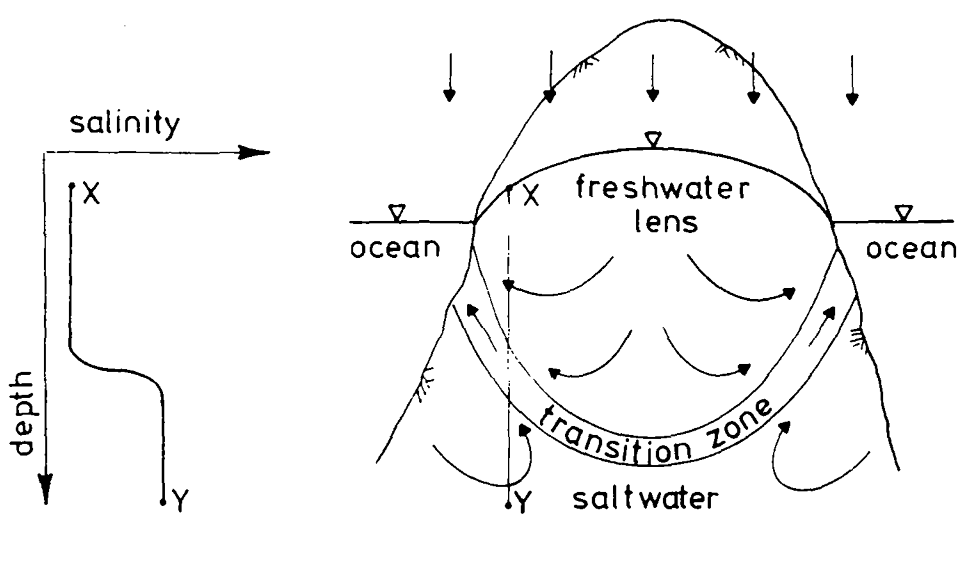

Figure 1. A freshwater lens in an island aquifer.

The width of the transition zone is determined by a number of factors. The primary geological factor is the branching nature of flow paths in the rock which gives rise to the mixing of waters with different salinities. This *dispersion* process can take place both at the microscopic scale, due to the granular nature of rocks, and at the macroscopic scale, due to heterogeneity such as layering or fissures.

Even with steady-state flow conditions there would be a transition zone. In practice the flow rates are continually changing due to pumping, tides and changes in recharge, and these changes enhance the size of the transition zone. Such processes are complex and no satisfactory quantitative description has been produced.

Should a long drought be experienced the lens will contract (even when there is no abstraction) and could effectively disappear. On the resumption of recharge the lens will begin to grow again, although the transition zone may extend up to sea level for a considerable period.

3. GHYBEN-HERZBERG APPROXIMATION

When the transition zone is relatively thin, it is often assumed that there exists a surface above which there is freshwater (at a constant density, ρ_f, of about 1000 kg/m^3) and below which there is saltwater (at a constant density, ρ_s, of about 1025 kg/m^3). This is known as the *sharp interface approximation*.

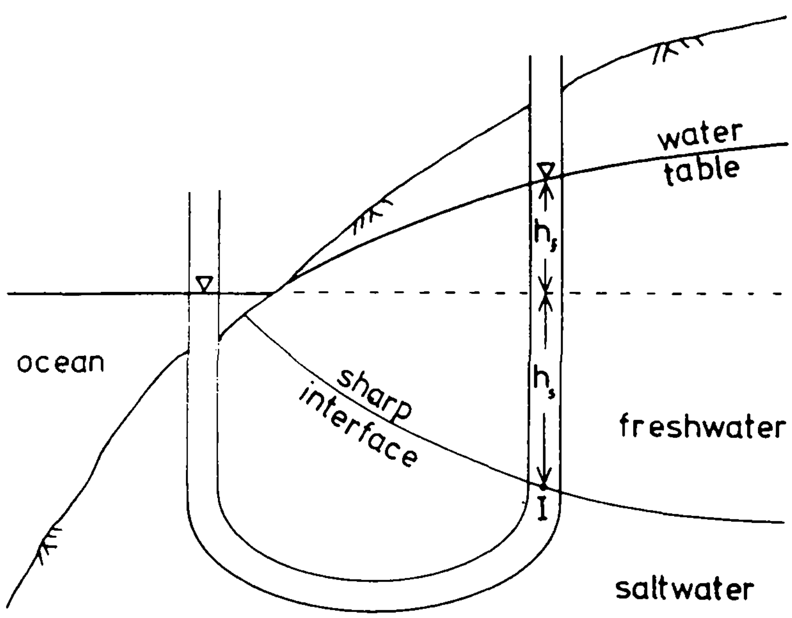

Figure 2. Definition sketch for the Ghyben-Herzberg approximation.

Figure 2 depcits a sharp interface in the vicinity of the coast. Consider the water within an (imaginary) U-tube extending from the ocean surface through the interface and up to the water table. Assuming that the water in the U-tube is in hydrostatic equilibrium, the pressure P at point I, on the interface, is that below a column of saltwater of depth h_s and also that below a column of freshwater of depth $h_s + h_f$. Therefore:

$$P = \rho_s\, g\, h_s + P_a = \rho_f\, g\, (h_s + h_f) + P_a$$

where g is the acceleration due to gravity and P_a is atmospheric pressure. This equation can be rearranged to give:

$$h_s = \delta\, h_f \qquad (1)$$

where $$\delta = \rho_f/(\rho_s - \rho_f) \approx 40 \qquad (2)$$

Equation (1), which is known as the *Ghyben-Herzberg approximation*, indicates that the depth of the interface below sea level should be about forty times the height of the water table above mean sea level. This is a very important result which gives rise to many useful formulae for estimating the position of the interface under various conditions.

In the case of a thick transition zone the Ghyben-Herzberg approximation can still be applied with reasonable accuracy provided the sharp interface is identified with the 50% seawater isochlor (about 10,000 ppm chloride).

The assumption of hydrostatic equilibrium in the U-tube (Figure 2) is satisfied when the saltwater is at rest and the freshwater flow is horizontal. Such conditions are often approached in practice.

4. SOME STANDARD SITUATIONS

4.1 A saltwater wedge

Figure 3 depicts a situation where a full lens is unable to develop because of a confining layer at depth B below sea level. The interface stretches inland a distance L, intersecting the top of the confining layer along a line known at the *toe*, with the saltwater body within the aquifer taking the form of a wedge.

Assuming that the aquifer is homogeneous and making use of the Ghyben-Herzberg approximation and Darcy's Law, an estimate of the length of the wedge is given by:

$$L = \frac{K \cdot B^2}{80 \cdot Q}$$

where K is the hydraulic conductivity of the rock and Q is the discharge rate of freshwater to unit length of the coast.

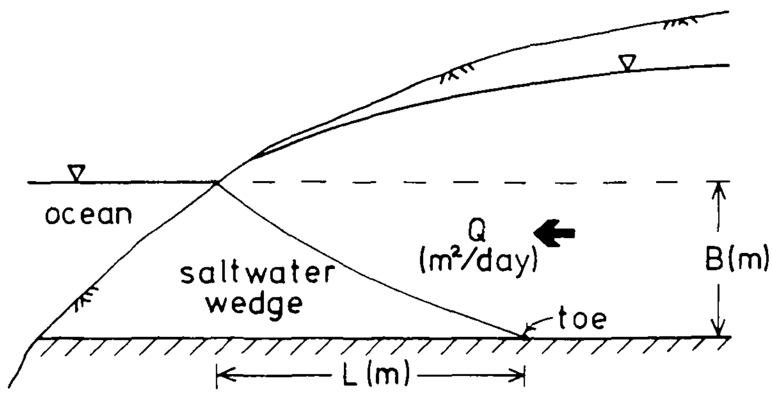

Figure 3. Definition sketch for a saltwater wedge in an unconfined aquifer.

From this equation it is obvious that if Q should decrease, either due to lack of rainfall or increased abstraction, the saltwater will encroach further into the aquifer. It also shows that the higher the conductivity of the aquifer the greater the extent of intrusion.

4.2 Single well near the coast

The above situation can be extended to include a single well which distorts the otherwise uniform flow to the coast. Figure 4a depicts the flow pattern while Figure 4b shows the water table and interface.

Water flows from the stagnation point S both towards the coast and towards the well. Should the toe of the interface encroach further inland than point S, saltwater will soon arrive at the well. A sufficient condition for this not to occur is that the freshwater head H at point S should exceed B/40 since then, according to the Ghyben-Herzberg approximation, there can be no interface above the confining layer. This condition can in turn be expressed in terms of a critical pumping rate which should not be exceeded (see: Strack, 1976; Bear, 1979, pg 399).

4.3 Upconing beneath a skimming well

A skimming well is simply a well that abstracts freshwater from above a saline interface. The harder such a well is pumped the higher the salinity of the abstracted water. Although this system is best described in terms of the transport of chloride in the water (Diersch et al., 1984), considerable insight into its behaviour has been gained by study of the sharp interface model (Bear, 1979).

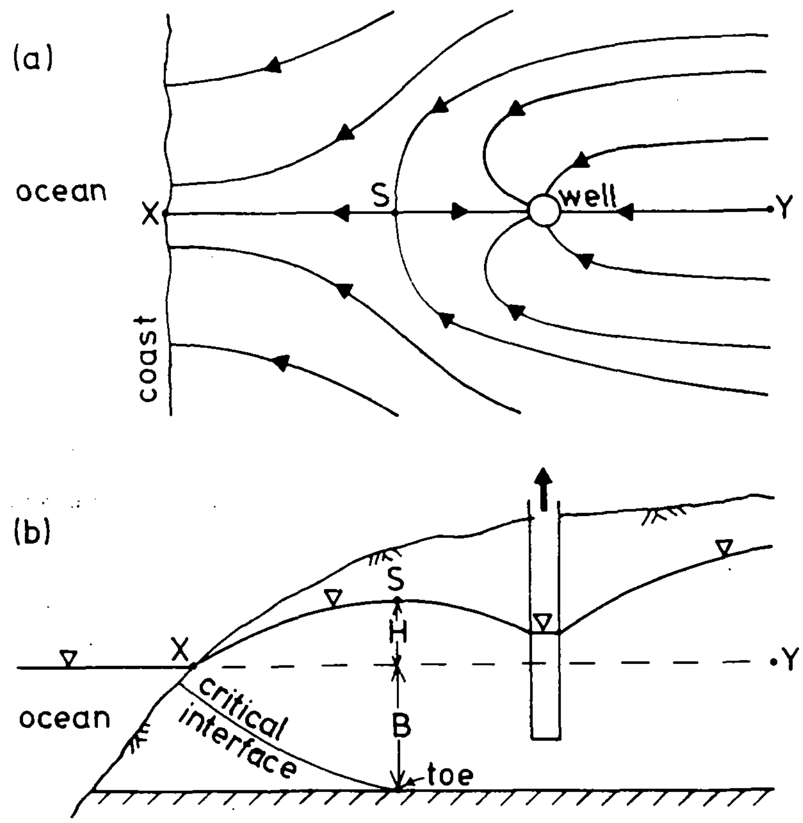

Figure 4. Flow to a well near the coast. (a) Plan view of flow pattern. (b) Vertical section perpendicular to the coast.

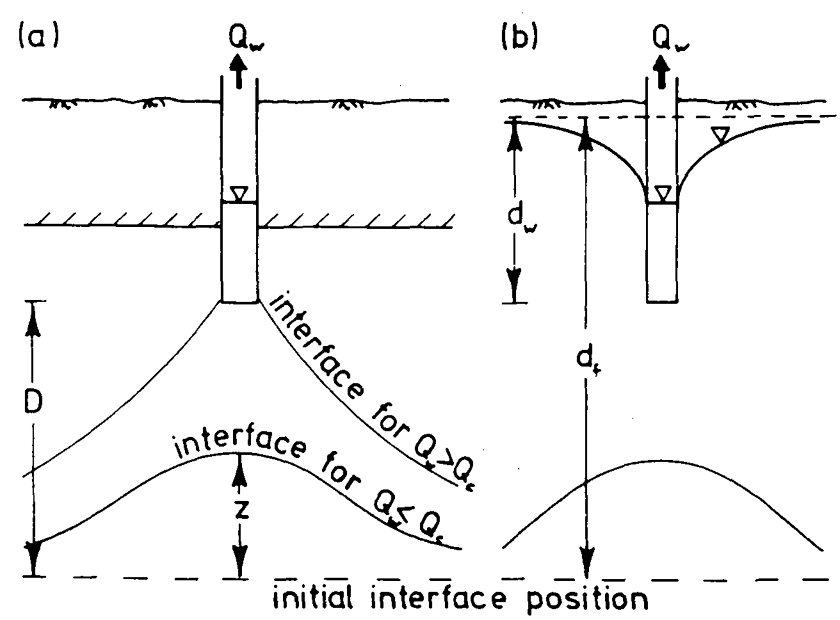

Figure 5. Definition sketch for upconing below a skimming well. (a) Confined aquifer. (b) Unconfined aquifer.

Figure 5 depicts skimming wells in both a confined and an unconfined aquifer. In the confined case (Figure 5a) it has been found that, if a certain critical pumping rate, Q_c, is not exceeded, the interface remains at some distance below the bottom of the well. However, if Q_c is exceeded, the interface rises quickly up to the well. In the case of a homogeneous, isotropic aquifer with hydraulic conductivity K, Q is approximated by:

$$Q_c = \pi D^2 K/40$$

and the rise of the interface, z, at this rate is about D/2 (e.g. Schmorak and Mercado, 1969).

These results will rarely apply with great accuracy because of aquifer heterogeneity, flow to the coast and the existence of the transition zone. However they do suggest that a skimming well should be made as shallow as possible (because of the D^2 factor in Q_c) and that the salinity of the abstracted water will rise relatively quickly if a certain pumping rate is exceeded. This rate can be found experimentally, perhaps using the value of Q_c given by the above expression as a guide.

Figure 5b depicts a skimming well in an unconfined aquifer. For very small drawdowns the behaviour will be the same as that in a confined aquifer, with an impermeable surface coincident with the water table, so the above discussion applies. However it is interesting to observe that, because of dewatering of the well with increasing drawdown, such a well has a limited production capacity. It is therefore possible to choose the well depth, d_w, such that upconing into the well is impossible, at least on the basis of the sharp interface approximation. This was investigated by Chandler and McWhorter (1975) who found, for example, that d_w should be less than $d_f/3$ (Figure 5b) for a homogeneous isotropic aquifer.

5. CONTROL OF SALINE INTRUSION

From what has been said it should be clear that certain measures can be taken to prevent excessive saline intrusion on small islands. Wells should be shallow, pumped at low rates and as widely dispersed as possible. When the freshwater lens is very thin infiltration galleries are obviously preferable to wells.

Other possible methods of control (e.g. Todd, 1980), such as the construction of subsurface barriers and the use of scavenger wells, are probably too expensive and technically complex to be of value on small islands.

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THE (IN)SIGNIFICANCE OF WATER IN PACIFIC ISLAND ECOLOGY[1]

Harley I. Manners

ABSTRACT

While water, the major emphasis of this workshop, is a significant factor in island ecology, in this paper I take the proposition that other factors are equally important in the ecology and development of atolls.

One indicator of the significance of water in the island environment is vegetation. Yet vegetation is related to other environmental factors: storms and hurricances, salt water tolerance, island size, geographic isolation and human disturbance, to name a few.

Through the title of this paper I suggest that water is a significant factor in island ecology, but that one cannot focus on water alone when considering the ecology of atolls.

1 Paper presented at the workshop on Water Resources of Small Islands. University of the South Pacific, Suva, Fiji, 2-9 July 1984. Sponsored by the Commonwealth Science Council.

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INTRODUCTION

Last year (1983) the leeward sides of Fiji experienced a severe drought which greatly reduced its sugar export earnings. The Republic of Nauru, which has the highest per capita income in the Pacific because of its phosphate deposits, imports water during periods of drought. In 1980, a number of papers at the Regional Technical Meeting on Atoll Cultivation (Tahiti) underscored the significance of water in atoll ecology, agriculture and development. Throughout the Pacific, the lack of water is an oft cited constraint towards development.

The theme of this workshop centers on water in the Pacific islands, and while the examples cited above certainly support the significance of water in the Pacific islands, my approach to the topic will be slightly different. As a geographer and an ecologist I will suggest through a number of examples that water is only one factor in the island ecology and development, and that other factors may be equally significant.

Water and vegetation ecology

All life requires water. A visible expression of the close ecological relationship between water and life is plants and vegetation. Plants, for example, have been classified according to water need and the terms hydrophytes, mesophytes and xerophytes are representative of such classifications. Similarly, we are familiar with descriptions of vegetation which incorporate or suggest a relationship between water and vegetation. Examples of this relationship include tropical evergreen rainforest, tropical dry deciduous forest, subtropical desert, sclerophyllous forest, savanna, mangrove and swamp. Each of these formations is indicative of a particular moisture regime and differs greatly in terms of ecological structure (species composition, numbers, vertical and horizontal stratification, nutrient, water and energy requirements) and function (nutrient and hydrologic cycling and energy flow). Water is a key factor in each of these vegetation formations. The ecological significance of water, as well as the islanders' understanding of it, is perhaps best exemplified by the 'babai' pits in Kiribati.

Kiribati (the former Gilbert Islands) is composed of 17 small low lying coral atolls which rise less than 4 meters above sea level. The islands are located in the dry belt of the Central Pacific and receive between 100 and 300 cms of rainfall per year. The main food crops of Kiribati are pandanus, coconuts and 'babai' (Cyrtosperma chamissonis) of which only the latter is said to be cultivated (Lambert 1982).

The 'babai' requires ". . . a more or less continuous supply of water to thrive" and is planted in pits, roughly 20 m x 10 m and 2-3 m deep, which reach down to the surface of the fresh water lens (Lambert 1982: 163). As babai is intolerant of salt or brackish water (Wiens 1962) most of the pits are located towards the atoll's center where the hydrostatic lens is thickest and contamination from salt water intrusion minimized. The plants are mulched with a mixture of humus and selected leaves and depending on the variety, require between two to 15 years before harvesting (Lambert 1982). Similar systems of babai cultivation are found in Mokil, Nukuoro and Kapingamarangi (Wiens, 1962).

The association of 'babai' pits and fresh water is also reflected by the nature of the atoll vegetation. Usually trees and other plants are larger, more numerous and more diverse where the lens is thickest. However, water is not the only factor to consider in analysing the vegetation ecology of these islands. Tolerance of vegetation to salinity, the strength and frequency of winds, tropical cyclones and tidal waves (Guerin 1982), human interference, island size and distance to a seed source are some other factors which affect the distribution and nature of vegetation in the islands. The rest of the paper will consider the importance of the first three of these factors.

Salinity

All plants vary in their tolerance to salt, whether contained in sea spray, soil or water. Most indigenous atoll plants are tolerant in varying degrees to salt (Wiens 1962), and on many islands there is a definite zonation of vegetation which can be correlated with salt whether contained in soil, water, or sea spray. According to Niering (1956) in decreasing salt tolerance are the following groups:

a) Cocos nucifera, Pandanus tectorious, Messerchimidia argentea, Scaevola sericea; and Guettarda speciosa;
b) Cordia subcordata and Clerodendrum inerme;
c) Terminalia samoensis;

d) *Premna obtusifolia* and *Morinda citrifolia*;

e) *Callophyllum inophyllum*;

f) *Artocarpus altilis*.

All of these plants or their close relatives, the majority of which are trees, are to be found on most islands of the Pacific. When species less tolerant of salt are found in more salt exposed conditions, they often display evidence of salt damage or are stunted and display a less vigorous appearance. On Nauru, where phosphate has been mined for almost 80 years, the most successful colonizers of the mined sites are 48 indigenous strand plants which are tolerant of the alkaline soil conditions (Manner, Thaman and Hassall 1984). Although approximately 400 plants have been introduced to Nauru, less than 5-10 of these species are capable of colonizing these abandoned mined areas. As salt is present in atoll environments, studies of salt tolerance in plants can contribute to the understanding of atoll ecology (Guerin 1982).

Tropical cyclones and storm surges

Tropical cyclones or hurricanes with winds exceeding 64 knots are not an uncommon feature of the South Pacific islands (see Table 1 in the Appendix). Between November 1969 and April 1980, Fiji experienced 18 storm wind speeds greater than gale force (Fiji Meteorological Service 1980c) of which 14 were classified as tropical cyclones (Krishna, R. 1981). Since March 1983, Fiji has experienced three tropical cyclones: Oscar and Sarah in March 1983, and Cyril in March of this year. Of these, the most serious was Oscar which will considered later in this paper.

The effects of a tropical cyclone and its associated storm surge on fresh water resources and vegetation can be devastating for small islands. Blumenstock (1958) noted that Typhoon Ophelia, which struck Jaluit (Marshall Islands) in 1958, uprooted or snapped off 70 to 90 per cent of the trees on Majatta and north Jaluit. The storm surge of salt water killed exotic plant species, scoured and shifted soils and gravels (which buried other plants), and reshaped the geomorphic features of these islands (Blumenstock 1958).

Destruction of the agricultural system and crops has also occurred during a hurricane. Wiens (1962) lists the following: salinization of soils which required six months to leach free; destruction of food trees (coconuts and breadruit), and infilling of taro pits.

Human influences

For the larger Pacific islands the significance of water in ecological functioning and development can be just as critical as it is in the smaller islands. The larger islands often receive higher rainfall totals (see Table 2 in Appendix), and because of their more complex geology, are usually better watered than the smaller islands. However, the precipitation is not evenly distributed spatially as much of it is orographically induced. Thus, for many of the larger islands, there is a definite rainshadow effect where drought sometimes occurs.

Tropical rainforest is the natural vegetation for these larger islands. However, in many areas of the Pacific where the climatic conditions are suitable for rainforest, the landscape is dominated by grassland vegetation. Parts of lowland and highlands Papua New Guinea, the northern coast of Guadacanal in the vicinity of Honiara, and the western side of Viti Levu and Vanua Levu are dominated by a grassland vegetation. While the presence of a grass cover suggests a dry climate or a period of water deficit, the origin and maintenance of these areas are partly ascribed to burning for pasture or clearance for shifting agriculture (Brookfield and Hart 1971, Paijmans 1976, Manner 1976). In Fiji these grasslands or 'talasiga' (literally sun-burnt lands) are located in the rainshadow. Thus, while they are of presumed anthropogenic origins, climate is an obvious contributor. Average annual rainfall and pan evaporation for two stations in this area are:

Station	Rainfall (cm)	Pan evaporation (cm)
Nadi Airport[1]	187	208
Lautoka Mill[2]	183	149

[1]Fiji Meteorological Service (1980a)

[2]Fiji Meteorological Service (1980b)

For decades, much of the economy of the western sides of Viti and Vanua Levu has revolved around sugar for the export market. But since the 1960's the Forestry Department, and later the Fiji Pine Commission (FPC) have reforested 33,263 hectares of the steeper 'talasiga' slopes with Pinus caribaea (Fiji Pine Commission 1984). A plantation of 60,800 hectares is planned for these areas (Fiji Pine Commission 1984).

While reforestation of these oft burned grassland slopes has economic as well as ecological benefits (erosion reduction, increase in soil water capacity, etc.), studies elsewhere indicate that evapotranspiration rates are higher and annual runoff totals are lower in areas under trees than under grass. Unfortunately for the FPC the coincidence of growing pine trees, drought and lowered stream levels have not gone unnoticed by the residents and sugar cane growers in the region, who consider the lower stream levels to be causally related to the pine reforestation scheme. However, the paucity of rainfall and stream discharge data for this area precludes any conclusions on the impact of pine reforestation on the hydrology of these grasslands.

In 1981 I submitted a project proposal to the FPC to assess the impact of Pinus caribaea plantations on the hydrology and nutrient cycling of these grasslands (Manner 1981). Briefly, the project involves the monitoring of precipitation and stream discharge in two adjacent third order watersheds of comparable size (approximately 450 hectares) and required the emplacement of weirs, stage level recorders and rain gauges. The Masi Creek watershed is largely unforested (there is less than 1 hectare of pines in it) and has been monitored for stream flow and precipitation for one and a half years. Monitoring operations in the Vatuma Creek watershed, which was reforested in 1980, began in 1982. Other ecological studies are in progress. The watersheds are also being studied for changes in nutrient cycling through the analysis of soil, water, and plant tissue; vegetation and biomass changes as a result of reforestation; erosion; and other ecological parameters. A detailed soil study of these watersheds will be published before the end of this year. It is expected that the above mentioned studies will be carried out over a complete growth cycle (17+ years).

The project is not without its share of problems. Firstly, heavy siltation of the streambeds caused by high magnitude discharge have temporarily rendered the stage recorders inoperative. Secondly and more importantly, it would have been theoretically ideal if both watersheds were unforested when the weirs and stage recorders were first emplaced. Such a situation would have allowed for a precalibration period in which it could be assessed whether or not the watersheds were hydrologically comparable. However, it was almost impossible to locate two such sites because of topographic or logistical problems. Thus the 1980 plantings in the Vatuma Creek watershed may make such an assessment impossible.

On March 1983, Hurricane Oscar devastated the 1980 plantations in the Nabou and Nadi Forest including the plantation in the Vatuma Creek watershed, to the extent that ". . . most areas in this category have been designated for complete clearance and replanting" (FPC 1984: 4).

It is perhaps fitting and ironic that a study which was designed to measure the impact of Pinus caribaea on the hydrology of these grassland ecosystems has been aided by a hurricane. While water is a critical factor in island ecology, other factors are likewise important in the development process. With the pressures of increasing development and populations in the islands, there is a need for basic water research and greater supplies of water. Rational development must consider also the effects of the other factors on the island environment.

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APPENDIX

Table 1. Tropical cyclones in the South Pacific by island groups.[1]

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Total	Annual Average Frequency
Fiji	21	15	22	5							1	13	77	2
Toñga	16	7	15	6	1						3	3	51	2
Samoa	10	2	8	2							2	6	30	2-3
Vanuatu	11	12	9	2	1					1	3	2	41	2
New Caledonia	12	13	10				1		1	2		5	44	3
Norfolk	5	9	7	3		2		1		2		1	30	2
Tuamotus	3	2	1						1				7	-5
Tahiti	3	1							1			3	8	-2
Solomons	2	1	2									1	6	-2
Cook	2	5	3									5	17	-5
TOTALS	85	67	77	20	2	2	1	1	3	5	9	39	311	
Percentage	30	20	25	6	.6	.6	.3	.3	1	2	2.5	12		

[1] Based on an analysis of 311 storms circa 1853 and 1924.

Adapted from Visher (1925: 27).

Table 2. Climate data for selected Pacific islands.

STATIONS	Average Annual Temperatures (°C) max.	min.	mean	R.H. (per cent) am	pm	Precipitation (cms)
Admiralty Islands						
Lorengau	32.2	22.2	27.2	87	-	391
Caroline Islands						
Palau	30.0	24.4	27.2	79	76	396
Ponape	29.4	23.3	26.4	85	77	485
Yap	30.5	24.4	27.4	89	78	
Cook Islands						
Aitutaki	28.9	22.2	25.6	79	71	197
Manihiki	29.4	25.6	27.5	80	79	248
Rarotonga	26.7	20.5	23.6	79	74	458
Pukapuka	30.6	25.0	27.8	80	73	298
Guam						
Sumay	30.0	24.4	27.2	86	73	227
Kiribati						
Ocean Island	31.1	25.0	28.0	78	82	189
Tarawa	31.1	25.5	28.3	77	71	200
Line Islands						
Fanning	31.6	25.0	28.0	75	-	251
Malden	32.2	23.8	28.0	63	76	70
Marianas						
Saipan	28.3	23.3	25.8	86	75	209
Marshall Islands						
Jaluit	31.1	25.0	28.0	84	78	403
Ujelang	30.5	25.0	27.8	84	78	196
Nauru	31.6	23.3	27.4	72	71	191
New Caledonia						
Noumea	27.2	19.4	23.3	73	70	110
Pagoumene	28.3	20.0	24.2	71	66	85
Niue	28.9	20.6	24.8	83	73	201
Papua New Guinea						
Daru	29.4	24.4	26.9	81	-	210
Madang	31.1	23.3	27.2	84	76	348
Port Moresby	30	23.9	26.9	72	69	101
Samarai	28.9	23.9	26.4	76	-	274
Rabaul	32.2	22.8	27.5	76	72	228
Kavieng	31.1	23.3	27.2	80	76	318
Phoenix Islands						
Canton	32.2	26.1	29.2	77	62	94
Solomon Islands						
Kieta	30.6	23.8	27.2	78	79	304
Tulagi	30.6	24.4	27.5	81	-	313

STATION	Average Annual Temperatures (^{o}C)			R.H. (per cent)		Precipitation (cms)		
	max.	min.	mean	am	pm			
Tahiti								
Papeete	31.1	21.1	26.1	82	77	163		
Tonga								
Nuku'alofa	26.7	20.0	23.4	79	73	161		
Va'vau	27.8	22.2	25.0	77	-	197		
Tokelau Islands								
Atafu	30.0	26.1	28.0	86	81	158		
Tuamotus								
Makatea	30.6	22.8	26.7	86	81	158		
Mangareva	28.3	20.6	24.4	-	74	222		
Tuvalu								
Funafuti	31.7	25.0	28.4	81	73	400		
Vanuatu								
Port Vila	28.3	21.7	25.0	77	73	210		
Tanna	26.7	21.1	23.9	78	84	240		
Western Samoa								
Apia	29.4	23.3	26.4	78	76	285		
Fiji							PAN(cms)	PE
Rotuma	29.4	23.9	26.6	84	77	350		167[3]
Nadi[2]	30.1	21.1	25.5	90	76	188	208	166[3]
Lautoka Mill						194[4]		154[3]

Sources of data

[1] Except for Fiji, all climatic data is from: Meteorological Office. 1958. Tables of Temperature, Relative Humidity and Precipitation for the World. Part VI. Australasia and the South Pacific Ocean. London, Her Majesty's Stationery Office.

[2] Fiji Meteorological Service. 1980. Climatological Summary Table - Nandi Airport 17^{o}45'S 177^{o}27'E 16 m. Information Sheet No. 51. Nandi Airport.

[3] Fiji Meteorological Service. 1980. Potential Evapotranspiration in Fiji. Information Sheet No. 60. Nandi Airport.

[4] Fiji Meteorological Service. 1981. Average Rainfall of Fiji Stations. Information Sheet No. 68. Nandi Airport.

APPLICATION OF TWO SURFACE-BASED GEOPHYSICAL TECHNIQUES IN ISLAND GROUNDWATER INVESTIGATIONS

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INTRODUCTION

Two surface-based geophysical methods, seismic refraction and electrical resistivity, have been used extensively in grounddwater studies conducted by personnel of the Water and Energy Research Institute, University of Guam. Information obtained from the application of these techniques has been extremely useful in determining subsurface structure and stratigraphy and in estimating the thickness of fresh-water lenses for a number of atoll islands. These methods have also been used in the study of Guam´s ground-water resources both on large and small scale projects (Camp, Dresser, and McKee, 1982; Ayers, 1982; Ayers and Clayshulte, 1983). Primary advantages of utilizing geophysical techniques are (1) relative ease in field setup and operation, (2) coverage of large areas with less time consumption and effort by field personnel (compared to methods involving subsurface exploration methods), (3) cost effective in terms of information obtained verus equipment and time involved in the operation, and (4) large amounts of subsurface data can be collected. Some disadvantages associated with geophysical applications are (1) initial cost of equipment may be high (depending on the level of instrument sophistication) and (2) interpretation of field data usually requires experience and sound hydrogeological judgement.

The aim of this paper is to present an introduction to the methods of seismic refraction and electrical resistivity and to show, by specific examples, the type of information that can be obtained from the field application of these methods. These examples are drawn from a study conducted on Kuttu Island, Satawan Atoll (Ayers and Clayshulte, 1983) located in the Lower Mortlock Islands of Truk State, Federated States of Micronesia. During the course of this study of salt-water intrusion, several seismic-refraction lines and resistivity stations were established across the small island. Results from the analysis of field data gave information on the layered nature of the subsurface and its possible composition, and information on the extent of fresh groundwater and the position of the transition zone between the lens and the underlying saltwater.

BACKGROUND AND METHODOLOGY

In this section, information related to the theory behind the two geophysical techniques is given and the methods used to analyze field data are briefly discussed.

Although the two techniques are very different in terms of methodology and the physical properties which they measure, seismic and resistivity surveys are often run together during hydrogeologic field studies. Results from both applications are complementary and thus ease the task of data interpretation. However, to insure a meaningful interpretation from any geophysical data, field methods should be confirmed by obtaining geological and hydrological information from independent means such as drilling and water-quality monitoring.

Seismic-Refraction Profiling

Seismic-refraction methods have been used in a wide variety of investigations involving the determination of subsurface structure. The object of refraction seismology is to obtain a time-distance graph from the first arrival of sound waves generated by an energy source. From time-distance graphs, seismic velocities can be calculated and depth determination can be made.

Detection of refracted sound waves generated by controlled energy sources (e.g., hammer striking a steel plate, weight drop, or explosion) usually produces a seismic record indicating one or more events that are caused by the change in velocity of the wave front. Seismic energy is transmitted through solid material as elastic waves. Abrupt changes in the elastic properties of the medium through which these waves pass will cause the waves to be refracted or bent. The degree to which the wave paths are refracted is related to Snell´s Law, that is, the sine of the angle of incidence is equal to the sine of the angle of refraction. Another way of expressing this law is by the following equation:

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

where,

i is the angle of incidence,

r is the angle of refraction,

V_1 is the velocity of transmission of the elastic wave in the incidence medium, and

V_2 is the veloctiy of transmission of the elastic wave in the refraction medium.

A primary concept in refraction work is that of the critical angle. Where r is equal to 90 degrees, sin i is equal to V_1/V_2. Here, the incident wave path or ray strikes the layer boundary at the critical angle and the refracted wave travels parallel to the boundary. A refracted wave front acts as a first arrival when its travel time from the source through the refraction medium to the detector is equal to or greater than the time required for the direct wave to travel from the source to the same detector. The path that first-arrival waves take is dependent upon the depth to the reference interface and the distance between the first detector and the energy source (Telford et al., 1976; Zohdy et al., 1974).

When first-arrival times derived from seismograms are plotted on a time-distance graph, a break in slope of the curve will occur where the time taken for both direct and refracted waves to travel from the energy source to the detector is the same. Seismic velocities are obtained from the slope on the time-distance curve (i.e., velocity is the inverse of the slope).

The most widely used of all field techniques in refraction work is profile shooting. To obtain the necessary time-distance data, shot points and detectors or geophones are laid out on long lines and repeated shots are taken at various positions at the ends and middle of the geophone spread. If successive spreads are necessary, the lines are overlapped by at least one or two geophones.

During field operations on Kuttu Island, several seismic-refraction lines or spreads were established across the study island. Each line was shot in both the forward and reverse order; several lines were shot at the midpoint of the spread. The energy source used in the refraction work was a sledge hammer striking a steel plate. Geophone spreads consisted of 12 detectors spaced at 25-foot intervals connected to a McSeis-1300 Signal Enhancement Seismograph. A permanent record was produced on light-sensitive paper. Figure 1 shows a schematic diagram of the field setup for the instrumentation.

Although a number of analytical approaches are available (see, for example, Telford et al., 1976 or Dobrin, 1976), the least time-consuming method utilizes computer processing of the time-distance data. The computer program used to process the Kuttu Island data was first published by the U.S. Bureau of Mines (Scott, 1972). The program generates a two-dimensional model representing a layered-earth depth interpretation. Travel times are picked from the seismogram by the user. These times, together with shot point and geophone locations and refraction layer control information, are used as program input. A first approximation delineation for each refraction boundary is obtained by a computer adaptation of the delay-time method. The approximation is then tested and improved by the computer through the use of a ray-tracing procedure in which ray travel times computed for the model are compared to field data. The model is

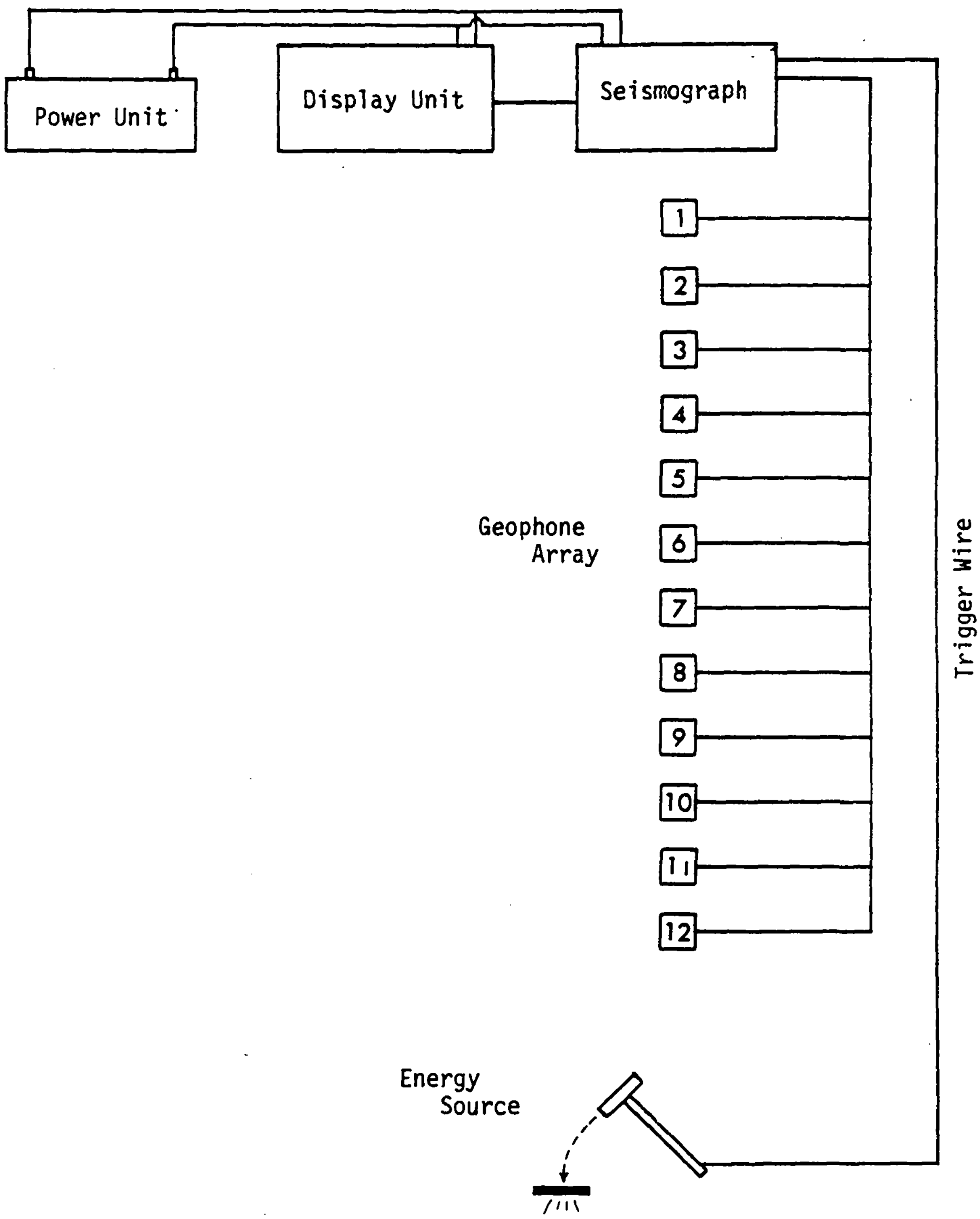


Figure 1. Schematic diagram of the field set up for seismic-refraction equipment.

subsequently adjusted in an iterative manner such that the discrepancy between computed and measured travel times is minimized. Seismic velocities and depths to refractor boundaries, among other information, are printed as the final step.

Earth-Resistivity Sounding

In addition to the application of seismic-refraction profiling in ground-water investigations, earth-resistivity measurements are widely used in the determination of subsurface characteristics and, in may cases, water quality. Essentially, the method involves measuring the electrical resistivity of earth materials by introducing an electrical currrent into the ground and monitoring the potential field developed by that current. In most earth materials, electricity is conducted electrolytically by the interstitial fluid, and resistivity is controlled more by porosity, water content, and water quality than by the resistivities of the matrix (Zohdy et al., 1974). Clay minerals, however, are capable of conducting a current electronically, and the electrical flow in a clay unit is both electronic and electrolytic.

In conducting earth-resistivity soundings, a commutated direct current or very low frequency (<1 Hz) current is introduced into the ground through two electrodes (Zohdy et al., 1974). The potential difference is measured between a second pair of electrodes; the current and potential measurements are used to calculate apparent resistivity.

The most commonly used electrode configuration for vertical electrical soundings, and the one used in the Kuttu study, is the Schlumberger array. Four electrodes are placed along a straight line on the ground surface such that the outside current electrode distance (AB) is equal to or greater than 5 times the inside potential electrode distance (MN). For any linear, symmetric array AMNB of electrodes, the apparent resistivity is given by (Zohdy et al., 1974):

$$\rho_a = \pi \frac{(\overline{AB}/2)^2 - (\overline{MN}/2)^2}{\overline{MN}} - \frac{\Delta V}{I}$$

where

ΔV is measured potential difference, and

I is electrical current.

A Soiltest R-60 resistivity unit was used to conduct the survey on Kuttu. The unit utilizes dry-cell batteries as a power source with a maximum output of 810 volts and 1.0 amps. All soundings utilized the Schlumberger configuration with a maximum current electrode (AB/2) spacing of up to 100 feet. Figure 2

A,B Steel rod electrodes

M,N Porous pot electrodes

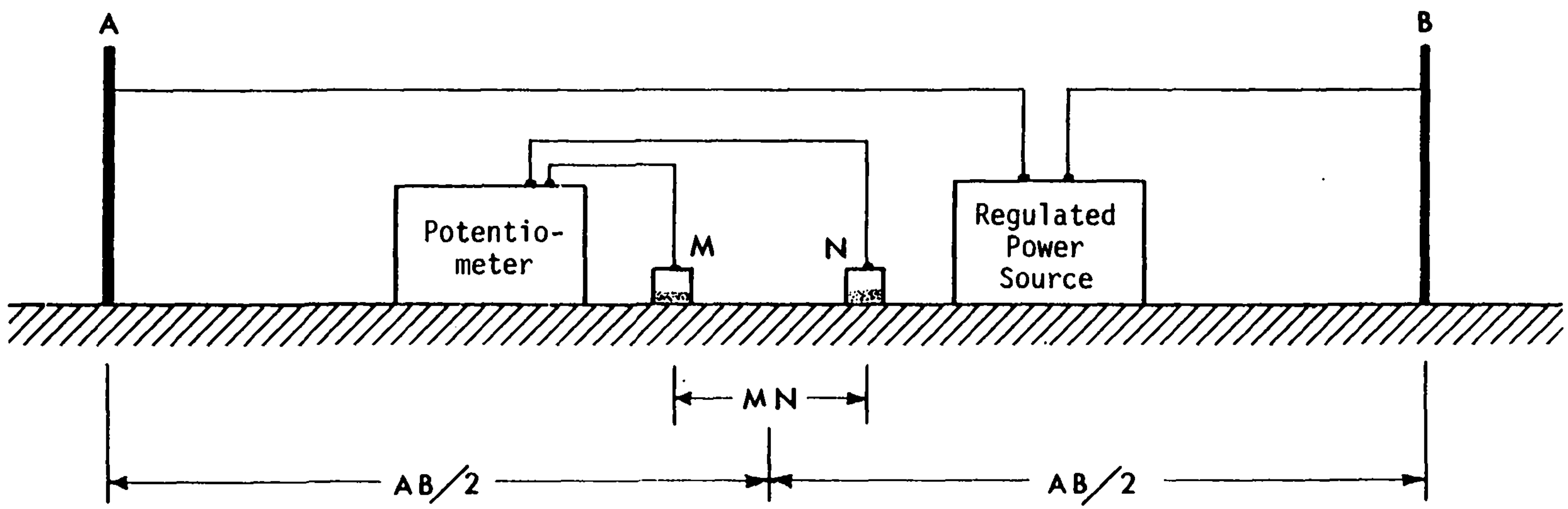


Figure 2. Schematic diagram of the field set up for resistivity equipment using the Schlumberger electrode configuration.

shows a schematic diagram of the field setup and instrumentation.

Resultant data generated during the resistivity survey were analyzed by a trial-and-error procedure of curve matching. The first step was to plot the field data on a graph of apparent resistivity versus electrode spacing (AB/2) for each station and smooth the vertical electrical sounding (VES) curve to remove the discontinuities produced by the method of measurement (see, for example, Zohdy et al., 1974). Next, an appropriate layer model was selected as a first approximation to the field VES curve. Layer thickness or depth and resistivity values are used as input to a computer program (Zohdy, 1974) which calculates the model VES curve. This model VES curve is then compared to the field VES curve for goodness of fit (usually a qualitative comparison). If necessary, the input values are adjusted and the program rerun. This procedure is continued until a reasonable match is achieved between the model and field curves.

As discussed by Zohdy (1974), for a given earth model composed of horizontally stratified, laterally homogeneous, and isotropic layers, the computer program calculates the Schlumberger apparent resistivity in two parts. First, the total kernel function $T = f(h, e, \lambda)$ is calculated for an n-layer model using Sundi´s recurrence formula which is given by

$$T_i = (h, \rho, \lambda) = [1-Q_i e^{-2\lambda h_i}]/[1+Q_i e^{-2\lambda h_i}]$$

$$Q_i=[\rho_i-\rho_{i+1}Q_{i+1}]/[\rho_i + \rho i{+}1 \; Q_{i+1}]$$

$$T_{n-1}(h, \rho, \lambda) = [1 - Q_{n-1}e^{-2\lambda h_{n-1}}]/[1 + Qn{-}1 e^{-2\lambda h_{n+1}}]$$

$$Q_{n-1} = [\rho_{n-1} - \rho_n]/[\rho_{n-1} + \rho_n]$$

where,

ρ_i is resistivity of the ith layer, and

h_i is thickness of the ith layer.

The second part in the calculation of the Schlumberger apparent resistivity is based on convolving the inverse filter coefficients (Ghosh´s coefficients) with the computed total kernel function curve. The convolution is made twice and six apparent resistivity values per logarithmic cycle are obtained. The abscissas of the computed points are logarithmically equally spaced, with

$$(AB/2)_{i+1}/(AB/2)_i = 1.468$$

where AB/2 is the Schlumberger electrode spacing.

STUDY RESULTS AND THEIR INTERPRETATION

Results from the Kuttu study are presented in this section and the meaning of these results are discussed. Although other interpretations are certainly possible those presented here represent the "best fit" in terms of additional field data collected during the course of the study. This additional information includes water-quality analysis, surficial geological data, and general observations.

Figure 3 shows a map of Kuttu Island with the locations of seismic-refraction lines and resistivity stations.

Seismic-Refraction Profiles

A total of 11 seismic-refraction lines were run across the island. Of the 11 lines, 10 produced useable results. As shown in Figure 3 eight lines were run along a pathway (through the village) and the remainder were shot near the ocean shoreline. Lines 1 through 4 and lines 5 through 8 were set up such that each spread overlapped the forward line by two geophones. Thus line 1 was coupled to line 2 and line 2, in turn, was coupled to line 3 and so on. This method was used in order to analyze the data either for a single line or all lines together. Lines 9 and 10 were treated as single spreads. Line 11 failed to produce usable results due to poor acostic properties of the ground.

Resultant seismic data obtained from the survey were analyzed on the computer using Scott´s (1974) program. From the computer study of seismic data, two types of information were obtained (1) velocity values for various subsurface layers and (2) depths to the top of the layers beneath each geophone. Seismic velocities are listed in Table 1 and layer depths are illustrated in the profiles of Figures 4 and 5.

A number of relevant points can be made with regard to the computer results. These points are summarized below.

1. Interpretation of seismic data from those lines established along the lagoon side of the island (spreads 1-8) indicate that the near surface structure is composed of three layers.

2. Interpretation of seismic data from spreads 9 and 10 established on the ocean side indicate that the near surface structure is composed of two layers.

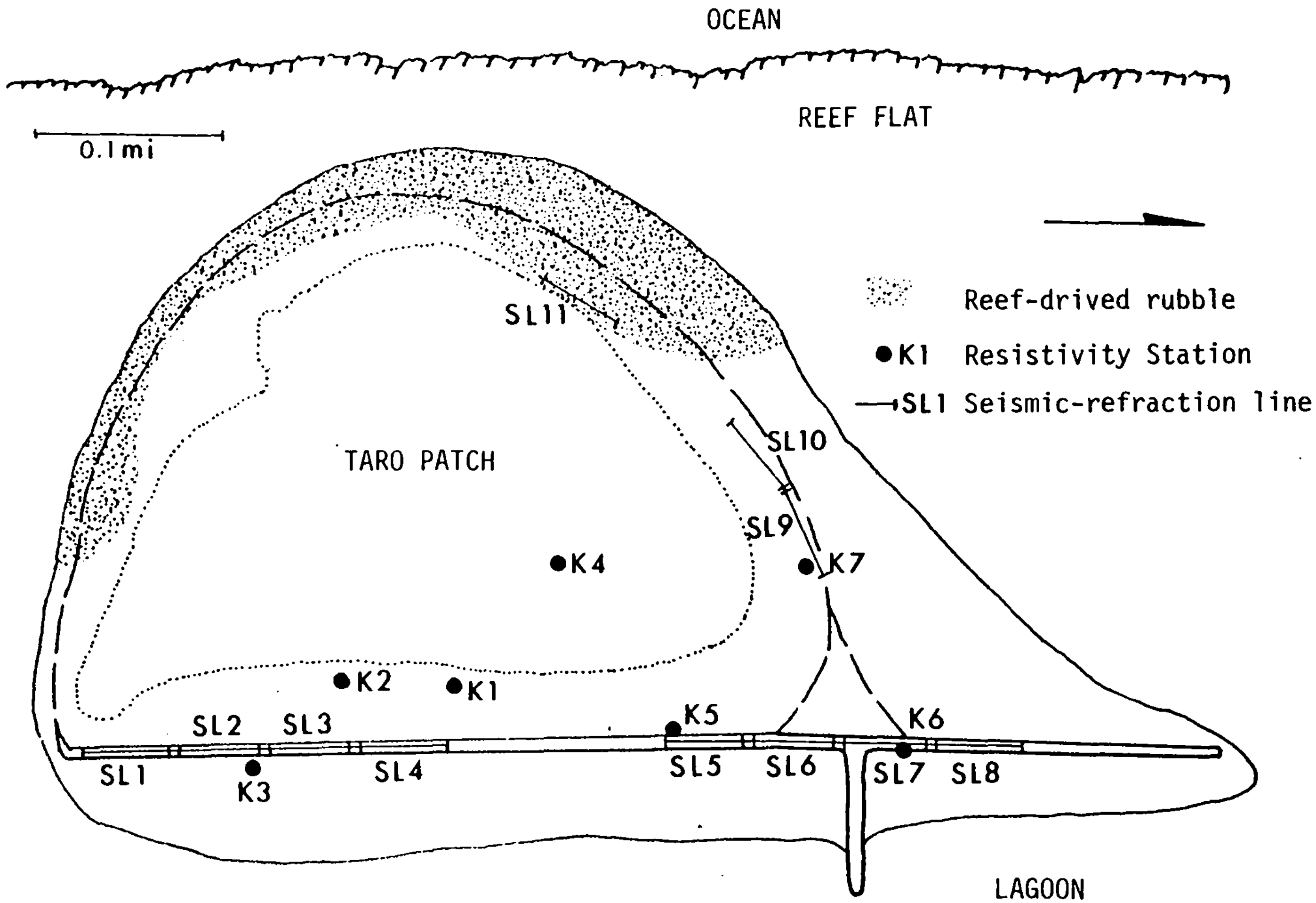
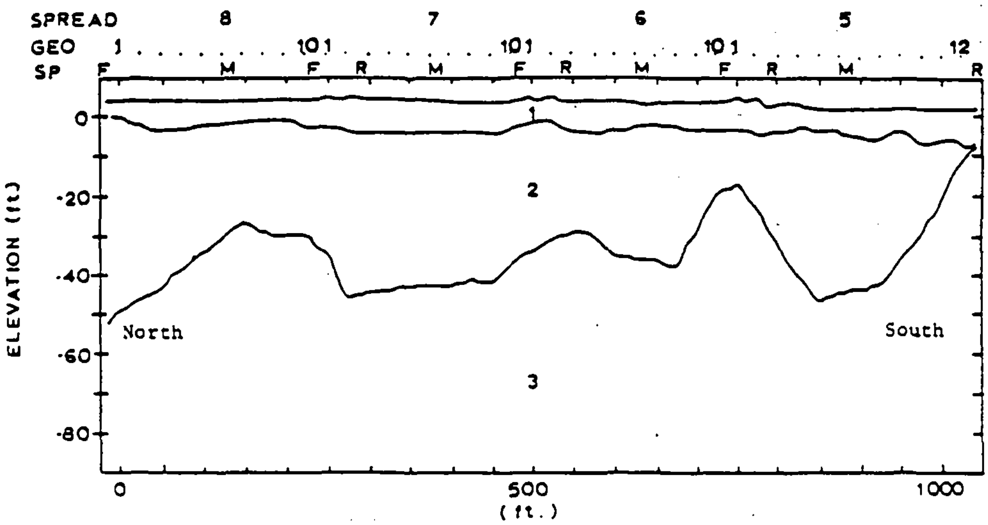


Figure 3. Map of Kuttu Island showing the locations of seismic-refraction lines and earth-resistivity stations.

Table 1. Layer velocities determined by the seismic-refraction survey conducted on Kuttu Island, Satawan Atoll.

Line		Layer 1 (ft/sec)	Layer 2 (ft/sec)	Layer 3 (ft/sec)
1		1186	5485	6213
2		1500	5634	7747
3		1345	5222	6612
4		1103	5160	5968
5		1175	5540	8852
6		1500	5200	6612
7		1158	5370	9162
8		1272	5549	6894
		------	------	------
	Mean Vel.	1280	5395	7258
9		1192	6134	
10		1083	5847	
		------	------	
	Mean Vel.	1138	5990	
*1-4		1201	5388	6472
*5-8		1207	5419	7361
		------	------	------
	Mean Vel.	1204	5404	6916

*NOTE: *Results from the computer analysis of coupled lines.*



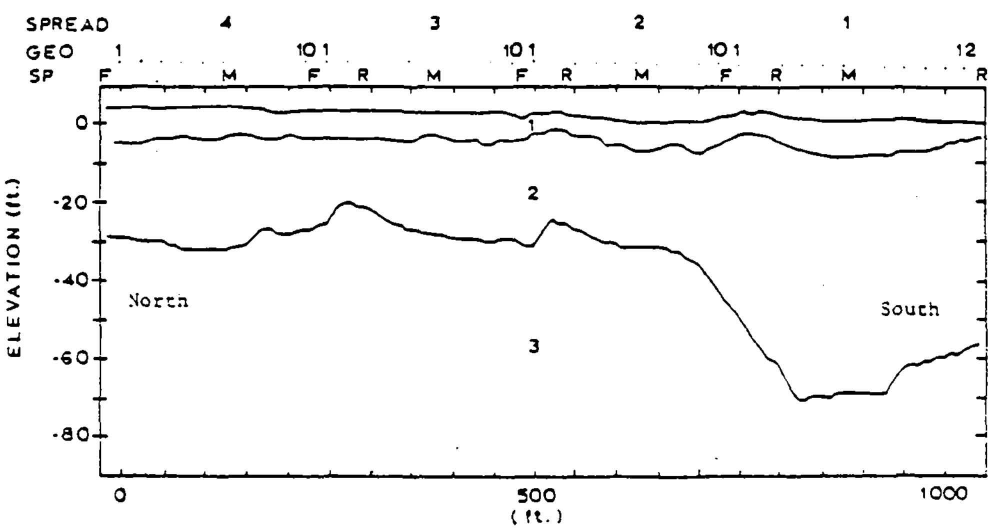


Figure 4. Seismic profiles derived from refraction lines 1 through 8 ajacent to the lagoon shoreline.

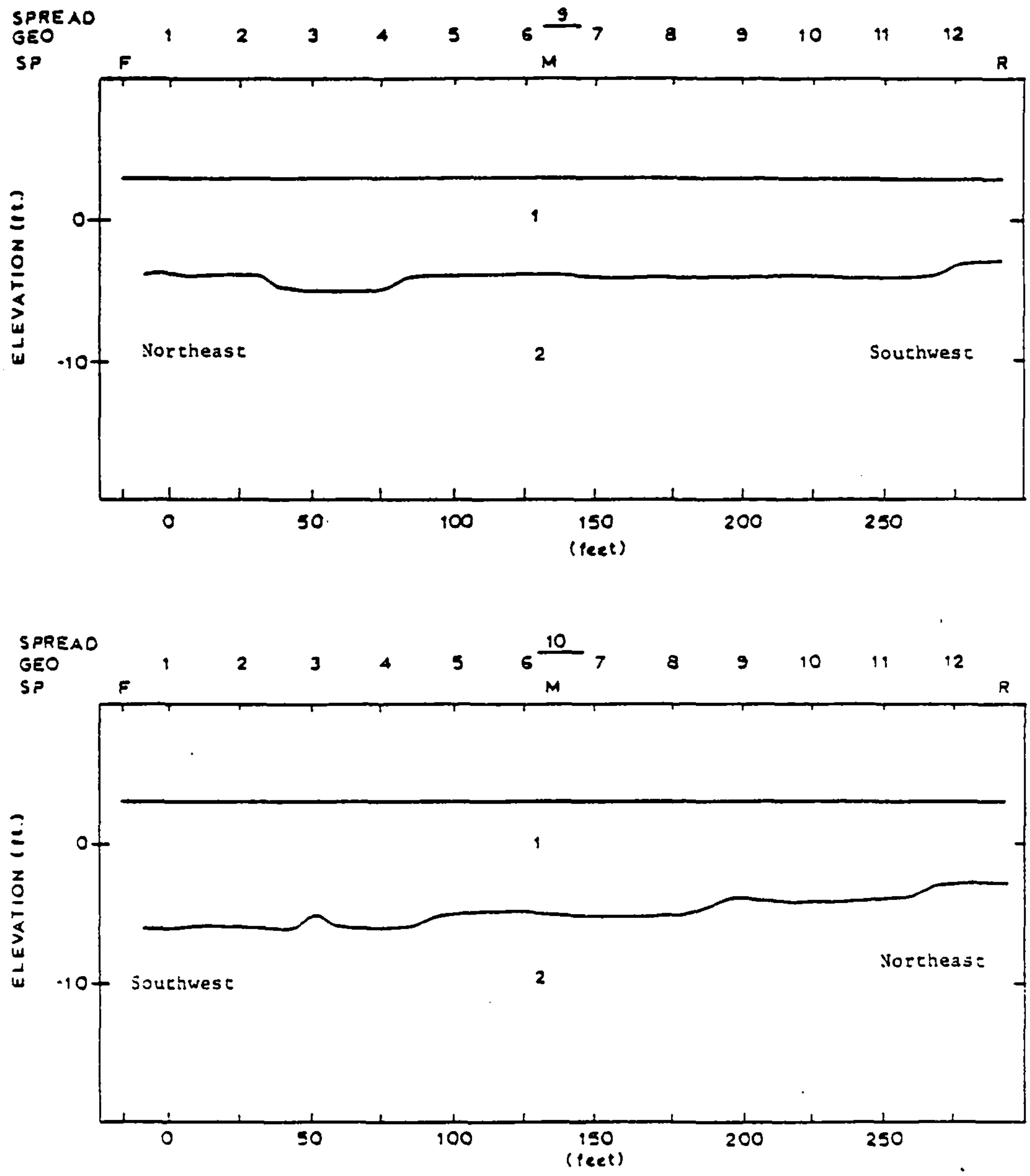


Figure 5. Seismic profiles derived from refraction lines 9 and 10 located near the ocean shoreline.

3. Velocities of layers 1 and 2 appear not to vary across the island, suggesting no significant change in composition or internal structure (i.e., intralayer construction). There is, however, distinct differences between the two layers.

4. Layer 3 appears to underly only that portion of the island along the lagoon shoreline. It should be noted however that the seismic-line coverage is inadequate to verify the presence of layer 3 elsewhere.

5. The top of layer 2 displays relatively little relief and is located at an average depth of 6.6 feet below the surface.

6. The top of layer 3 is very irregular with a relief of about 20 feet to 25 feet beneath spreads 5 to 8 and about 10 feet to as much as 40 feet for spreads 1 to 4. It is noteworthy that the surface of layer 3 is greatly depressed beneath spread 1; this location corresponds to an area of severe damage to root crops by salt-water intrusion.

7. The average depth to the top of layer 3 is roughly 40 feet beneath spreads 5 to 8 and 35 feet beneath spreads 1 to 4 except for spread 1. Here the top of layer 3 exceeds a depth of 60 feet.

Earth-Resistivity Soundings

Seven resistivity stations were established at various sites across the island (Figure 3). The purpose of utilizing this field technique was to determine the thickness of the fresh-water lens at selected locations by vertical electrical soundings.

The conceptual model of the island system formulated for analytical purposes was composed of four layers of different thicknesses and electrical properties. These layers represent a dry surface unit, a second unit saturated with freshwater, a third layer saturated with a mixture of freshwater and seawater (transition zone or zone of mixing), and finally a fourth layer of infinite thickness saturated with seawater. Layer thicknesses and their corresponding resistivities are adjusted during the iterative procedure until a reasonable combination is found.

Analytical results (Table 2) indicate that at the time of measurement the fresh-water column probably was 10 to 12 feet in the thickest part of the lens. On average, the transition zone or zone of mixing between fresh groundwater and the underlying seawater, may be on the order of 12 feet thick, or about the same thickness as the fresh-water nucleus near the center of the lens. These values are subject to about a 15% error, however, they do serve as a first approximation of water availability.

Table 2. Fresh-water lens and associated transition zone thicknesses derived from earth-resistivity data obtained from surveys conducted on Kuttu Island, Satawan Atoll.

Station	Fresh-water Lens Thickness (ft)	Transition Zone Thickness (ft)
K-1	6	14
K-2	10	8
K-3	8	12
K-4	12	8
K-5	8	12
K-6	6	12
K-7	15	10

CONCLUSION

Information obtained from the application of seismic-refraction and electrical-resistivity methods to the Kuttu Island case aided the study in evaluating problems of salt-water intrusion. These methods are relatively inexpensive to use compared to the alternative of drilling, are very portable and easy to operate, and are less time consumming in their field application. One additional advantage is that the methods can be utilized at all levels of detail within the scope of a given project. That is, these methods can be used to obtain information quickly for reconnaissance level surveys or be used to obtain rather detailed data for more sophisticated studies. All of these advantages plus the availability of the equipment make these geophysical techniques valuable tools to the investigator of island ground-water resources.

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GROUNDWATER OCCURRENCE BENEATH ATOLL ISLANDS

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INTRODUCTION

A recent study by the Water and Energy Research Institute (Ayers et al., 1984) has shed light on the problematic subject of atoll island hydrogeology. Deke Island on Pingelap Atoll, Ponape State, was the study area for a relatively comprehensive investigation of island hydrogeology and groundwater occurrence. Field work included the installation of a network of observation wells, water-level monitoring, installation of a lagoon tide gage, core drilling, surface geological and topographical mapping, geophysical surveys, and water-quality analysis. Information obtained from field work on Deke indicates a much more complex hydrogeology than would ordinarily be expected for such a small, and seemingly uncomplicated, island. Discovery of a hard substrate underlying much of the island and documentation of its profound effect on the occurrence and behavior of groundwater may force a re-evaluation of earlier-held views of atoll island hydrology.

A number of practical aspects have already come to light based on the work on Deke. For instance, on islands similar to Deke, such as Nukuoro and many others in Micronesia, it is now obvious why salt-water intrusion occurs in areas of root-crop cultivation (e.g., taro). Steps necessary to control the problem are also obvious. We have a somewhat better understanding of flow paths within the lens system and why fresh groundwater occurs where it does. We also have a better understanding of how to deal with the interpretation of field data, particularly raw water-level information. Finally, a set of guidelines for directing future studies on atoll island hydrogeology has been developed.

The purpose of this paper is to present a discussion of atoll island hydrogeology using the results of the Deke study as an example. The primary objective is to present a conceptual model of atoll island hydrogeology and groundwater occurrence based on the intrepretation of the results obtained from the investigation of Deke Island. The point of using Deke as an example is that Deke is representative of many islands within the Western Pacific region in terms of its geological makeup, configuration of the reef tract and relative position of the island, and the relative position of the fresh-water lens within the hydrogeological framework. There are, however, cases that do not fit the Deke model and therefore such cases should be considered on an individual basis.

LOCATION AND DESCRIPTION OF DEKE ISLAND

The study island of Deke is located on Pingelap Atoll which some 175 miles east of Ponape, Eastern Caroline Islands (Figure 1). Deke is one of three islands situated atop the atoll platform and is located along the northwestern margin. Deke is typical in the sense that it is low lying, densely vegetated, and composed primarily of reef- and lagoon-derived sediment. The island is approximately 4260 feet long, on the average is 1300 feet wide, and is somewhat arcuate in shape. For the most part, the ocean shoreline is exposed to wind-driven waves generated by the prevailing northeast trades.

Deke Island was selected as the study site for a number of reasons. First and foremost, the configuration and size of the island is such that a substantial fresh-water lens should be present. Second, the island appeared to be typical of other atoll islands located elsewhere in the Western Pacific. Third, the island is uninhabited and therefore the groundwater-flow system could be studied in its pristine environment without the effects of human activities. Results of this study could then be compared to study findings obtained from similar insular hydrogeologic settings in order to evaluate the impact of settlement. Finally, air service would be available in case of emergency and equipment replacement or repair.

METHODS OF THE DEKE STUDY

Emphasis of the hydrogeologic investigation of Deke was placed on documenting relevant aspects of island hydrology. These aspects included the extent of the freshwater lens and its relative position with respect to the geological components beneath the island, the behavior of the lens system to influential factors such as rain-derived recharge and sea-level fluctuations (ocean and lagoon tides), and the control, if any, that particular geological units may exert on the occurrence and movement of fresh groundwater. In order to collect data relevant to the goals of the study, many approaches were used during the course of the field work. Some of the field activities included the installation of a network of observation wells (including several standpipe-piezometric pairs; locations of water-level observation sites are shown in Figure 2), the application of geophysical techniques (seismic refraction and earth resistivity; station locations shown in Figure 3), core drilling, topographical and geological mapping, and water-quality evaluation. These activities and others were designed to lead to an understanding of the dynamics of the lens system beneath the island.

RESULTS OF THE DEKE STUDY

Results from the field work and subsequent data analysis and interpretation are given below in outline form under three general headings: Geomorphology and Geology; Water-Level Monitoring; and Hydrogeology and Groundwater Occurrence.

Geomorphology and Geology

1. Initially, Deke appears to have formed as two small separate islands. Each of these small islands was surrounded on three sides by well-developed ridges of coarse coral gravel. The former tidal pass between the two islands is represented by a north-south zone of sandy coarse pebbles that cuts through the center of the island (Figure 4).

2. Currently, the island is prograding lagoonward as evidenced by the reef-derived sediments accumulating on the lagoon beach and the angle-of-repose slope just offshore in the lagoon. Further evidence is provided by extensive development of tidal deltas and spits along the southeastern and southwestern margins of the island (which gives Deke a concave shape to the south).

3. The surface geology of the island (see Figure 4) is composed of four main components: a set of ridges composed of cobbles and boulders adjacent the ocean shoreline; a series of coalescing wash-over fans consisting of coarse pebbles and cobbles; a narrow band of coarse to medium pebbles and sand more or less centrally located (the central depression); and a low berm composed of sand with scattered medium pebbles along the lagoon shoreline.

4. The geology beneath Deke is composed of several distinct units (see the paper on the geology of atolls for details). Underlying part of the island is the hard substrate of the reef-flat plate. The plate is wedge shaped in cross section, thinning toward the lagoon and eventually grading into sediments of the sand apron (Figure 5). Poorly consolidated to unconsolidated sediments underly the reef-flat plate. This sediment package varies considerably in thickness across the island (Figure 6 shows seismic profiles across Deke; bottom of sediment package corresponds to boundary between V1 and V2). Similar to the reef-flat plate, this unit appears to grade lagoonward into the unconsolidated sediments of the sand apron. A Halimeda-rich unit underlies the unit beneath the plate and extends to an unknown depth. This Halimeda facies also appears to grade lagoonward into a unit composed of finer-grained unconsolidated sediments.

Water-Level Monitoring

1. Tidal fluctuations diminished inland and there was an inland-increasing time lag for the occurrence of highs and lows (Figure 7). Close to the shoreline, the tidal range was considerably larger in the north (oceanside) than in the south in part because the range in the lagoon was considerably less than in the open ocean. Overall, the lateral attenuation of the tidal signal was such as to dampen a 5.0 ft fluctuation in the north and a 3.0 ft fluctuation in the lagoon to less than 0.5 ft in the interior of the island. The tidal signal signal required 3 to 4 hours to reach the interior.

2. Where the hard substrate of the reef-flat plate was present beneath the island, the tidal fluctuation was larger and generally occurred earlier in the groundwater below the plate then in the groundwater resting upon its surface (Figure 8). This difference indicates that the reef-flat plate acts as a confining bed. Where the plate pinches out toward the lagoon, fluctuations within the two ground-water bodies (i.e., above and below the plate) became less different and eventually became identical.

3. There was a pronounced asymmetry of the lagoon tidal variation due to the impeded exchange between the open ocean and the lagoon (Figure 9). The lows are truncated and lag some 2 hours and 20 minutes more than the highs so that, on the average, the time between a high and a low was 7 hours 48 minutes and that between a low and high was 4 hours 17 minutes (Figure 7).

4. Substantial day-to-day variations in measured water levels were observed at all wells. The principal control was the variation in daily sea level as measured in the lagoon; rainfall also causes obvious changes in ground-water levels (Figure 10).

5. Day-to-day variability in water levels in the unconfined water resting upon the reef-flat plate was larger than that measured in drilled or dug-through piezometer. This was probably a rainwater-catchment effect and thus a temporary condition. Also, it appears that during wet periods the level in the unconfined groundwater over the plate is slightly higher than the piezometric surface of the confined groundwater (i.e., the lens system itself). However, the difference was slight and over a period of several weeks the average water level in the unconfined portion was about the same as that in the confined system.

6. Water level data, when plotted on a map and contoured, indicated an asymmetric surface to the top of the fresh-water lens (Figure 11). A ground-water ridge occurs on the lagoon side of the island, south of the pinchout of the reef-flat plate. This ridge marks the region where the system is under water-table conditions and is the recharge area for the confined aquifer that underlies the reef-flat plate.

Hydrogeology and Groundwater Occurrence

1. There are four main components comprising the hydrogeology of the Deke lens system: the island itself; the reef-flat plate; the sand apron lagoonward of the plate; and the partly consolidated, partly unconsolidated sediments beneath the reef-flat plate. Each of these units plays a unique role in the hydrology of the island.

2. The main function of the island is to catch rainwater and transmit it to the subsurface flow system. Numerous aspects of the hydrologic cycle such as plant interception and evapotranspiration are involved in the transmittal process.

3. A significant component of the hydrogeology is the reef-flat plate. The plate acts as a leaky confining bed and extends over a large portion of the groundwater-flow system.

4. Fresh groundwater is stored within the two remaining units. It appears that sediments of the sand apron have a lower permeability (about 150 ft/day) than the sediments beneath the reef-flat plate (about 1500 ft/day). The latter seem to be associated with the plate and may represent a non-indurated equivalent.

5. Fresh groundwater occurs as a complex lens displacing sea water. The configuration of the lens is asymmetric with the thickest part located within the less permeable unit adjacent to the lagoon shoreline.

6. Where the reef-flat plate is present the system is under confined conditions; elsewhere, the system is under water-table conditions. Primary recharge to the system takes place over the area not underlain by the plate.

7. Flow directions follow two routes, one from the groundwater divide directly to the lagoon beach face and the other toward the ocean beneath the reef-flat plate exiting the system somewhere between the island shoreline and the reef (Figure 11).

8. The transition zone between fresh and salty groundwater is created and maintained by sea-level fluctuations, particularly the tides. Its thickness is dependent on the frequency of the sea-level oscillation and on the permeability of the aquifer. The thinnest transition zone is associated with the less permeable unit adjacent to the lagoon shoreline.

DISCUSSION

Under ideal conditions where the aquifer is homogeneous and isotropic, the system is recharged uniformly, and there are no outside influential factors (e.g., sea-level variations), a symmetric Ghyben-Herzberg lens would be maintained. This, however, is not the usual case for real atoll island systems and is certainly not the case for Deke Island. The fresh-water lens beneath Deke is partially confined, is maintained within complex geologic units possessing disparate water-bearing properties, is subjected to recharge events of variable magnitude, and is greatly affected by sea-level variations due to tidal frequencies, barometric pressure changes, and seasonal or long-term ocean-level oscillations (steric effects).

A conceptual model of the fresh-water lens system beneath Deke is presented in Figure 12. This model was developed in order to generalize the complex dynamics of the flow regime and its hydrogeologic framework. The data base for the model consists of information obtained from water-level reduction calculations, specific-conductance measurements in boreholes, water-quality analyses, and the application of geophysical techniques. It should be noted for clarity that the vertical dimensions have been greatly exaggerated. In reality representation of the lens thickness would be little more than the width of a single line.

A number of important points relevant to the subsurface flow system of Deke are illustrated by Figure 12. Among these points are (1) the asymmetry of the lens configuration, (2) the relative position of the reef-flat plate and the primary recharge area, (3) the groundwater-flow pattern, (4) the zone of ground-water discharge, and finally, (5) the thickness variability of the transition zone. These points are discussed below.

One of the most obvious features of the model is the asymmetric configuration of the lens. Fresh groundwater is stored within two hydrogeologic units, that is, in units 4 and 5. It was mentioned previously that these units differ in permeability; the unit with the lowest permeability is adjacent to the lagoon. The thickest portion of the lens occurs within this (relatively) low permeable unit. Resistance to ground-water flow due to the low permeability tends to maintain higher heads which in turn depresses the position of the transition zone thus producing a thicker lens.

Direct recharge occurs over that portion of the lens where the reef-flat plate is not present. Infiltrating rainwater enters the system across the water table. This direct influx of water is an additional factor which contributes to the asymmetry of the lens.

The combination of asymmetric head distribution and localized ground-water recharge, in addition to the hydraulic effects of the reef-flat plate, produce an unusual subsurface flow pattern. Two flow paths are possible (refer to Figure 11). If a particle of water enters the system on the lagoon side of the flow divide, the path taken is relatively short, under unconfined hydralic conditions, and discharges directly into the lagoon. The zone of discharge is in the vicinity of the beach face. If, however, a particle of water enters the system on the ocean side of the divide, the path taken is much longer. The water particle will travel under confined hydraulic conditions beneath the reef-flat plate and discharge from the system somewhere between the island shoreline and the reef margine. Because of the presence of a confining bed, it is not appropriate to assume that the ocean shoreline of the island is the discharge zone. Under confined conditions the island unit is not a factor in the control of ground-water movement. What does control flow is the hydrogeology of the reef complex; the island merely plays the role of a rainwater catchment. Misinterpretation of atoll island systems similar to that of Deke can arise if this concept is overlooked.

Specific characteristics of the zone of mixing or transition zone between fresh groundwater and the underlying salty water were not well documented during the field work on Deke. However, from conductance profiles and indirect evidence some general features can be deduced. Sea level fluctuations, in particular tidal responses, are factors mainly responsible for creating and maintaining transition zones in island systems. As the level of the sea oscillates, the lens must also move in concert with the change because the flow system is in hydraulic link with the surrounding ocean. With the rise and fall of the fresh-water body, mixing between fresh and salty water occurs at the lower boundary of the lens. The thickness of the transition zone or the degree to which this mixing occurs is dependent on (1) the frequency and amplitude of the sea-level oscillation and (2) the permeability of the aquifer. In units of low permeability, the transition zone is relatively thin due to a greater attenuation of the landward propagating signal generated at the shoreline by a given sea-level oscillation, such as a tidal signal. In units of higher permeability, the opposite is the case, that is, a thicker transition zone develops. Based on the Deke field work, there is a disparity in permeability between the two units within which fresh groundwater is stored. This difference is reflected in the head distribution and location of the thickest part of the lens along the lagoon side of the island. It follows that the thinnest transition zone will occur where the lens is the thickest (i.e., where permeability is the lowest) and the thickest transition zone will occur where the lens is the thinnest.

Additional support for the above argument can be deduced from the known distribution of tidal efficiency (refer to Figure 7). Tidal efficiency variations across the island reflect the inland permeability-dependent attenuation rate of sea-level oscillations generated at the ocean and lagoon shorelines. Based on the graph of Figure 7 and other data, the attenuation rate is greater within units adjacent to the lagoon (i.e., the signal is dampened at a greater rate over a shorter distance as compared to units adjacent to the ocean). Thus it follows that the transition zone would be thinner where the attenuation rate is the greatest because of the dynamic relationship between sea-level fluctuations and the freshwater/seawater mixing phenomenon.

CONCLUSION

Results from the hydrogeologic investigation of Deke Island have led to a better understanding of the geological construction of an atoll platform and how fresh groundwater occurs within this framework. Of equal importance is the recognition of the various factors that control the behavior of the fresh-water lens and its associated transition zone. All of these general aspects are important components of the overall picture of atoll island hydrology.

A number of practical aspects have already come to light as a result of work performed on Deke. The study findings help to explain why certain problems related to ground-water occurrence, movement, and supply are experienced by atoll island communities. Among the major problems are salt-water intrusion and seasonal water shortages. By applying what is known of the flow system, many of these problems can be avoided or their effects greatly reduced. Although the subject of water quality was not directly addressed by this paper, the results of the Deke study could be applied to efforts in solving problems related to well contamination, control of water-borne diseases, locating sanitary facilities, and so on.

It is now readily apparent why, on some islands similar to Deke, salt-water intrusion into cultivated areas occurs. From first-hand observations, the favored area for growing food plants, taro in particular, is within the central depression (a geomorphic feature which formed between the boulder ridge and the lagoon sand berm). The usual practice is to remove the original sediment to about the ground-water level and refill the area with organic matter until a relatively thick humus soil is produced; planting takes place within this new soil. As time passes and the demand increases for additional food to support the community, the area of cultivation is gradually enlarged. On many islands the expansion was toward the ocean and over the reef-flat plate and the highly-permeable unit beneath. During the dry season, when little recharge is available to maintain the lens configuration, the greatest reduction in fresh-water storage occurs within the highly-permeable units. The fresh-water column decreases and the transition zone thickness increases resulting in a well-mixed brackish water zone underlying the food crop. With the strong tidal pumping action through the reef-flat plate, very saline water enters the root zone of the cultivated taro.

Water shortages experienced by island inhabitants during the annual dry season or during droughts, for the most part, could be avoided by properly locating wells and applying appropriate design criteria. The fresh-water nucleus of most lens systems is fairly stable even during extended times of little or no rainfall. With accurate mapping of the fresh-water lens, the resource could be sensibly developed to meet the long-term needs of the community.

If sensible decisions are to be made related to the practical solutions of water-related problems on atoll islands, then more information must be collected in order to gain an understanding of these complex groundwater-flow systems. Much was learned about the fresh-water lens of Deke and geologically similar islands, but the model presented in this paper must yet stand the test of time and the practicing hydrogeologists must learn a great deal more about the atoll island environment before such models can be applied universally.

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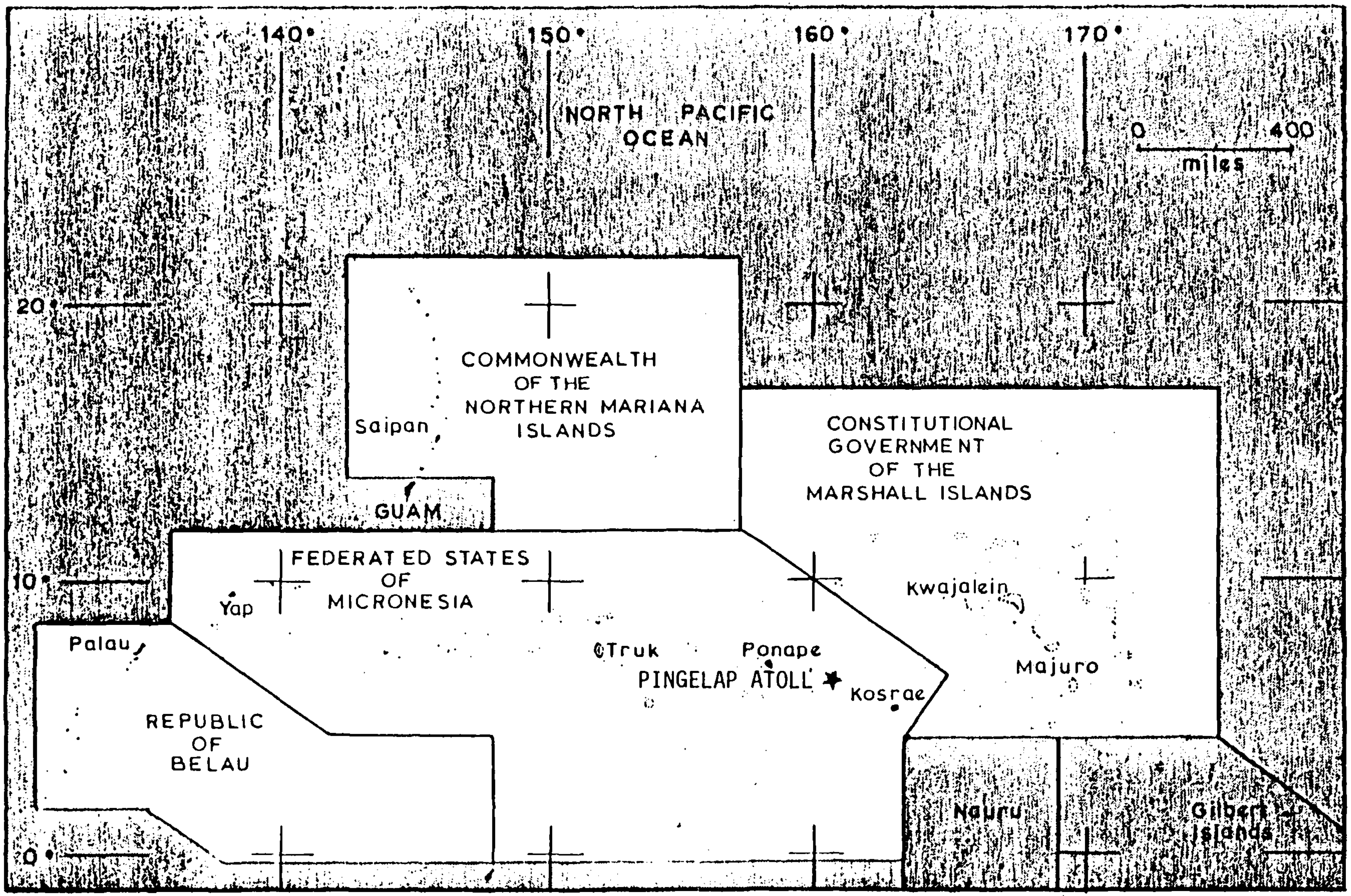


Figure 1. Map of Micronesia showing the location of Pingelap Atoll.

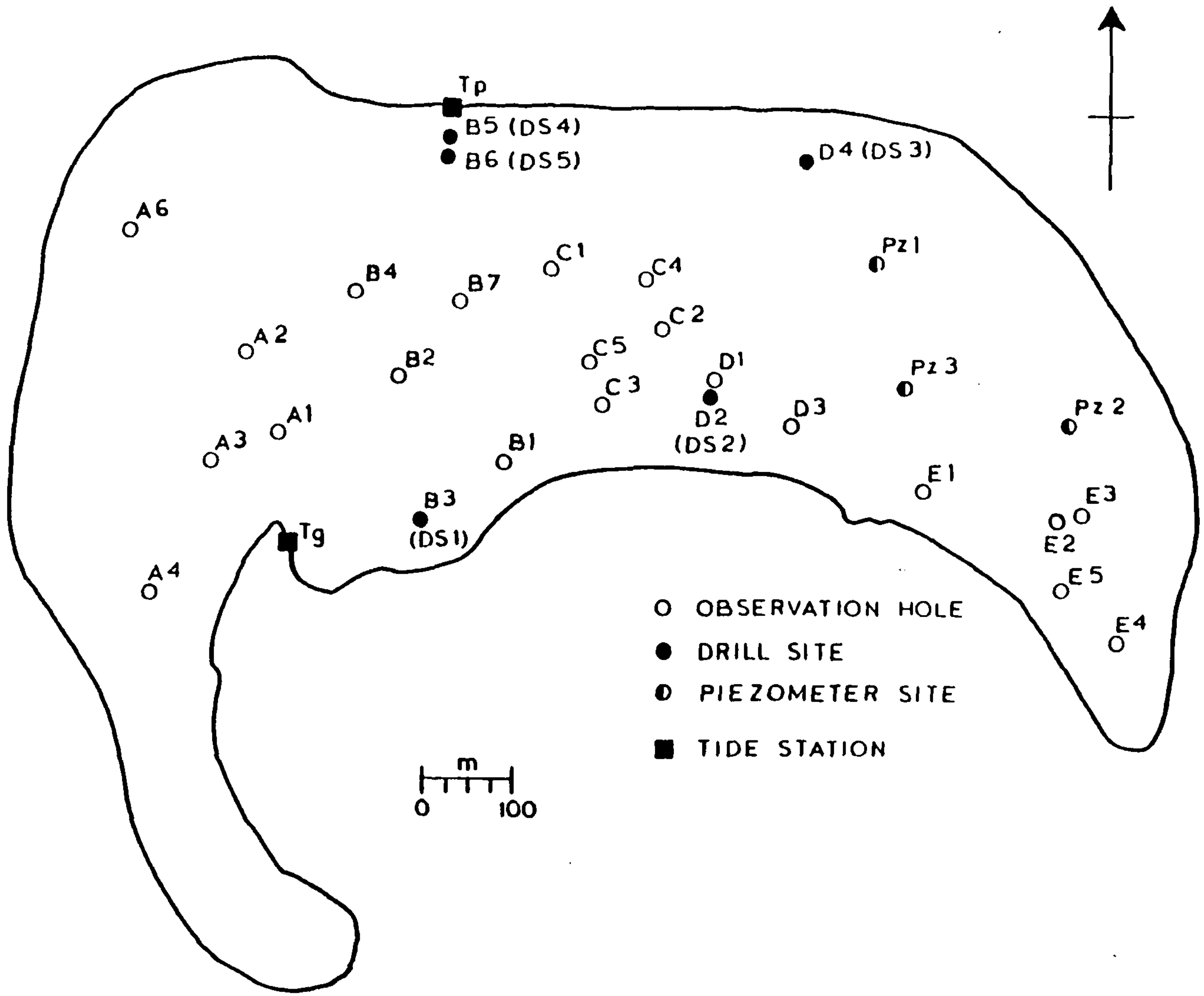


Figure 2. Map of Deke Island showing the location of water-level observation sites.

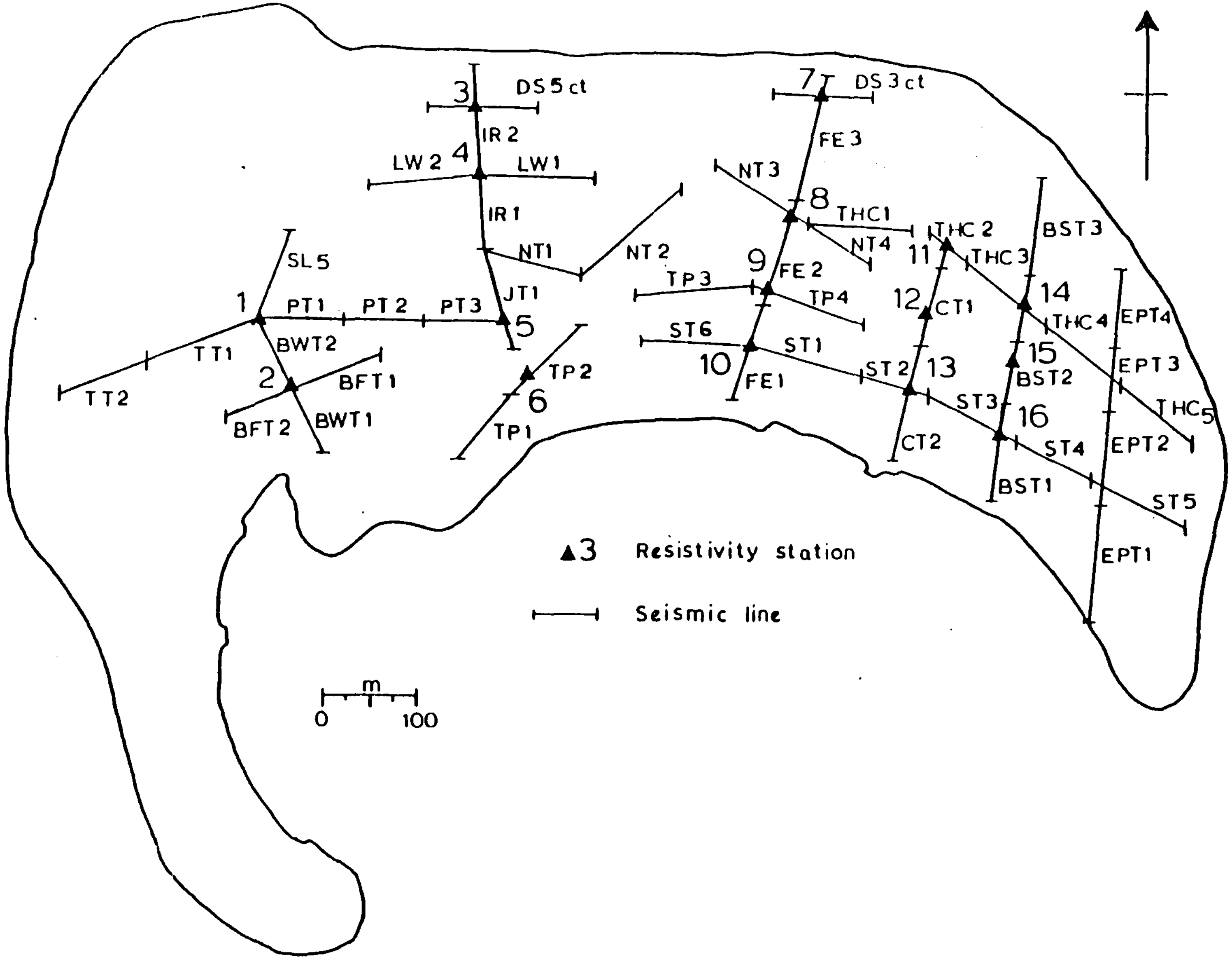


Figure 3. Map of Deke Island showing the location of seismic-refraction lines and resistivity stations.

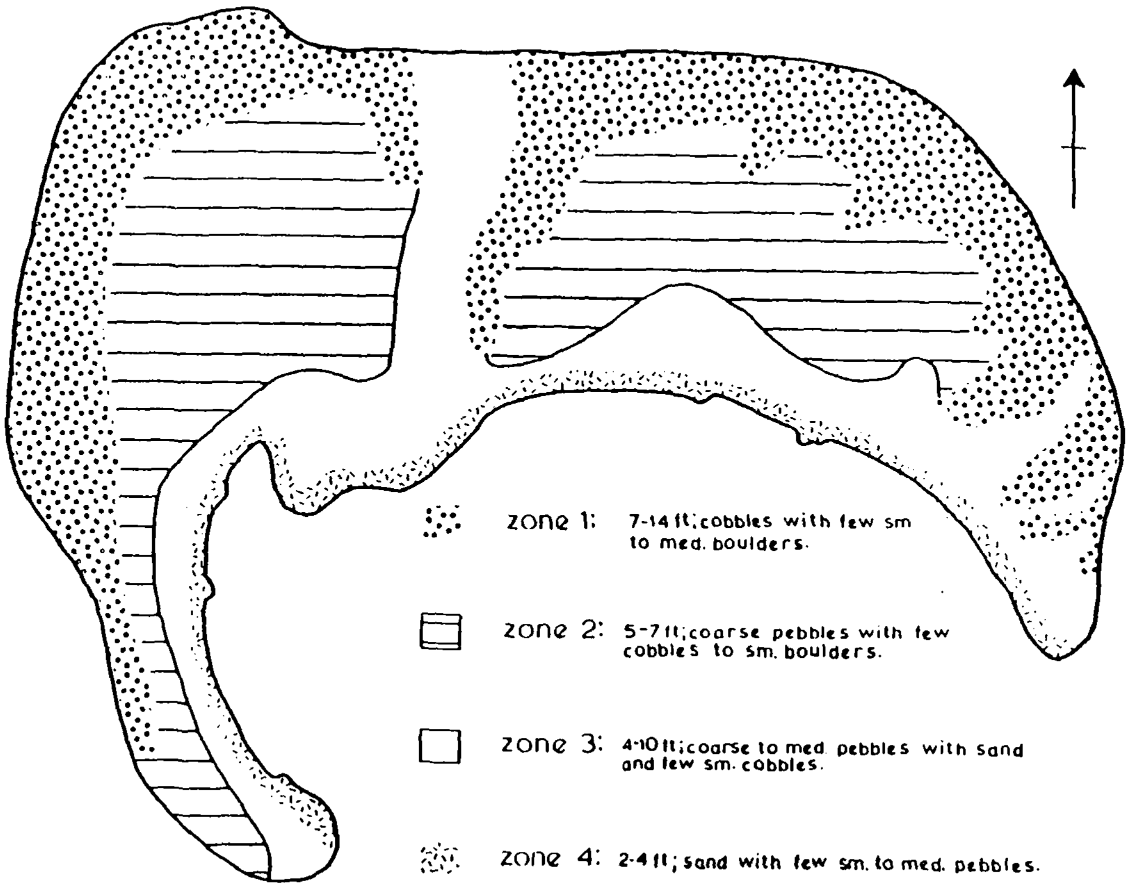


Figure 4. Surficial geological map of Deke Island. Each zone represents both a geological and a geomorphological component of the overall physical makeup of the island.

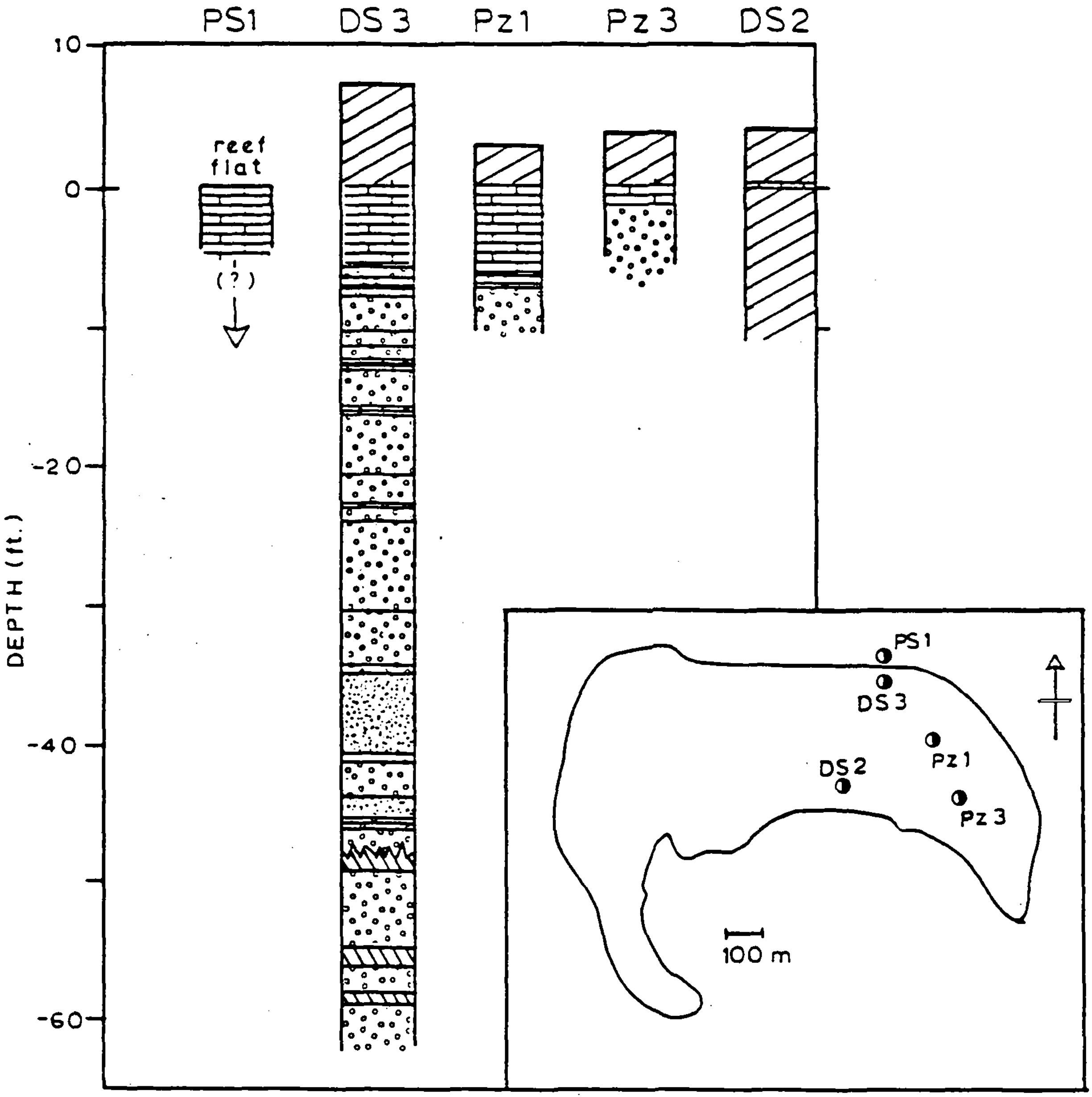


Figure 5. Geologic logs of cored boreholes located across the island. Note the lagoonward thinning of the reef-flat plate.

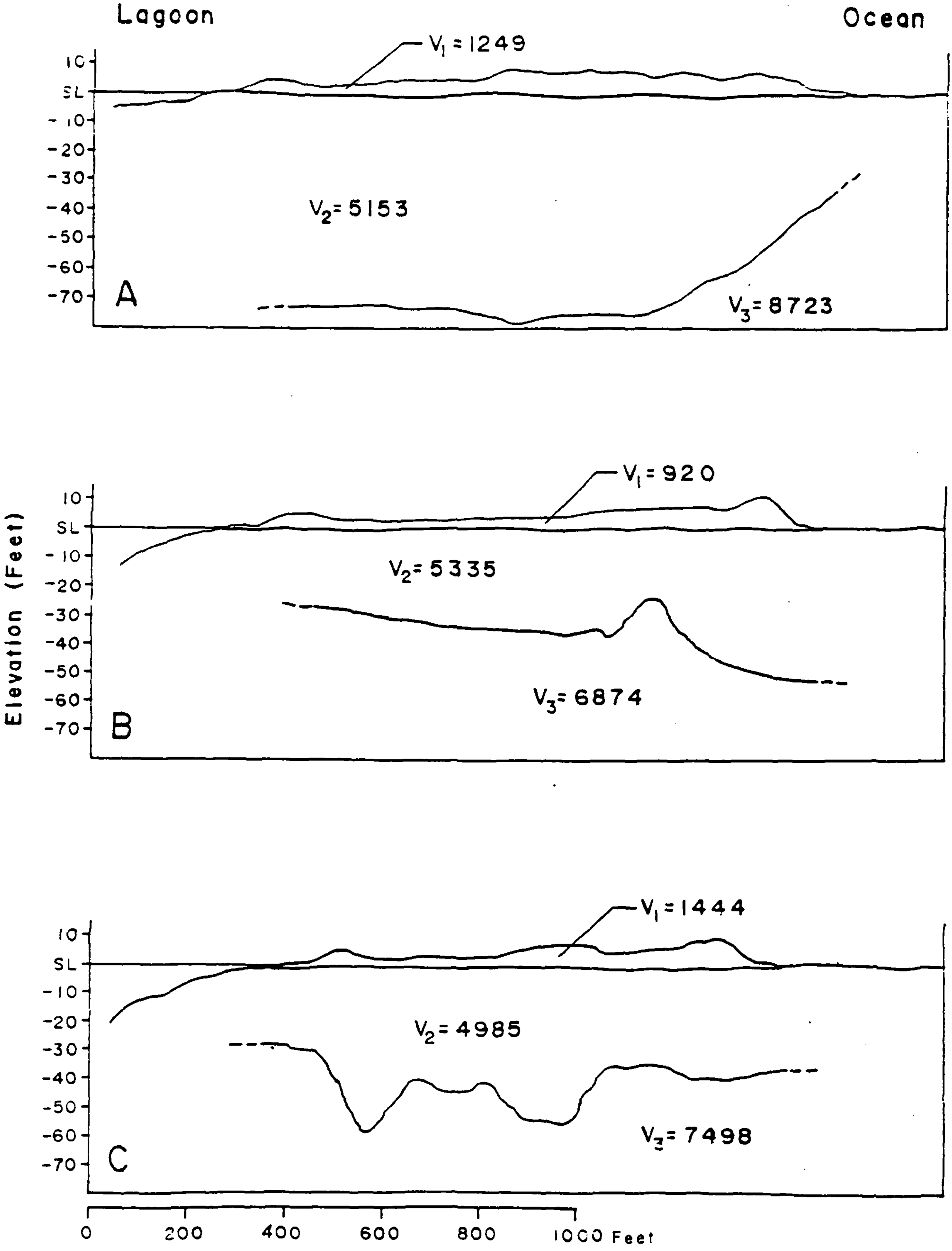


Figure 6. Seismic profiles across Deke Island. The profiles show a three-layer structure to the subsurface geology. The boundary between V_2 and V_3 corresponds to the contact between sediments beneath the reef-flat plate and the underlying *Halimeda* facies.

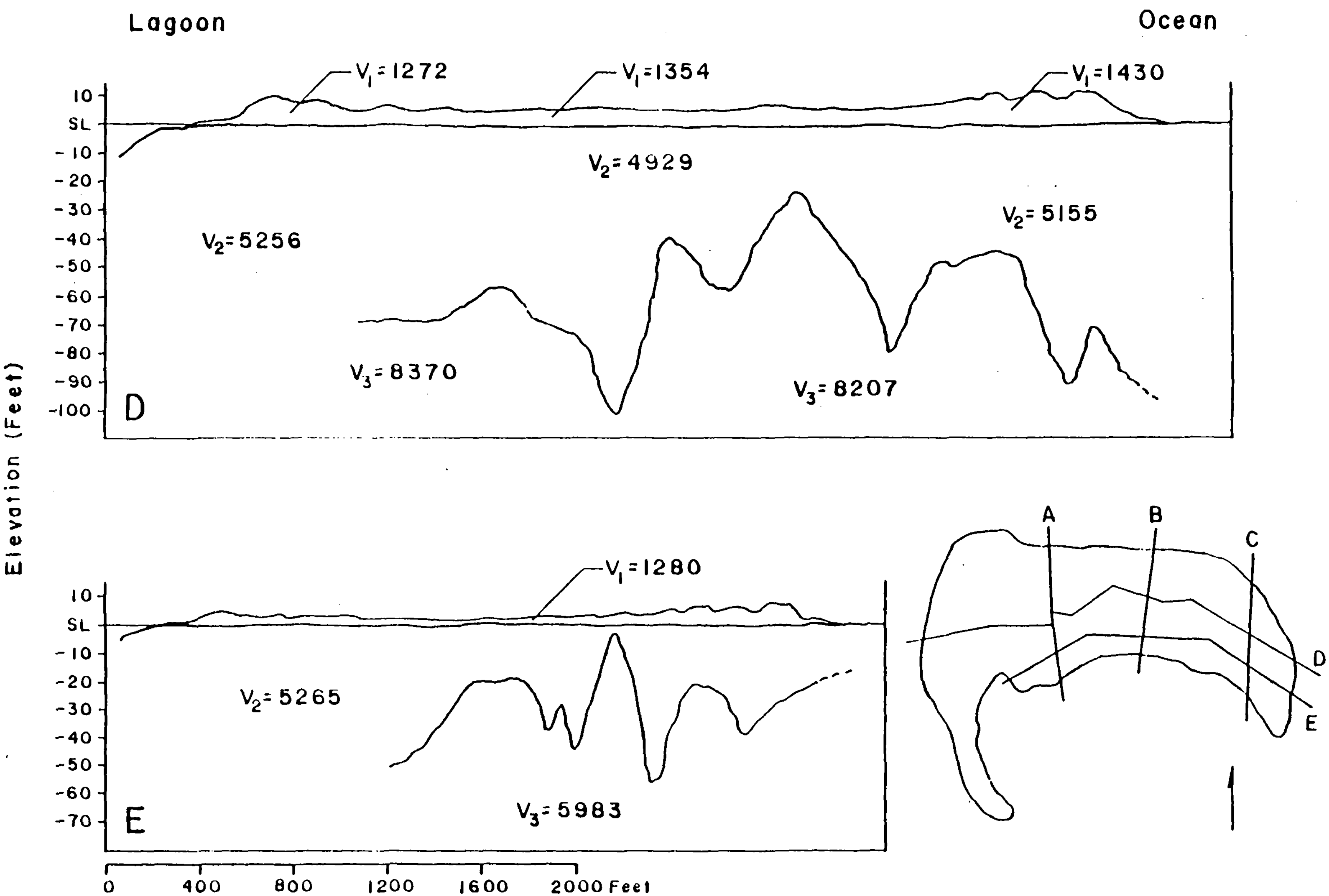


Figure 6. Continued.

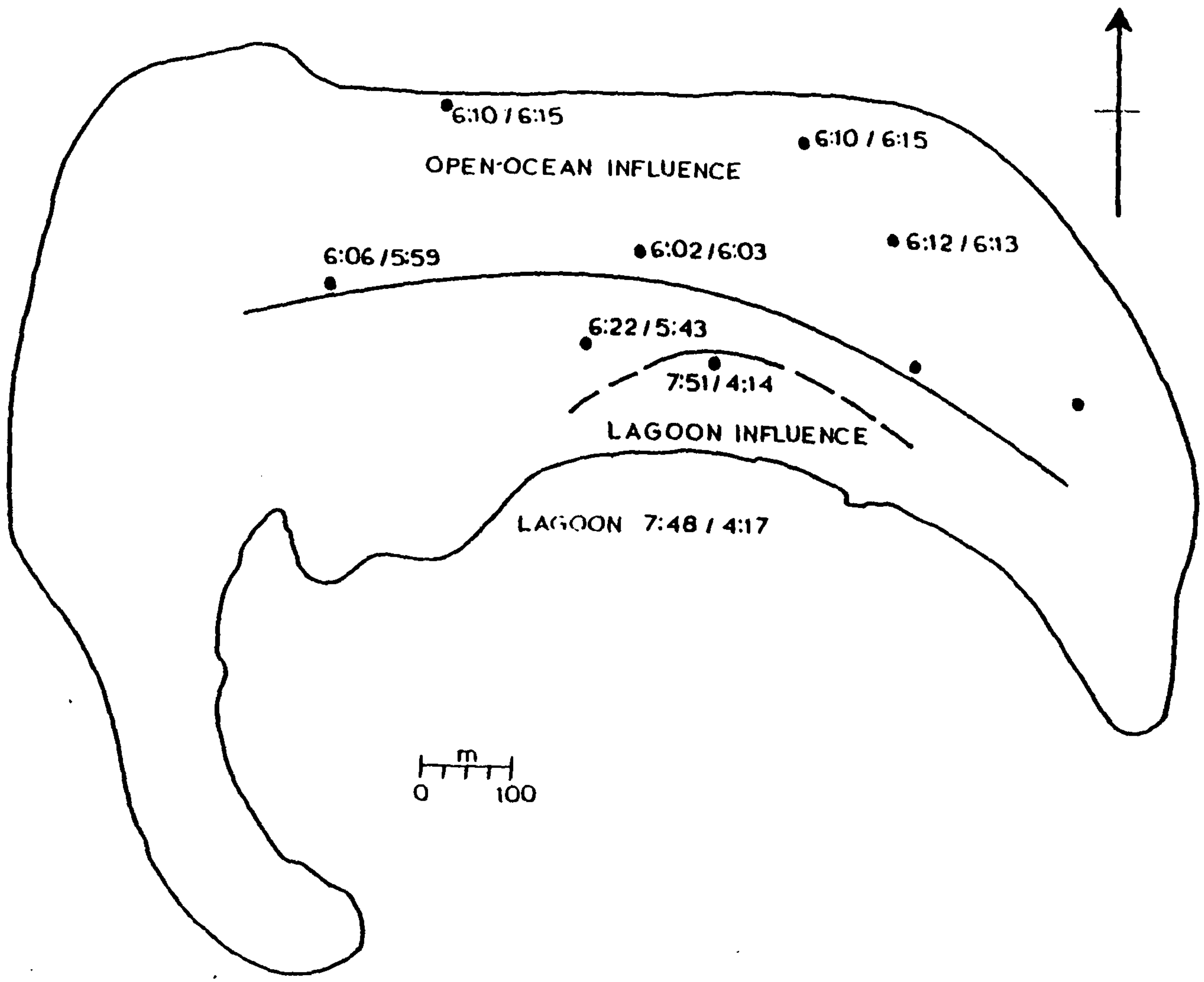


Figure 7. Map of Deke Island showing the geographical distribution of the time lag between tidal lows and highs. Note the time lay between the lagoon tidal oscillation and the open ocean fluctuation. This difference in response is due to the impedence of flow caused by the enclosing reef tract acting as a dam to the free exchange of water between the lagoon and the open ocean.

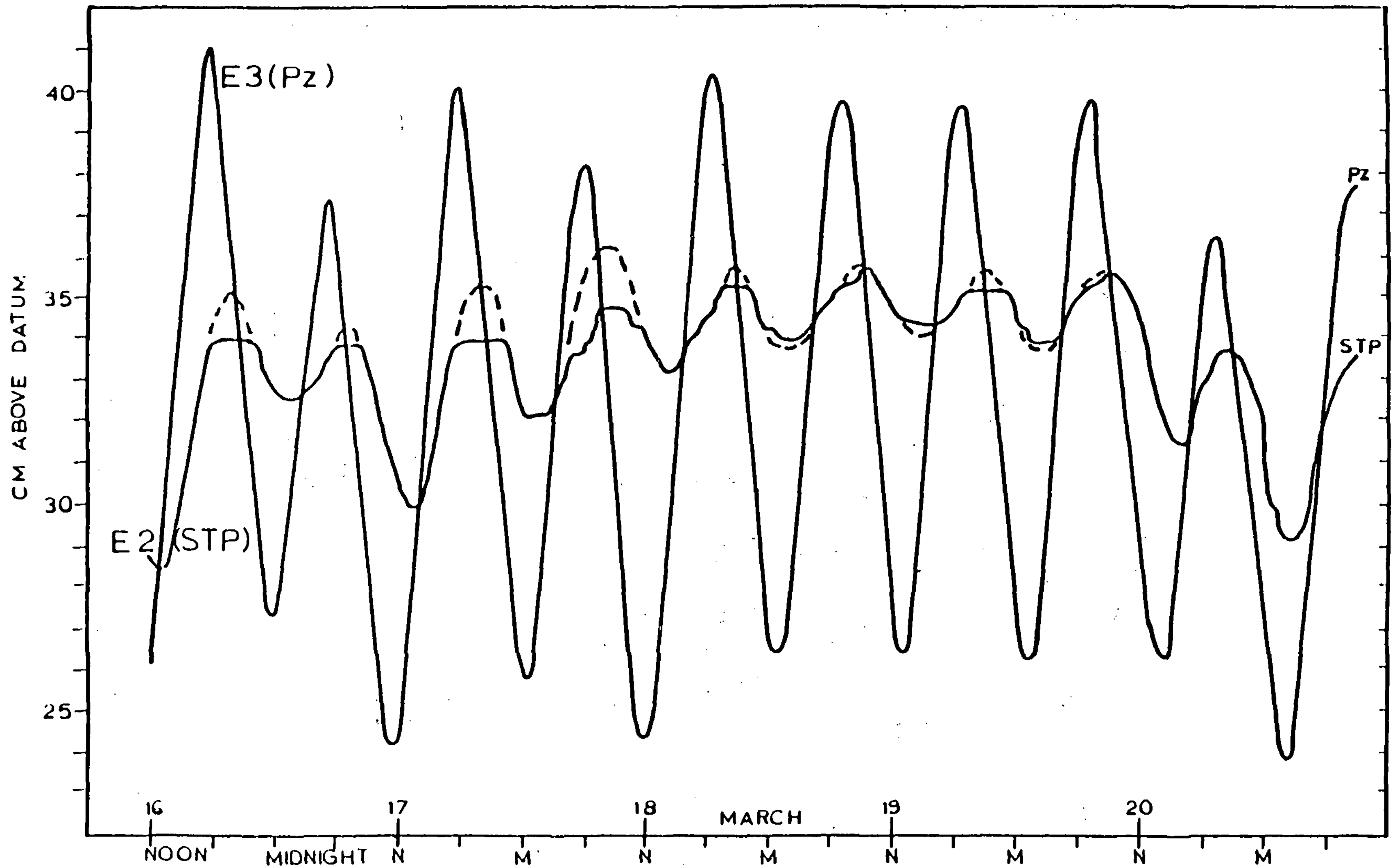


Figure 8. Simultaneous continuous recordings at two observation wells. E2 is a standpipe situated atop the reef-flat plate and E3 is a piezometer installed in a hand-dug well penetrating the reef-flat plate (see Figure 2 for location).

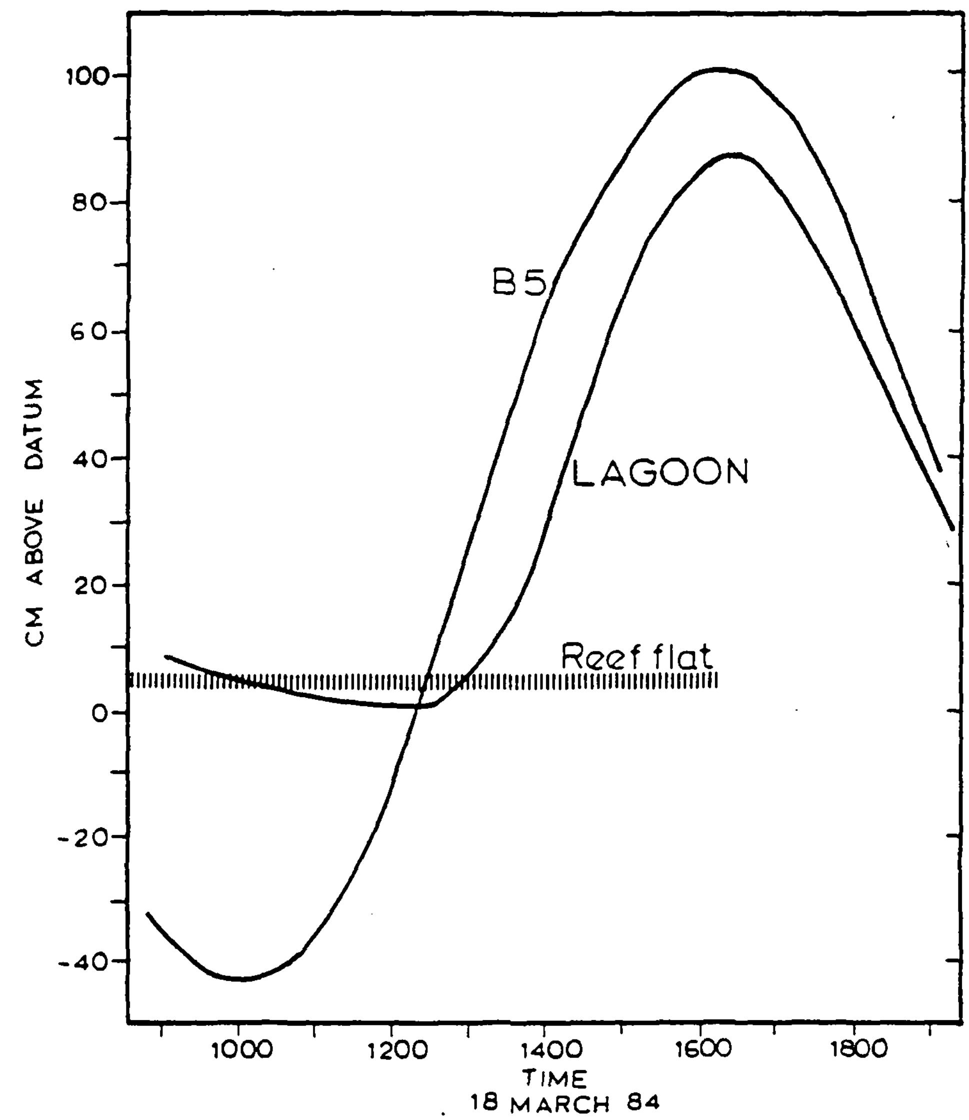


Figure 9. Hydrographs showing a tidal cycle in the lagoon and at a deep piezometer located near the ocean shore. Note the relative position of the reef flat and the truncation of the lagoon low tide.

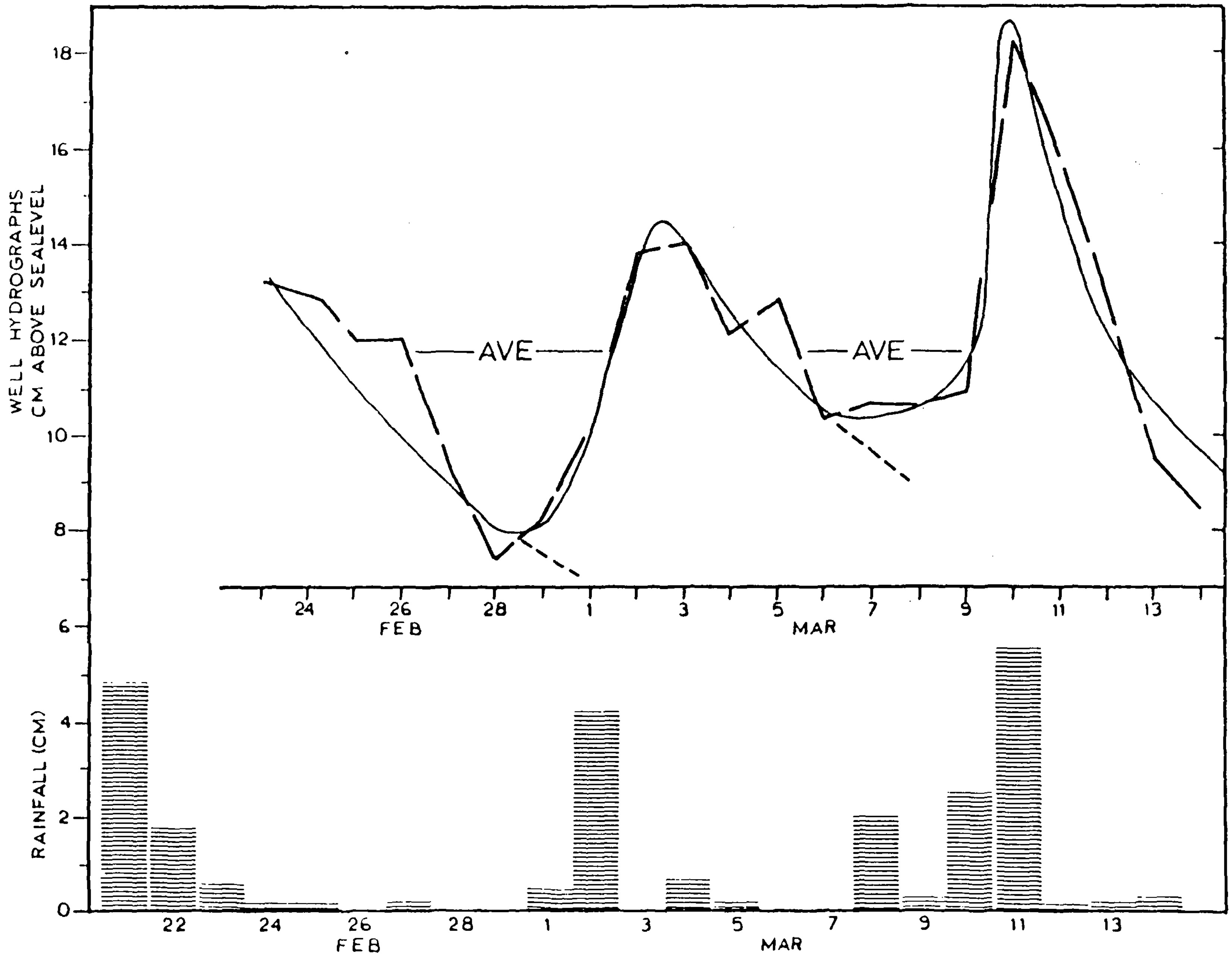


Figure 10. Fresh-water lens response to recharge derived from rainfall events. Note the configuration of the well hydrograph and its similarity to stream-flow recession curves.

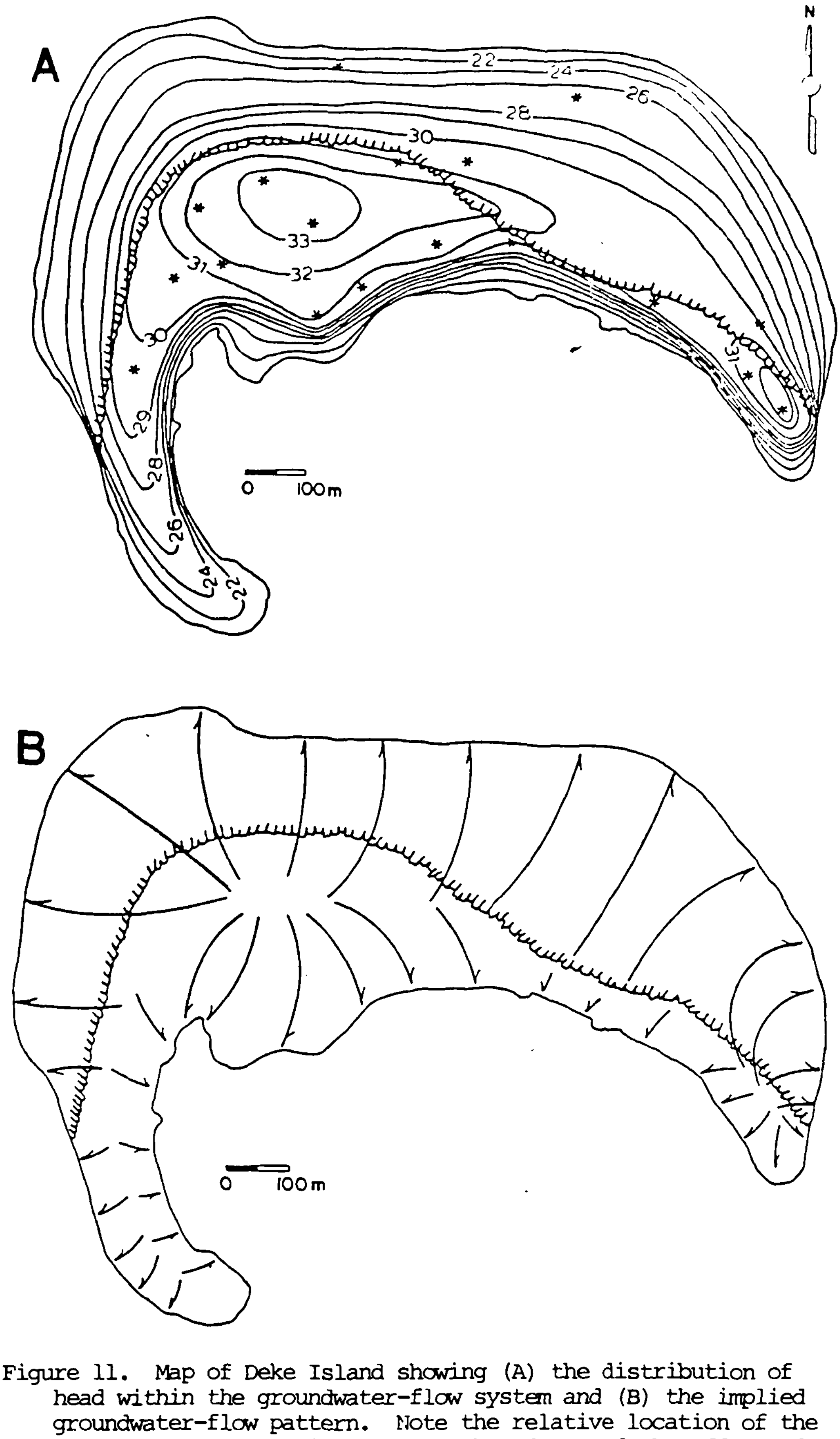


Figure 11. Map of Deke Island showing (A) the distribution of head within the groundwater-flow system and (B) the implied groundwater-flow pattern. Note the relative location of the reef-flat plate and its southern boundary and the affect of its presence on the occurrence and movement of groundwater.

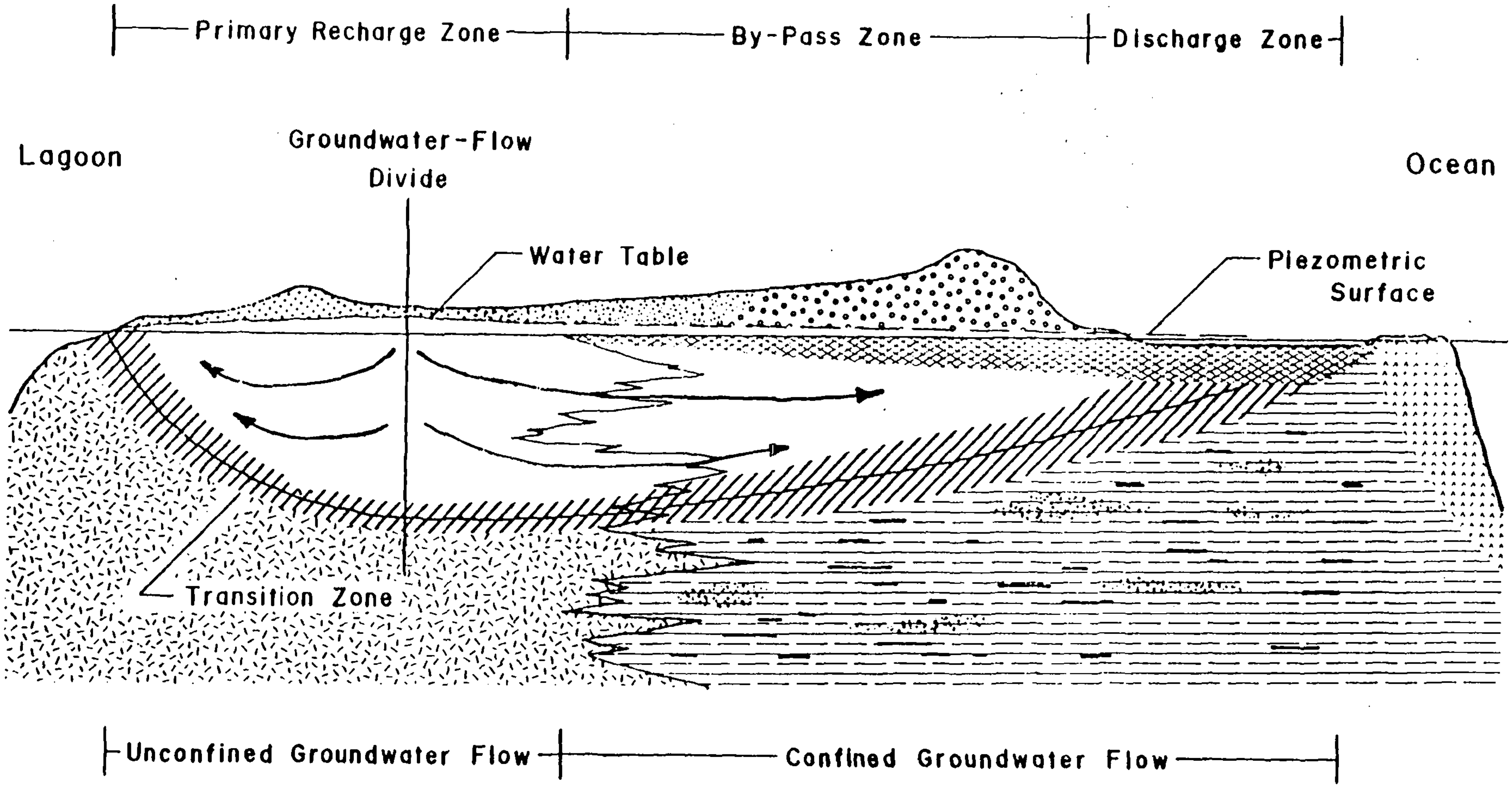
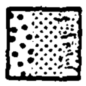
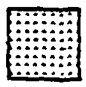
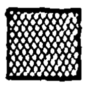
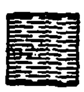
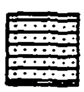


Figure 12. Conceptual model of the occurrence and movement of fresh groundwater within the hydrogeologic framework of an atoll island. See Table 1 for legend and brief description of each unit.

Table 1. Legend and brief description of stratigraphic units shown in Figure 12.

Unit No.	Symbol	Description
1		Unconsolidated sediment comprising Deke Island.
2		Reef struture.
3		Well indurated sediments of the hard layer (reef flat); Permeability is very low.
4		Unconsolidated to poorly consolidated sediments probably associated with back-reef deposition; Permeability is very high.
5		Mostly unconsolidated sand-size sediments probably deposited in the sand apron behind the reef flat; Permeability is high.
6		_Halimeda_ facies composed of poorly consolidated sand- and gravel-sized reef rubble; Permeability is very high.
7		Unit composition is unknown, may be associated with lagoon deposition; Permeability is probably similar to that of unit 5.
		Unit contact established by measurement.
		Hypothetical unit contact; represents a gradation between units.

A REVIEW OF SOME OF THE MORE IMPORTANT DIFFICULTIES ENCOUNTERED IN SMALL ISLAND HYDROGEOLOGICAL INVESTIGATIONS

by J.W. Lloyd *

ABSTRACT

Selected hydrological and hydrogeological controls are discussed. The importance of long-term rainfall trends and return drought periods are stressed, and the need for detailed recharge inputs emphasised. The difficulty of using groundwater head fluctuations for recharge and resource model calibration leads to the proposal that more attention should be paid to lens base fluctuations as a possible calibration factor. Ground layering is postulated as being one of the most important hydrogeological controls that may be encountered in a small island and examples of layering influences upon pumping-test data and saline groundwater level responses are given.

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1. INTRODUCTION

Small island hydrogeology naturally contains all of the elements that are encountered in the hydrogeology of a large unconfined coastal aquifer area. Many aspects of the groundwater conditions, however, are more accentuated in the small islands because of two important controls. These controls are:

(i) The very limited area and normally low elevation of small islands, which preclude the establishment of fresh groundwater bodies or lenses of any significant extent or thickness.

and (ii) The isolated maritime locations of small islands, which impose highly dynamic groundwater responses within the islands and thus make the quantitative study of conditions very difficult.

In many small islands such as those in the Pacific and the Caribbean a tropical climate exists with an inherent seasonality in precipitation. This gives rise to a certain dependence upon groundwater in dry seasons, through the lack of other suitable storage facilities, but in itself provides a further unpredictable hydrogeological control, namely the lack of reliability of precipitation and subsequent recharge.

In the ground, geological variations within a small island are likely to be more significant than in a large area simply because of the scale factor. Geological layering is a common feature of limestone islands resulting from variations in lithological deposition, diagenetic modification, caliche formation and variable permeability development. In volcanic islands geological inhomogeneity is the rule rather than the exception. Such variations complicate the establishment of fresh water bodies and control to a considerable extent the utilization of the groundwater resources.

The highly dynamic groundwater conditions in small islands influence the relationship between the fresh water body and the underlying saline waters. The dynamism accentuates mixing between the two groundwaters and thus reduces the amount of fresh groundwater available as a resource.

Within the very small island areas therefore there exist intricate hydrogeological inter-relationships that have become established over geological time periods but which are being rapidly changed over periods of a few years to meet the water demands of growing populations. The hydrogeological balances are being disturbed often without real understanding of the hydrogeological consequences or possible ecological repercussions. While the utilization of the groundwater resources must clearly proceed, the process will undoubtedly prove difficult in many islands and although the hydrogeological complexity may prove to be the over-riding factor, three other factors may also be important:

(i) Finance for a proper understanding of hydrogeological conditions can be difficult if not impossible to obtain.

(ii) The utilization of groundwater resources may often be taken to limits normally unacceptable in other aquifers.

and (iii) Long-term hydrological and hydrogeological data may not be available.

In this paper some aspects of the hydrological and hydrogeological controls and complexities that can occur in small islands are discussed. The purpose is to pose the difficulties and raise questions rather than to provide simple answers to the problems of a hydrogeological environment about which we know very little.

2. HYDROLOGICAL CONDITIONS

2.1 Hydrological Cycle

A simplified hydrological cycle for a small island lens may be given as follows:

$$P = E_i + R_f + E_s + R_c \qquad (1)$$

and

$$R_c = E_g + \Delta S_y + Q_f + Q_b + A_b + I_r + A_r \qquad (2)$$

where:

P	is precipitation
E_i	is precipitation intercepted and evaporated (interception)
R_f	is surface runoff
E_s	is evapotranspiration from the unsaturated zone
R_c	is recharge to the fresh groundwater lens
E_g	is evapotranspiration directly from the lens
ΔS_y	is the change in groundwater storage
Q_f	is the fresh groundwater flow from the lens
Q_b	is the component of fresh groundwater within the brackish groundwater flow in the transition zone at the base of the lens
A_b	is abstraction
I_r	return flows from irrigation
A_r	return flows from other abstractions

In the following discussion only the most generally important parameters are considered.

2.2 Rainfall

Rainfall data are probably the most comprehensive hydrological data available in small islands and form the fundamental data for the hydrological balance. Frequently one rain gauge on an island will have a comparatively long-term record. Irrespective of climate, rainfall distribution and intensity, and rain gauge location, three aspects of the precipitation can be of value in understanding the extent and changes in the configuration of fresh groundwater lenses. These are:

(i) Long-term rainfall trends

(ii) Drought return frequency

and (iii) The time-step to be used for the recharge balance.

Long-term rainfall data may be examined from the particular island under study or from a 'nearby' area. The value of the data is to determine indications of possible long-term changes in lens geometry. This is important not only in terms of how the fresh groundwater resource may be responding but also allows the particular study period data to be put into the long-term perspective, and helps in selecting starting conditions should groundwater modelling be contemplated.

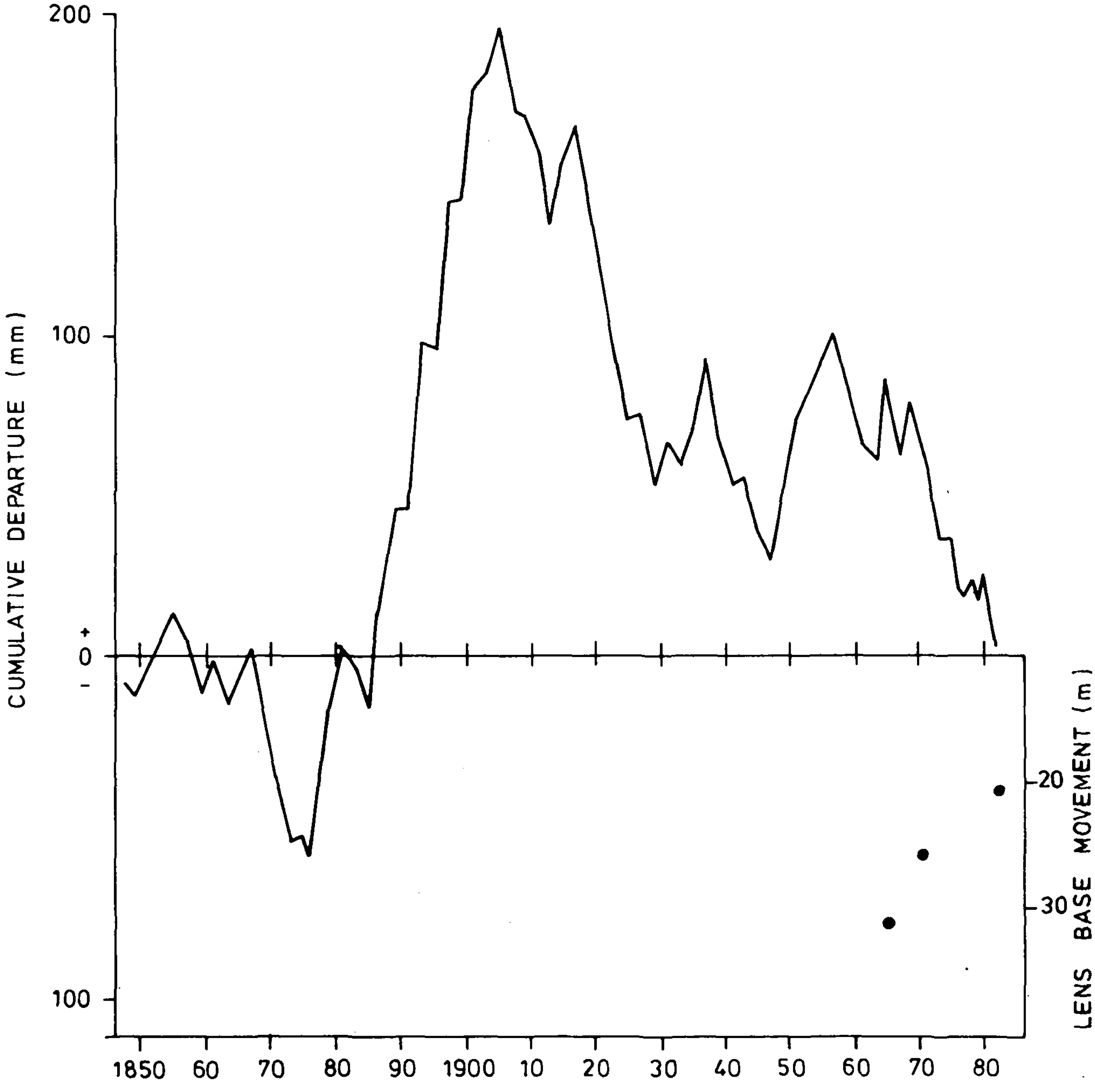
In very small islands long-term trends may be insignificant but where thick lenses can develop (say greater than 20m) long-term changes can underlie the dynamism induced by wave and barometric influences. In Fig. 1. the long-term rainfall trends for a limestone island in the Carribbean are shown. The decline in rainfall from the mid-1950's can be correlated with a 10m rise in the 600 mg/l isochlor between 1963 and 1980 where the lens thickness was 30 m (in 1963). In this particular case the long-term rainfall data trend helped in showing that over-pumping was not causing diminishment in the fresh water resource.

Drought return frequency is a vital statistic for any small island groundwater appraisals: the smaller the island and lens, the more important is the statistic. Such information clearly helps in determining the limit of a lens resource under unfavourable recharge conditions. Standard probability methods can be applied (Wilson, 1971) but the application of the results in the resource assessment may pose difficulties. The type of results obtained are shown in Fig. 2, for Kiribati.

The rainfall data that are required for an island recharge balance may depend upon other data factors such as the availability of evaporation data. Howard and Lloyd (1979) have shown that daily recharge balances are more reliable than those for longer periods but such balances are probably unrealistic for many small islands where climatic data are limited and the lack of groundwater hydrograph data precludes the possibility of comprehensive recharge-hydrograph correlations (see below). In many small islands annual rainfall data are used in balance determinations (Stanley, 1978) and are substantiated by annual hydrochemical balances (Jordan and Fisher, 1977, Vacher and Ayers, 1980). Because of the seasonality in lens decay, however, it would appear sensible to use monthly rainfall data, at least, as the basis for a recharge balance.

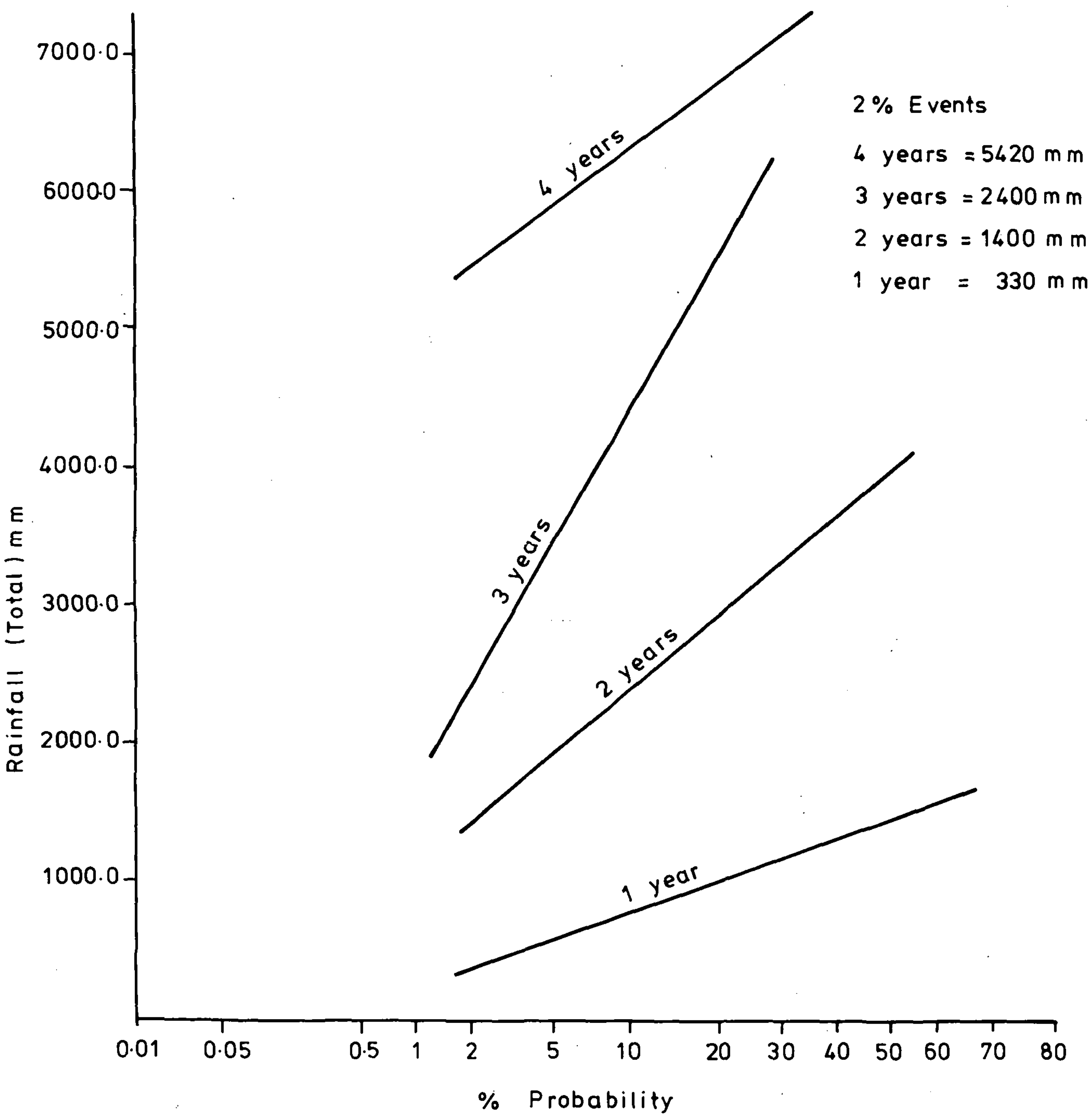
2.3 Interception

Precipitation by the leaves of trees has long been recognised as an important parameter in the more tropical of the small islands (West and Arnell, 1976). The large fronds of the coconut trees are particularly influential in intercepting precipitation which is subsequently evaporated. West and Arnell in their work in Mali found that interception amounted to some 15% of the total precipitation.



CUMULATIVE DEPARTURE FROM MEAN OF ANNUAL AVERAGE ISLAND RAINFALL AND ASSOCIATED LENS BASE MOVEMENT

FIGURE 1



DROUGHT PERIOD PROBABILITY FOR TARAWA, KIRIBATI

FIGURE 2

In studies in Tarawa a value of 7.5% was used by Lloyd et al. (1980). The value for interception are clearly significant and the subject could be studied further to advantage.

2.4 Runoff

Runoff is one of the most difficult factors to determine in the hydrological balance of a small island. Apart from in some of the more rugged volcanic islands and geologically older limestone islands surface water courses are not common. The low elevation, lack of clay soil formation and development of high permeability in limestone islands militate against the development of water courses. Channelled surface runoff does not readily occur and therefore cannot be easily gauged. When groundwater heads are low most rainfall reaching the ground enters the soil profile ; however, with high heads near to the ground surface, sheet runoff can occur with intense rainfall and is a feature of many low elevation Pacific atolls. In calculating water balances for Kiribati Lloyd et al. (1980) found that it was necessary to attribute 90% of rainfall as runoff when the amount of rainfall reaching the ground exceeded 260 mm in a month, which in fact is a fairly rare event.

2.5 Recharge

As discussed in Section 2.2. recharge may sensibly be calculated at least on a monthly basis. The procedures adopted usually entail soil moisture balance calculations related to effective rainfall and evaporation (Penman, 1950). In this case the effective rainfall is usually the rainfall minus the intercepted rainfall in that runoff may not be easily quantified and may have to be removed within the balance in respect of groundwater head response. A typical balance is shown in Table 1.

While the methodology of the soil moisture balance approach to recharge is straight forward and it is probably the most easily applicable to small islands, there are certain inherent weaknesses in its application in any hydrogeological environment (Wellings and Bell, 1982). During dry seasons the method accentuates soil moisture deficits and in consequence delays the onset of recharge. Lloyd et al. (1980) found it was necessary to allow 10% of effective rainfall to instantaneously enter the ground after dry periods in order to avoid a delayed ground water head recovery in atoll lenses. Similar rapid recharge inputs have

Table 1. Example of part of an initial recharge balance for a lens

C = 87 mm D = 115 mm

10-day Period		$p - E_i$	E_p	Δ	Δa	Σ
	1	-	24.3	24.30	-	115.00
Nov	2	5.17	26.2	21.03	-	115.00
	3	12.17	14.3	2.13	-	115.00
	1	13.23	17.9	4.67	-	115.00
Dec	2	34.68	8.8	-25.88	-25.88	89.12
	3	-	21.2	21.20	2.12	91.24
	1	107.35	18.5	-88.85	-88.85	2.39
Jan	2	202.26	13.3	-188.86	-188.96	-186.57
	3	-	18.0	18.00	-	18.00
	1	51.66	26.9	-24.76	-24.76	-6.76
Feb	2	41.00	22.3	-18.70	-18.70	-18.70
	3	-	28.3	28.30	-	28.30
	1	1.84	41.0	39.16	-	51.30
Mar	2	3.14	37.9	34.76	-	86.06
	3	30.06	52.2	22.14	3.06	89.12
	1	13.57	50.2	36.63	3.66	92.78
Apr	2	5.04	64.3	59.26	5.93	98.71
	3	-	87.7	87.70	8.77	107.48

Total recharge = 212.03 mm

P = rainfall weighted over area, E_i = intercepted rainfall

$P-E_i$ = effective rainfall, E_p = potential evaporation

Δ = $E_p - (P - E_i)$, Σ = progressive soil moisture balance

Δa = 0.1 where > C and <D, where Δ is negative no adjustment

C = root constant = field capacity x root depth, D = maximum deficit.

been found necessary in other limestone terrains (Fox and Rushton, 1976).

Apart from obvious defects in methodology the problems of assessing recharge in small islands are inherently related to poor climatic data and the estimation of evaporation. Penman (1948) or Thornthwaite (1948) evaporation data tend to be used. The former is difficult to apply because of the number of parameters required while the latter, which only uses temperature, can under-estimate evaporation in hot sunny climates.

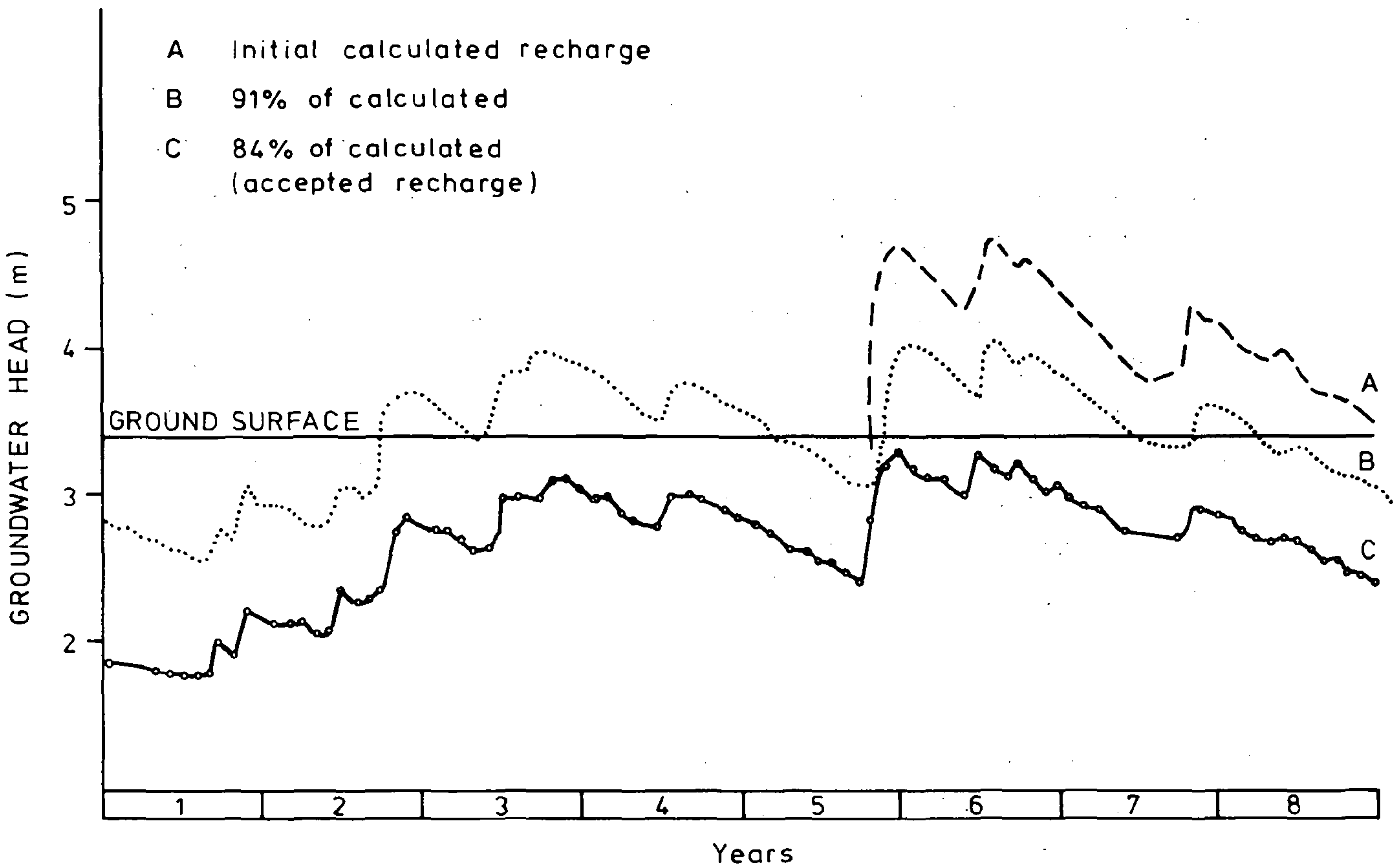
Within the soil moisture balance the deficit (C and D in Table 1) values are normally not known so have to be estimated using information from similar soil/geology terrains. This coupled with a poor evaporation estimation can result in gross errors in recharge calculations.

One of the saving features in the assessment of recharge in small islands, however, is the normally shallow depths to groundwater. In determining recharge therefore and modelling groundwater head response the ground surface provides an excellent upper head boundary that with over-estimations of recharge becomes effective fairly rapidly and provides a means with which to empirically modify the estimation. In Fig. 3. a typical modification to recharge is shown.

The empirical modification of recharge with respect to the ground surface is not only necessary because of poor recharge estimation but is also necessary because of groundwater hydrographs are frequently non-existent or difficult to interpret in the dynamic conditions as discussed below.

Any modification in the recharge infers that the transmissivity - specific yield relationships are known for the aquifer. In any aquifer this is difficult but as is also discussed below it is particularly so in small island lenses.

In most hydrogeological environments the recharge element is a resultant function of moisture evapotranspired from the soil zone. While this is also true of small island lenses the shallow depth to the groundwater surface must allow direct evapotranspiration from the lens by trees particularly at lens edges. In island lenses little is known about this



GROUNDWATER HEADS MODIFIED TO ISLAND GROUND LEVEL BY ADJUSTING RECHARGE INPUT

FIGURE 3

feature which must effect the usable water resource, although Chidley and Lloyd (1977) have invoked evapotranspiration directly from the groundwater body by mangroves in the Cayman Islands.

3. HYDROGEOLOGICAL CONDITIONS

3.1 Introduction

In this section attention is drawn to the inhomogeneity of ground conditions influencing island lenses and the various dynamic factors effecting the groundwater heads. The combination of these two controls poses considerable hydrogeological difficulties.

3.2 Layering in the Ground

Layering in the ground is probably one of the most important aspects of hydrogeology and is one of the least understood. In sedimentary materials the layering is largely depositional and lithological, although in limestones solution layering or fissuring is often predominant. In volcanic terrains layering also tends to be depositional but can be related to preferential lava chilling etc. In many small islands layering is a common and complicating feature as depicted on Fig. 4 which shows a geological cross-section from Enjebi Island in the Enewetak Atoll of the western Pacific.

Ground layering normally gives rise to permeability-porosity layering, the importance of which will depend upon the relationship of lens size to the degree and frequency of layering. Obviously the smaller the lens the more important will become the influence of small scale and frequent layering. In hydrogeological terms the layering is significant in a number of ways among which are:

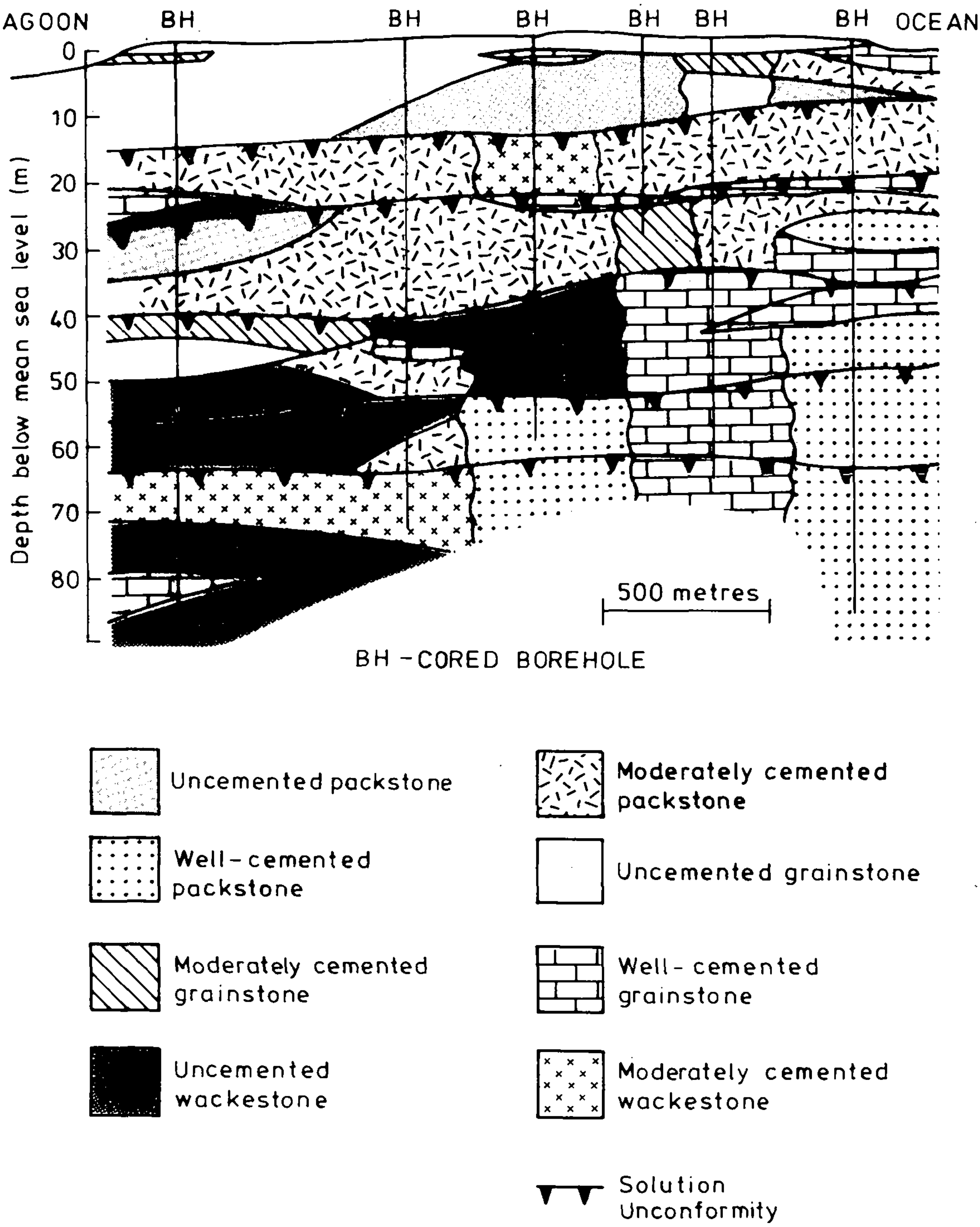
(i) Its determination may require comprehensive geological investigation (with all the financial connotations).

(ii) It can make geophysical interpretation difficult.

(iii) It complicates groundwater hydrograph response.

(iv) It effects groundwater hydraulics such that pumping-test data can be difficult to interpret.

(v) It may control to a marked degree the response of saline groundwater to fresh water abstractions.



AN EXAMPLE OF GROUND LAYERING FROM THE ENEWETAK ATOLL

FIGURE 4

The problems of geological and geophysical investigations are outside of the scope of this paper except to note that the geological section shown on Fig. 4 is based on coring and gives an indication of drilling frequency and depth that may be necessary for a comprehensive geological understanding. Geophysical aspects of permeability layering, particularly with respect to fresh-saline groundwater, conditions, have been outlined by Barker and Griffiths (1981), while for example, Bugg and Lloyd (1976) and Jacobson and Taylor (1981) give an indication of the situation in small islands.

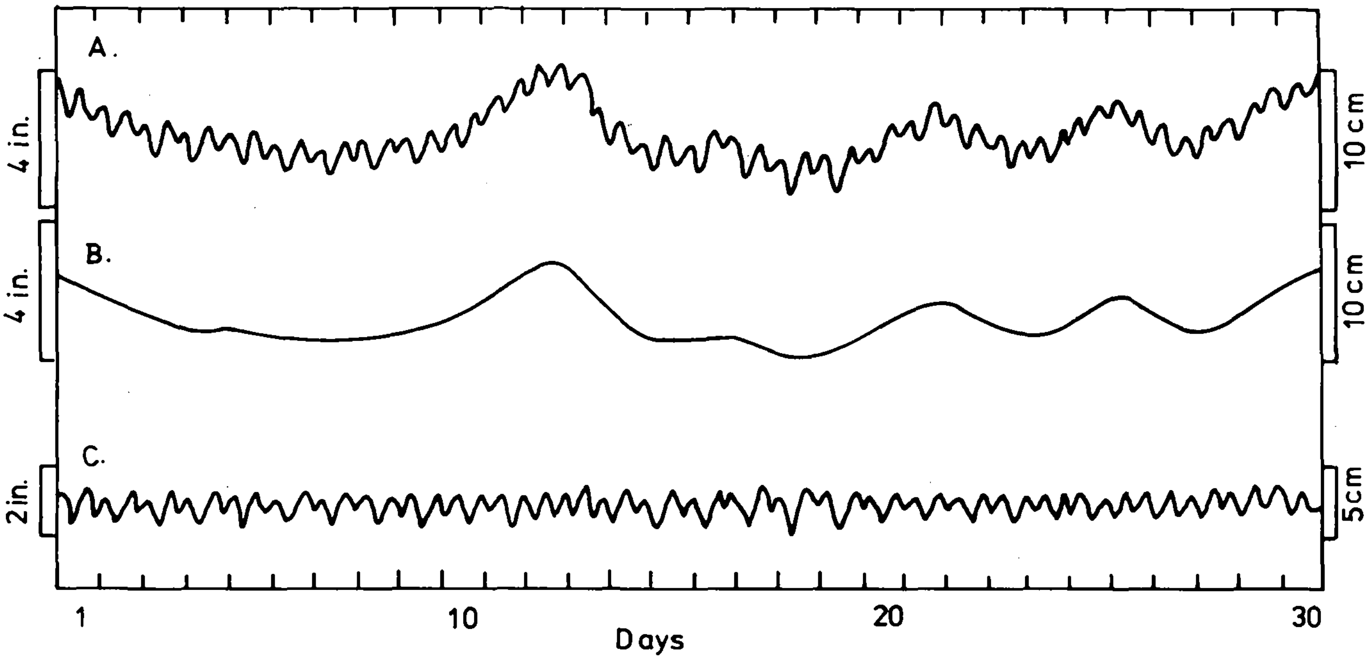
The other influences that may relate wholly or in part to layering are discussed below within the context of other general hydro-geological features of small island lenses.

3.3 Groundwater Head Fluctuations

In most hydrogeological studies fluctuations in groundwater heads are used either to calculate recharge directly (Freeze and Cherry, 1979) or to provide a calibration control in groundwater resource modelling (Rushton and Redshaw, 1979). In such studies the head fluctuations are predominantly a function of the recharge, transmissivity and storage, but in small islands fluctuations can be over-whelmingly complicated by tidal and barometric influences.

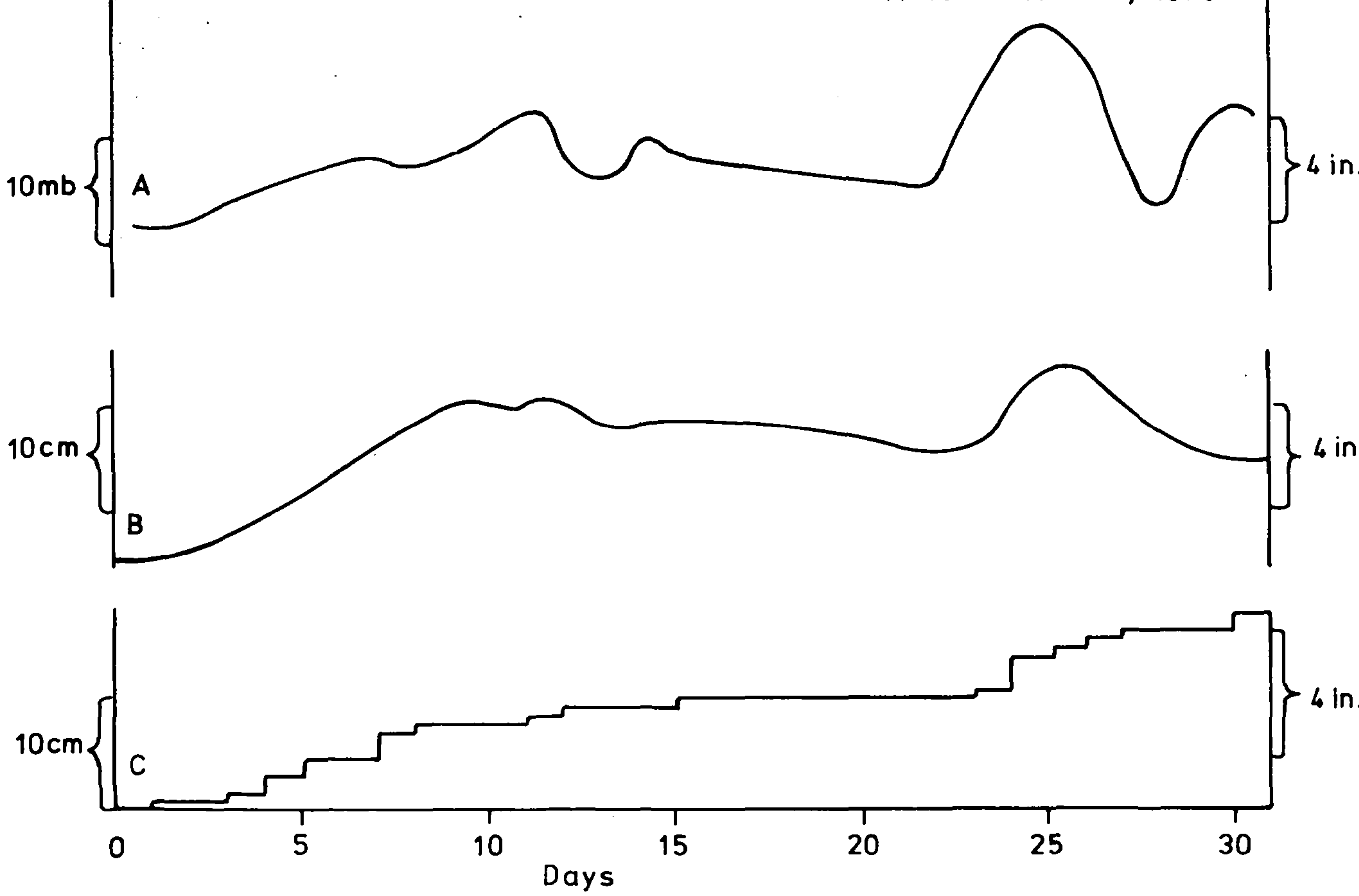
On Fig. 5 groundwater head fluctuations are shown from the Devonshire lens in Bermuda. Filtering of the tidal influences shows a sequence of positive residual responses that may normally be assumed to ensue from recharge. Vacher (1978), however, has shown that the residual responses are in part horizontally transferred, pressure changes propagated by isostatic adjustment in the oceans to barometric changes that may or may not occur concurrently with precipitation and recharge as indicated in the lower part of Fig. 5. The head response to two possible effects obviously poses problems in understanding recharge and denies the modeller one of his most useful calibration tools unless the barometric effects can be filtered-out or incorporated in the model, which is not easy (Ayers and Vacher, 1983).

The situation can be further complicated by ground layering. Wheatcraft and Buddemeier (1981) have demonstrated that vertical responses



GROUNDWATER HYDROGRAPHS FROM BERMUDA. A-NATURAL HYDROGRAPH, B-RESIDUAL HYDROGRAPH FILTERED FOR RESPONSE TO WAVES, C-RESPONSE TO WAVES

AFTER VACHER, 1978



GRAPHS SHOWING: A-INVERTED ATMOSPHERIC PRESSURE, B-FILTERED GROUNDWATER HEAD, C-CUMULATIVE RAINFALL.

GROUNDWATER HEAD FLUCTUATIONS WITH RESPECT TO WAVES, BAROMETRIC EFFECTS AND RAINFALL.

FIGURE 5

to oceanic induced pressure changes are more important than horizontal responses in a layered atoll where high permeability layering underlies lower permeability ground. Whether this is so if the layering is reversed is not clear.

The highly dynamic hydraulic conditions in small island lenses raises the question of the value of groundwater hydrograph data, particularly where only limited data are available (Bugg and Lloyd 1976). It would be interesting to examine in more detail isochlor distribution changes induced by the various influences on the base of a lens to ascertain whether this latter type of data may be more valuable than the traditional head data in terms of recharge calibration. The collection of such data, however, also poses problems as discussed below.

3.4 Aquifer Characteristics

Lithologies of certain small islands allow the determination of aquifer permeability by laboratory testing of cores but in the majority of cases reliance is placed upon some form of pumping-test data analysis. Inevitably difficulties exist both in the execution of testing and in the data interpretation.

Three points merit discussion:

(i) Test well depth with respect to the depth to saline groundwater
(ii) Length of testing with respect to groundwater head fluctuations and the onset of delayed yield
(iii) Drawdown response with respect to layering.

There is frequently a reluctance to drill fully penetrating test wells to a lens base in small islands. The reluctance stems from the fear of creating an artificial preferential permeability path which may allow upward saline groundwater movement into the fresh groundwater. Whether in fact significant flows and contamination does result is difficult to ascertain although as discussed below hydraulic disequilibrium within a lens may provide the right differential head conditions within a fully penetrating well. Because partial penetration of test wells is practiced, the use of partial penetration analyses (e.g. Hantush, 1962) tends to be used (Wheatcraft and Buddemeier, 1981) : however, whether the inherent assumptions of the methods are applicable in layered ground is open to question.

With respect to the length of testing some of the difficulties encountered are illustrated on Fig. 6. While permeability is an important parameter to determine from testing, specific yield is clearly equally important but may normally require several days pumping to be established. As would be expected (Section 3.3) the drawdown response is complicated by pressure head fluctuations which can prove extremely difficult to filter out bearing in mind the propagation direction complexities discussed in Section 3.3.

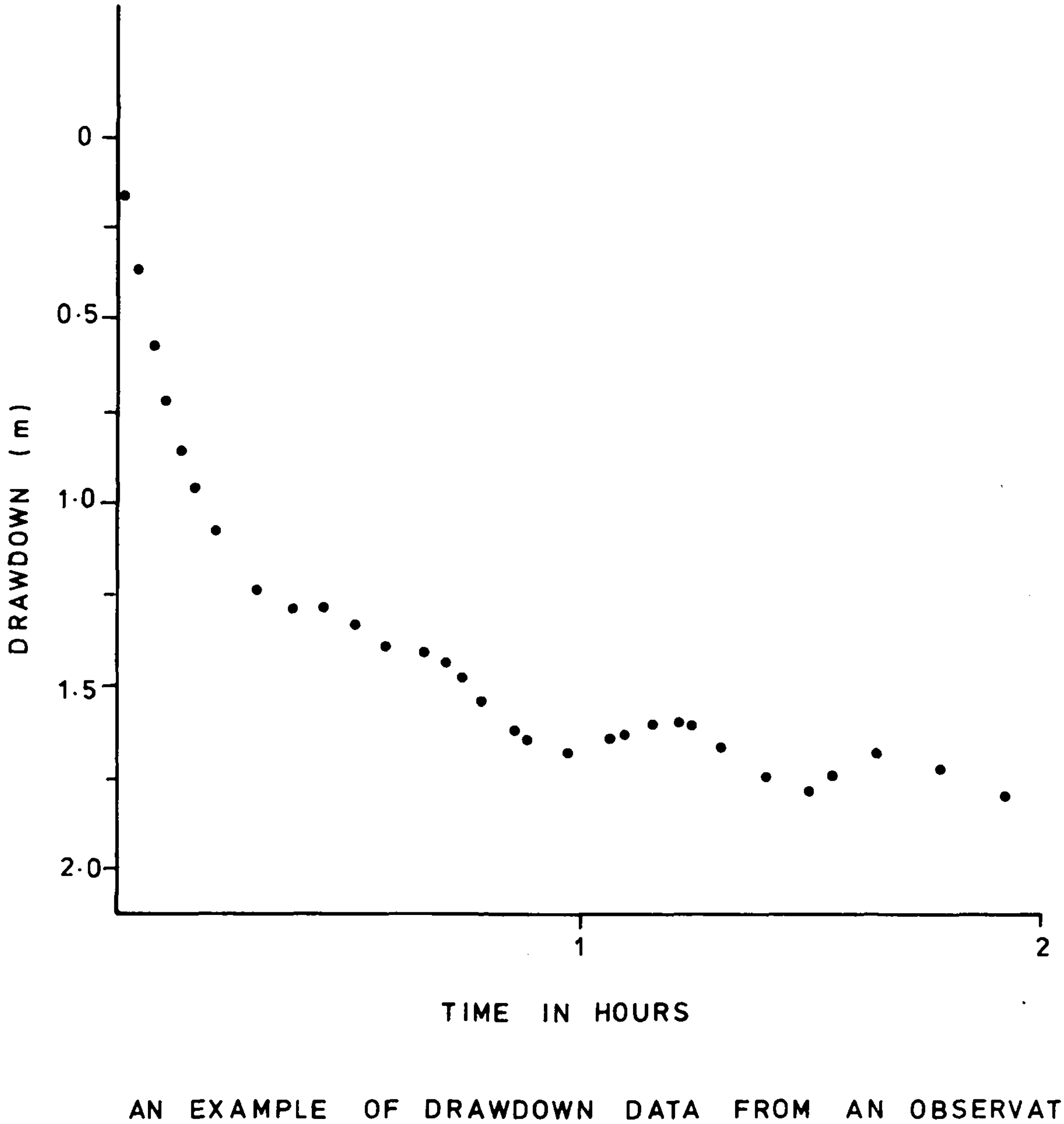
In practice it would appear that in many small island lenses the determination of specific yield is not feasible from pumping-test data even through the facilities of digital radial-flow models. If this proves to be the case then short-period permeability testing (possibly steady state) may be appropriate with specific yield determination being provided by trial and error through a distributed time-variant resources model (Chidley and Lloyd, 1977). This method, however, implies a good understanding of recharge particularly, which in itself is difficult as discussed in Section 2.5.

Irrespective of oceanic pressure effects during a pumping-test period there also exists the problem of ground layering and its consequent influences upon drawdown response. On Fig. 7 the drawdown response from a set of nested piezometres adjacent to a pumping well in a limestone aquifer is shown. The differences in drawdown for the different permeability layers are to be expected but are difficult to analyse for permeability because of the need to proportion the total pumping flow to individual layer flows. More important is the inference for drawdown responses in open pumping and observation wells. In such wells, that are the norm in small islands (and indeed in most aquifers), the multiple piezometer responses are integrated to provide one response the analysis of which must be questionable.

4. FRESH AND SALINE GROUNDWATER RELATIONSHIPS

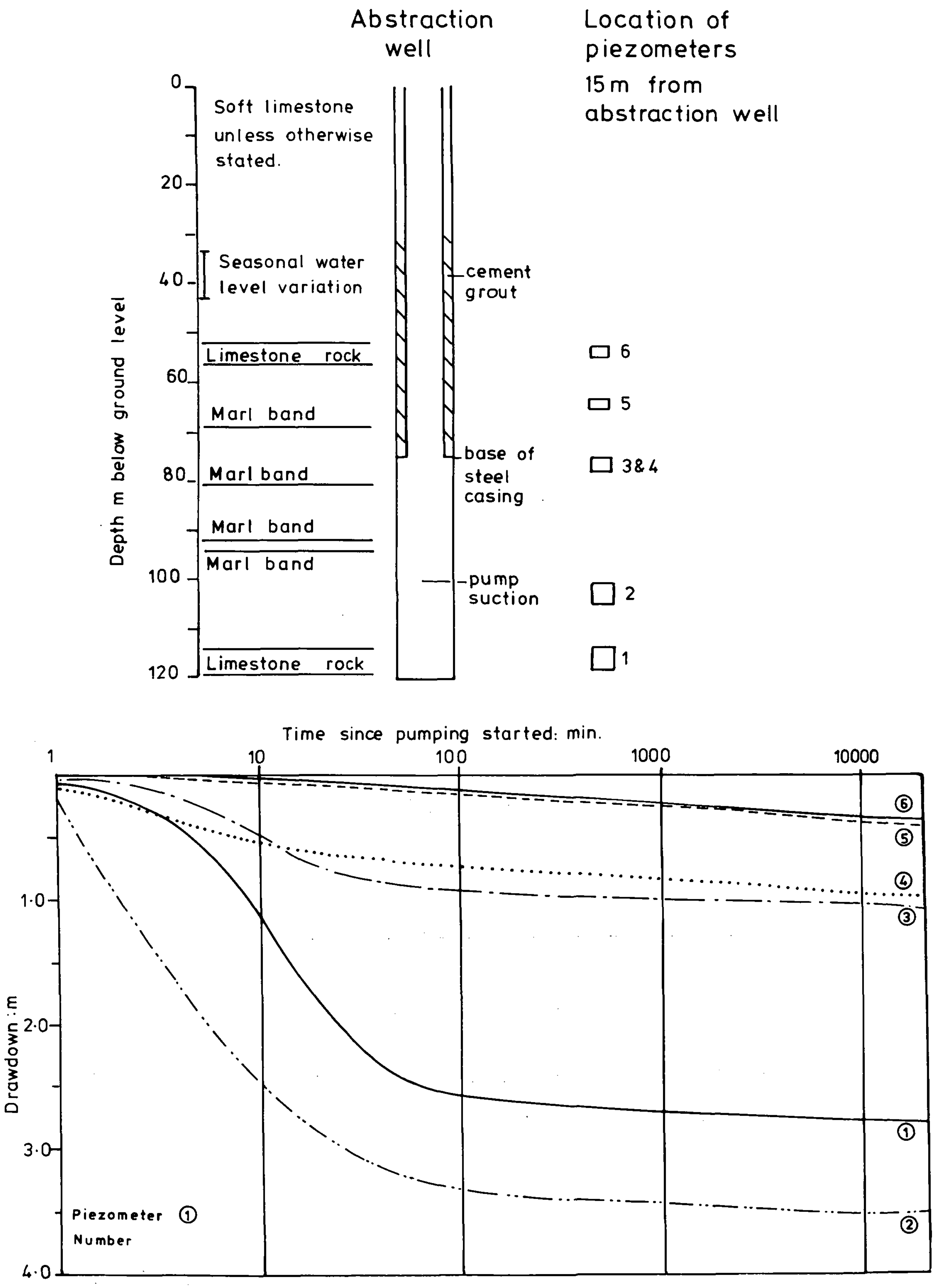
4.1 Introduction

The general principles of fresh and saline groundwater relationships have been discussed at length by Bear (1979) and Todd (1980) etc. and need not be considered here. It should be noted, however, that the classical Ghyben-Herzberg steady-state relationship is not truly



AN EXAMPLE OF DRAWDOWN DATA FROM AN OBSERVATION WELL ADJACENT TO A PUMPING-WELL IN A SMALL ISLAND LENS.

FIGURE 6



DRAWDOWN RESPONSES IN PIEZOMETERS IN AN OBSERVATION WELL ADJACENT TO A PUMPING WELL IN A LIMESTONE.

FIGURE 7

applicable in the dynamic situation found in small islands and that the concept of a fresh-saline groundwater interface is unrealistic because of the presence of a transition zone of brackish groundwater between the fresh and saline groundwater. As flow occurs in both the fresh and saline groundwaters (Cooper, 1959) the brackish waters are the result of mixing with chemical diffusion being minimal (Lloyd et al, 1977).

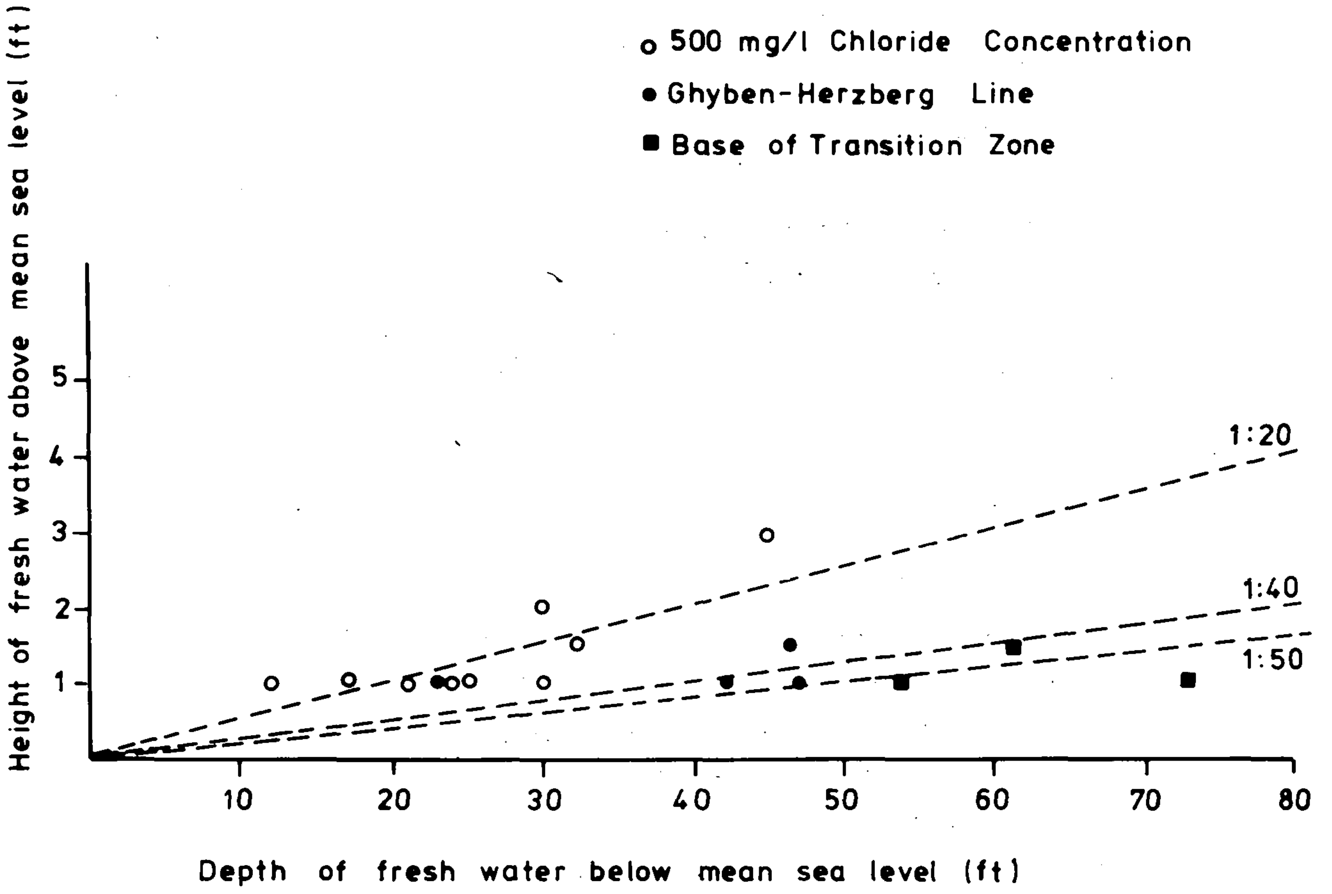
In this section the existing dynamic fresh-saline groundwater flow theories are accepted and attention is paid to the difficulties of the determination of the salinity conditions at the base of a fresh water lens and aspects of saline groundwater response to the pumping of a lens. Clearly the determination of the distribution of the base of usable groundwater in a lens is important in resource terms but also as suggested in Section 3.3. isochlor responses could possibly provide information about recharge events and lens thickness changes when a lens is stressed.

4.2 General Lens Base Density Relationship

In practical attempts to determine the approximate size and shapes of lenses, density relationships of the Ghyben-Herzberg style have been used as shown in Fig. 8. The information which is based upon borehole electrical conductivity logging, indicates that for the delineation of potable lens resources a 1:20 relationship exists (e.g. Vacher 1974: Lloyd, 1980) while the classical 1:40 relationship occurs within the brackish water transition zone. The 1:20 relationship appears to hold reasonably well for the thicker lenses (say > 20 m) but may not be applicable in thin lenses as shown in Fig. 9. While such a relationship is somewhat hypothetical more comprehensive data on lens thickness in relation to head above sea level would be useful to establish general conditions for 'first estimates' of fresh water resources in islands where data are limited.

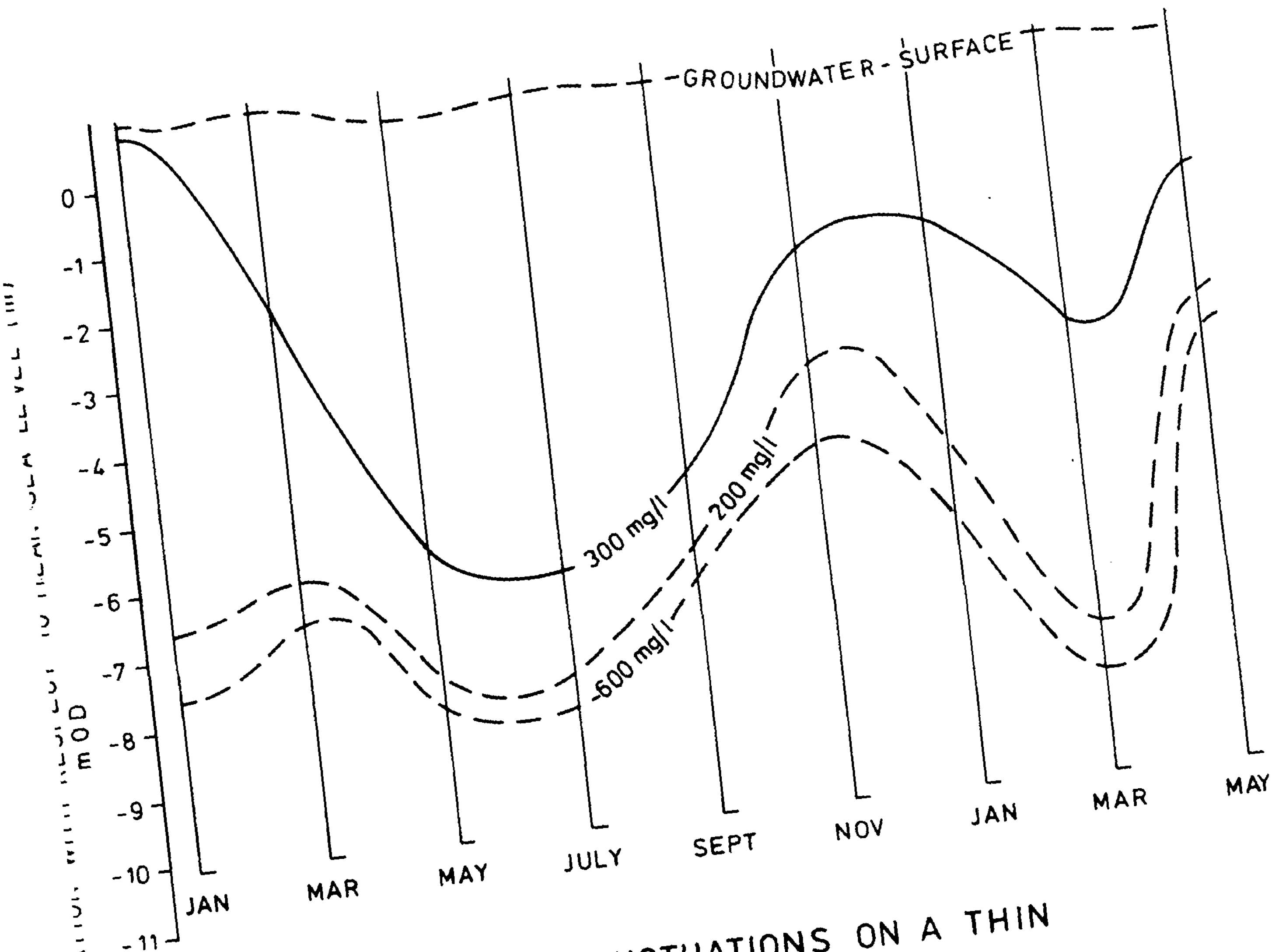
4.3 Measurement of Lens Base

Both surface and borehole geophysical techniques can be used for the measurement of a lens base. Surface geophysics can give important general distribution information but the detail is normally obtained from electrical conductivity logging.



RELATIONSHIP OF LENS BASE TO GROUNDWATER HEAD FOR THE CAYMAN ISLANDS. LENS BASE DEFINED AS 500 MG/L CHLORIDES.

FIGURE 8

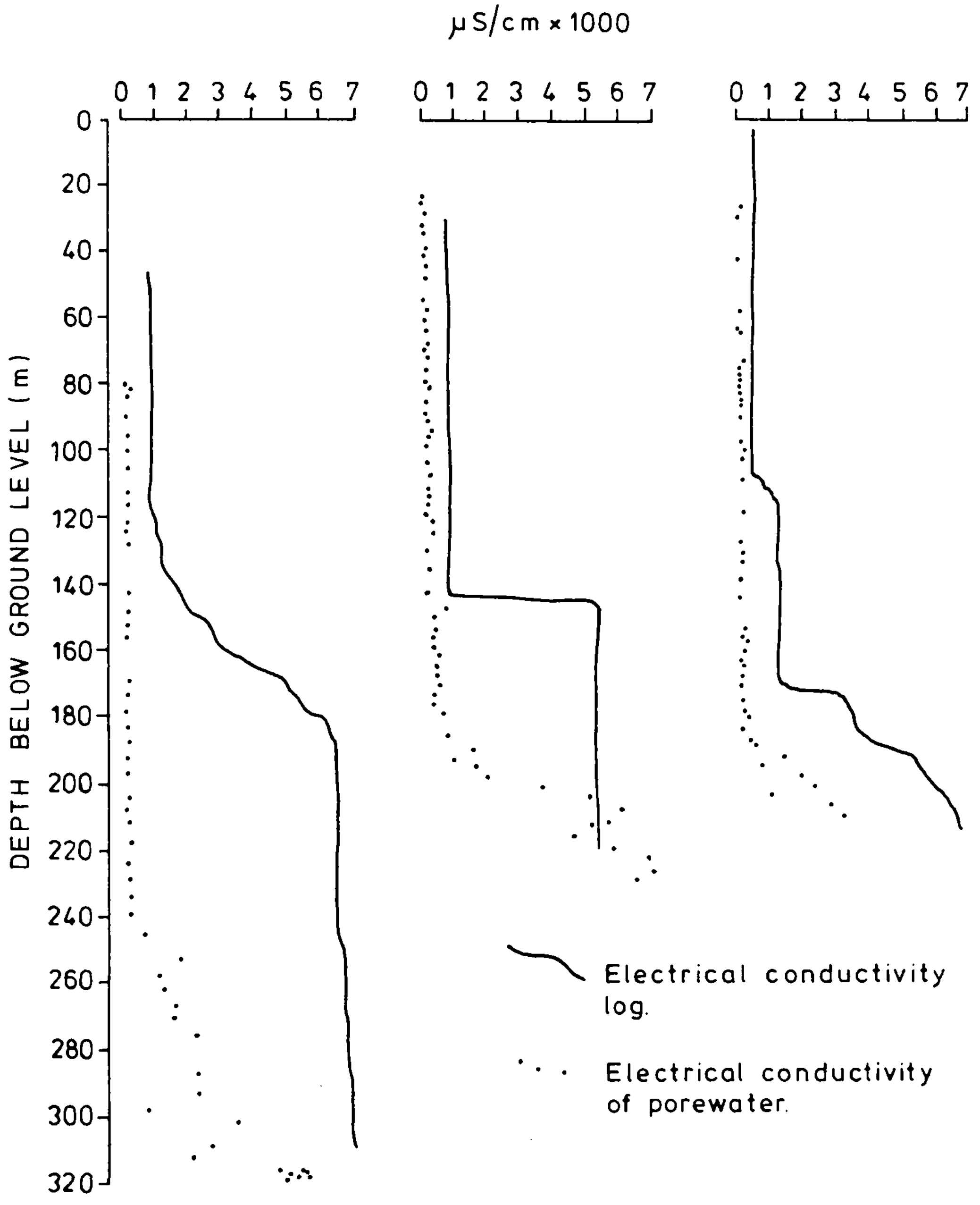


SEASONAL FLUCTUATIONS ON A THIN LENS BASE

FIGURE 9

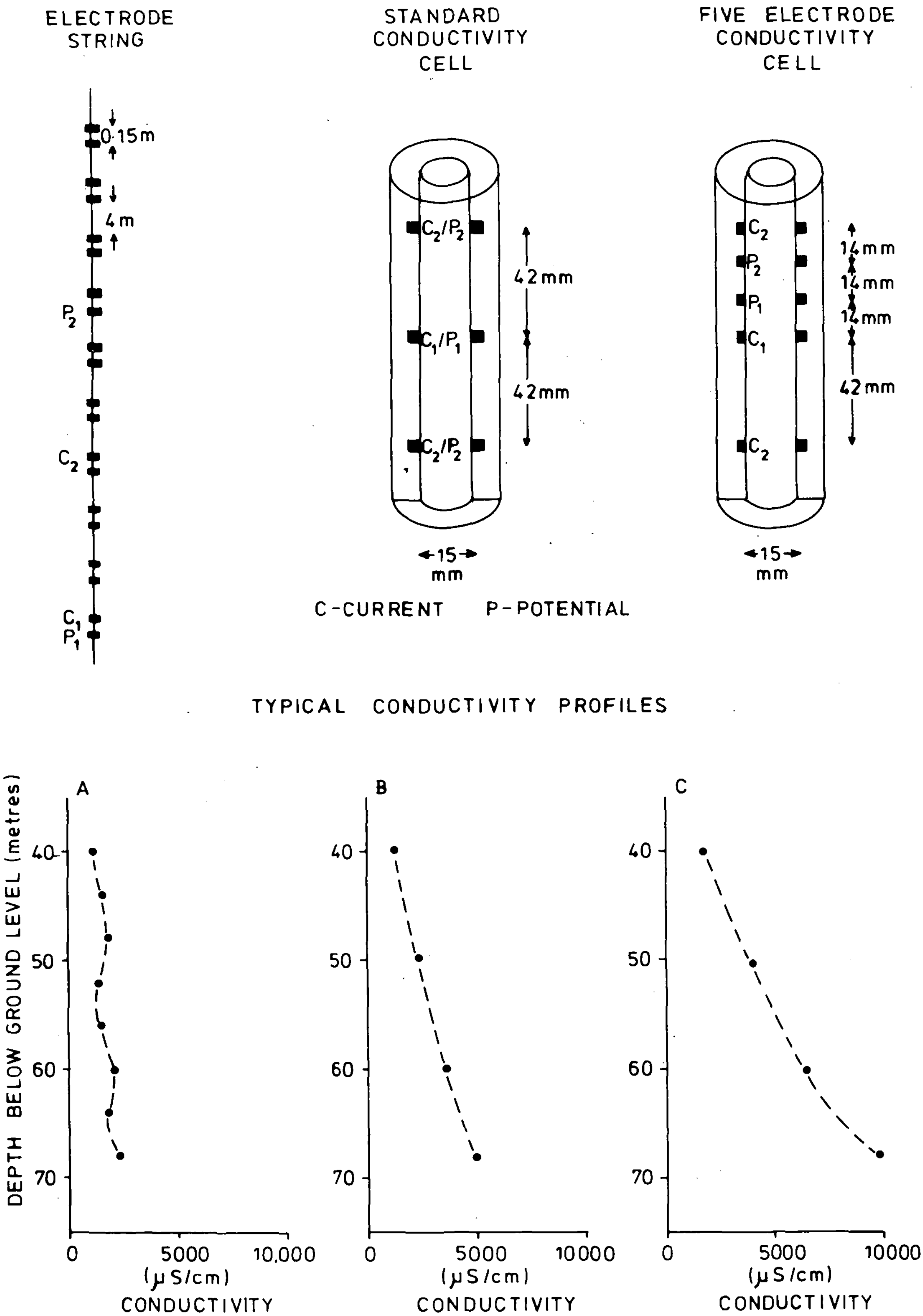
One of the difficulties being encountered in logging is that the conductivity in a borehole does not necessarily represent the salinity within the aquifer. On Fig. 10 some extreme examples of the problem are shown for a sandstone aquifer. The examples are not from a small island but illustrate the type of discrepancy that can occur. Two factors give rise to the discrepancy, one, ground layering that constrains a higher head in saline groundwater at depth which is reflected in the open borehole, and two, the delay in response in the deep saline groundwater within the aquifer to fresh water abstracting because of resistance to flow and storage, which is not reflected in an open borehole because of its storage and permeability. The degree to which aquifer and borehole salinity discrepancies occur in island lenses is not known but should be examined. While electrical conductivity is conventionally used for logging it may be worth examining more extensively the use of resistivity which measures the formation matrix and groundwater as opposed to the borehole water. Without deep resistivity penetration or perhaps focus logging, however, the sensitivity may not be good with saline water present in the borehole.

Automatic monitoring systems are becoming more prevalent these days and comparatively cheaper with the advance of microelectronics. In the monitoring of fresh-saline groundwater conditions electrical conductivity cells are becoming available which can be kept permanently in a borehole and monitored as required. On Fig. 11 an electrode string is shown with two types of conductivity cell and three profiles from a measured borehole. Although the profiles shown on Fig. 11 have been taken from the same borehole under the same hydrogeological conditions, profiles A and B have subdued conductivity when compared with profile C; the A profile also exhibits formational effects. The reason for the subdued responses is considered to be the weathering of dual electrodes in the first two profiles causing increases in resistance on electrode faces and false readings of conductivity. In profile C five-electrode cells have been used which offset the weathering problems by the incorporation of independent current and potential electrodes. This latter method is clearly more dependable, although more expensive, and should provide reliable lens base data.



COMPARISON BETWEEN PORE WATER CONDUCTIVITY AND BOREHOLE FLUID CONDUCTIVITY FROM THE SAME BOREHOLES

FIGURE 10



METHODS OF MEASURING ELECTRICAL CONDUCTIVITY IN BOREHOLES AND TYPICAL PROFILES

FIGURE 11

4.4 Movement of Lens Base with Abstraction

An understanding of the upconing of saline groundwaters in response to the abstraction of overlying fresh groundwater is vital in the management of small island lenses. Work on the dynamics of upconing has discounted the importance of the classical Ghyben-Herzberg relationship and underlined the importance of specific yield (Schmorak and Mercado, 1969); however, as with many other aspects of small islands the ground layering may prove to be the dominant control. Field data are difficult to obtain showing responses in layered ground so that for illustration a modelled result is used. On Fig. 12 an idealized example of radial flow to a partially penetrating area is shown together with the vertical flow velocities beneath the well obtained from introducing various ground conditions in pumping situations. The cases examined are as follows:

(i) Aquifer homogeneous and isotropic, K = 1.5 m/d (i.e. no zone A)

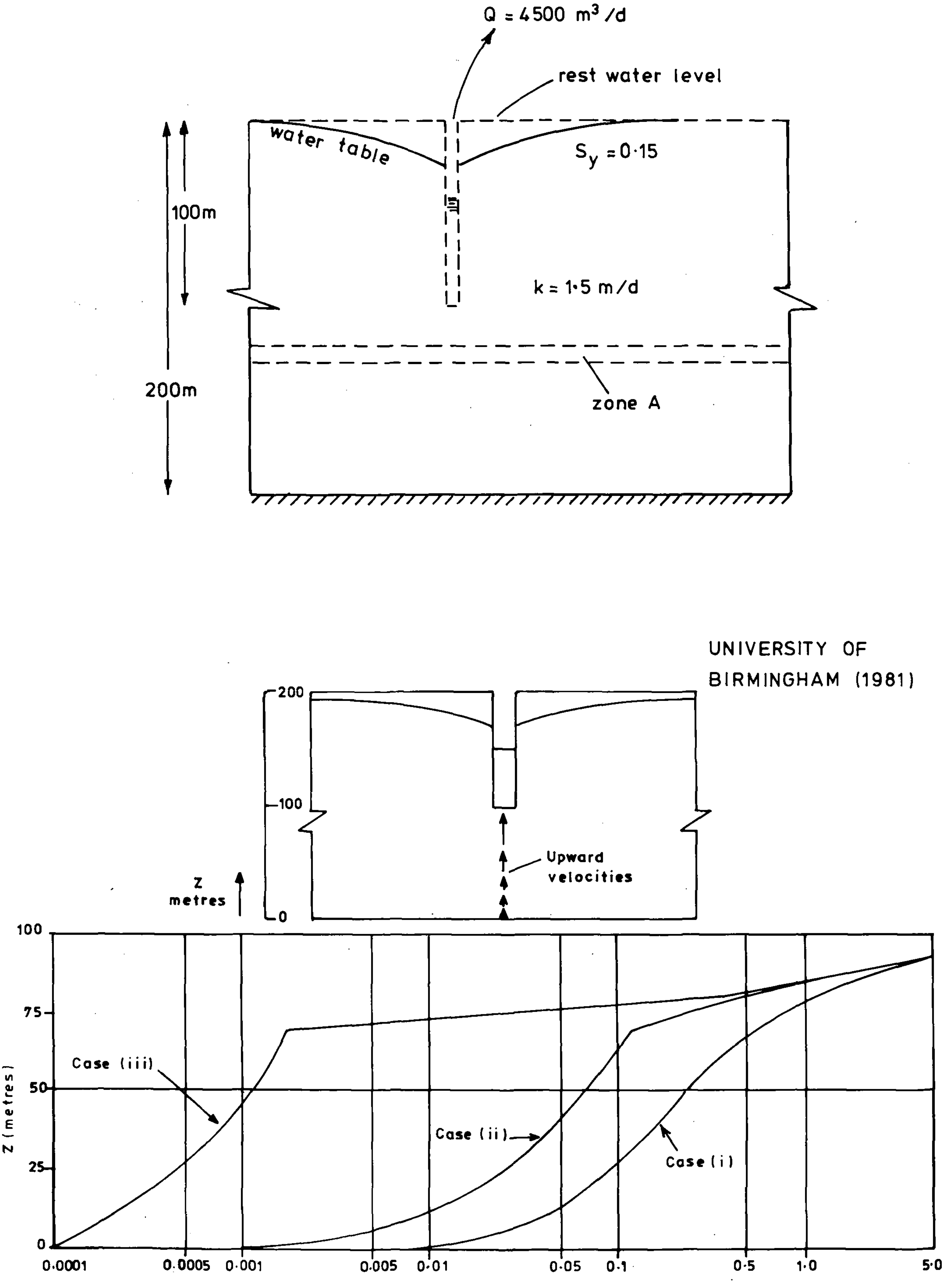
(ii) A layer of lower permeability (zone A) introduced below the pumping well with K_A = 0.15 m/d (10% of K)

and (iii) Case (ii) but with K_A = 0.00045 m/d (0.03% of K) for zone A.

As can be seen from the lower part of Fig. 12 the presence of a lower permeability zone radically reduces flows in the lower part of the aquifer. In saline groundwater terms for case (i) the calculations show that saline water 30m above the base of the aquifer would rise the 70m to the well in about 150 days but in case (iii) the time required for the saline water to rise into the area would be about 130 years. These very marked differences in saline groundwater response help show something of the hydrogeological significance of ground layering and have considerable inferences for small island studies.

5. CONCLUSIONS

Groundwater conditions in small islands form one of the most difficult hydrogeological environments. The increasing importance of small island lens resources, however, dictates that more is learnt about these environments and more data are accrued. The reliable quantification of resources will undoubtedly prove difficult as at



GROUNDWATER FLOW VELOCITY DISTRIBUTIONS BENEATH A PUMPING-WELL FOR DIFFERENT PERMEABILITY CONDITIONS.

FIGURE 12

present only fairly simplistic analyses can be applied, nevertheless, as work progresses the significance of the various hydrogeological controls will increasingly become apparent.

In this paper a number of hydrological and hydrogeological difficulties have been briefly discussed. While some of them are well recognised and are under study, it is considered much more attention should be paid to three very important aspects: detailed recharge input, ground layering influences and responses on a lens base. The evaluation of these factors may well prove expensive but will significantly improve the understanding of the long-term management of a lens groundwater resource.

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CHEMICAL HYDROLOGY OF SMALL TROPICAL ISLANDS

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ABSTRACT

The factors controlling the natural chemical characteristics of waters in small tropical islands are discussed. The influence of ocean aerosols, saltwater intrusion and the reactions between water and host rocks are important in determining the composition of natural waters. Only a limited amount of data is available from the Pacific islands for the confirmation of baselines and the need for a programme of regular sampling and analysis is stressed.

The aim of this paper is to present a review of the factors that control the natural quality of waters in small tropical islands. An examination of the water cycle as applied to small tropical islands (Fig. 1) shows that the following types of water should be considered:

- rainwater
- surface water
- streams and small rivers
- groundwater
- seawater

In these water systems the chemical composition is controlled by a number of basic reactions and processes coupled with physical factors such as dilution, concentration, mixing and intrusion. It should be noted that this paper will concentrate on natural processes; the pollution of water systems is discussed elsewhere (see BRODIE et al.)

The starting point for any discussion of the chemistry of water systems is the water molecule itself. This ubiquitous and apparently simple molecule, the most abundant at the Earth's surface, has unique properties which are not fully understood. The chemistry of the water molecule is often simplified to

$$H_2O \rightleftharpoons H^+ + OH^-$$

with the $\{H^+\} = 10^{-7}$ mol dm^{-3} at 25°C (298 K) and one atmosphere

(1.013×10^5Pa) and thus pure water (if we could find it) has a pH of 7 under these conditions.

RAINWATER

In small tropical islands the closest one can normally get to pure water is rainwater. Rainwater usually has a pH of less than 7 (see later) and a total dissolved material of about 7 mg dm^{-3}. An estimate of the global mean composition of rainwater has been made by Garrels and Mackenzie (1971) and the data is given in Table 1.

These figures are all well and good but they do not indicate one of the greatest difficulties of discussing rainwater data i.e. that of the considerable variability in the data. The composition varies with time in two ways. First there are normal seasonal variations with the composition of rainwater being different in wet and dry seasons. Secondly variations in composition may occur during a given storm as the early rain frequently contains most of the dissolved material while the later rain may be relatively dilute. The chemical composition of rainwater also varies with distance from the coast but this is not likely to be very significant in small island situations. At this point it is appropriate to stress the importance of making a few measurements (e.g. pH and temperature) at the time and place of sample collection (for all water samples) as these may change before any further analyses are made.

Earlier it was indicated that the pH of rainwater is usually less than 7. Why is this? One of the most important factors is related to the fact that rainfall is an atmospheric phenomenon and the rainwater is in equilibrium with gases therein (particularly CO_2).

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-} \qquad (1)$$

This set of equilibria is extremely important as it directly or indirectly affects the composition of nearly all natural waters. At normal atmospheric pressure ($\rho_{CO_2} = 10^{-3.5}$atm) the dissolution of carbon dioxide in water gives rise to a pH of 5.7.

A number of other processes influence the composition of rain water. These include the following:

1. Aerosol from the ocean (wave generated particles carried by the wind). At this point it is appropriate to digress and consider the composition of seawater (see Table 1) as this will have an important influence on

aerosol composition. The total dissolved material in seawater is about 35,000 mg dm^{-3}. It is important to note that although the absolute concentrations of species may vary there is a degree of constancy in the relative levels of the various species throughout the oceans. Assuming that the ocean aerosol reflects a similar relativity then an explanation of some aspects of the composition of rainwater is apparent e.g. Na:Cl ratio ≈ 1:2, $Na:SO_4$ ≈ 4:1, Na:Mg ≈ 3:1. In small tropical islands surrounded by ocean, ocean spray is likely to be the major source of dissolved material in rainwater.

2. Dissolution of dust collected over land (e.g. $CaCO_3$). This effect is extremely important for continental rainfall but the extent of land in the oceanic areas is such that it is likely to be of only limited importance.

3. Gaseous emissions from plants. These emissions are usually nitrogen or sulphur containing compounds. Although the land area is small in oceanic areas it should be noted that marine flora (including algae) may also be producing such emissions.

4. Industrial gaseous emissions. Again nitrogen and sulphur compounds are the most important. More information on this is included in the discussion on pollution (see relevant page) but the limited data available tends to indicate that in the Pacific Islands the levels of such emissions in the rain are relatively low.

Some rainfall analyses for samples from the South Pacific are given in Table 2. The data show that the rainwaters have small amounts of dissolved material and that the compositions are relatively similar to that given as the world average with the exception of the sample from Niue that has relatively high Ca^{2+} and SO_4^{2-} probably caused by the sample being collected in a concrete tank.

SURFACE WATER AND GROUNDWATER

When the rain reaches the surface several things can happen depending on the quantity and intensity of the rainfall:

- o Rainfall is intercepted by vegetation but eventually water will fall off the vegetation carrying with it any soluble material (e.g. dried sea spray) on the leaf surfaces

- o Rainfall impacts on the ground surface followed by infiltration or surface runoff depending on the rainfall and ground surface characteristics. Water will then move to groundwater or run off as streams or small rivers.

- o As water moves through the soil the carbon dioxide content usually increases as the soil atmosphere commonly contains much more of this gas than the atmosphere due to the processes of respiration and decay of organic matter
- o Water then percolates the substratum and various reactions may occur depending on the nature of the substratum. In small tropical islands the substratum is usually composed of reef derived carbonate material, basalts or andesites and weathered derivatives, or sediments derived from these components.

Most river or stream waters, although less pure than rainwater are still quite pure in that the total dissolved material is only of the order of 100-120 mg dm^{-3}. Groundwaters tend to contain more dissolved material than stream water because of their more intimate and longer contact with organic material, soil and rock particles. Groundwaters tend to be less well mixed than surface waters. Often there is a fairly direct relationship between the composition of a given groundwater and its host rock as summarised in Table 3.

However, this does not always held true. Other factors include:

1. the porosity and permeability of the host rock
2. the abundance and type of organic matter in the host rock
3. the length of time since contact (of the groundwater) with the atmosphere.

The chemical explanation of this behaviour can be found in a series of equations and equilibria. The equations have been simplified in order to illustrate the points. Firstly for basalts/andesites the host rock is dominated by silicate and aluminosilicate minerals and these react with percolating water (saturated with carbon dioxide) as indicated in the following examples:

$$\underset{\text{forsterite}}{Mg_2SiO_4} + 4H_2CO_3 \rightleftharpoons 2Mg^{2+} + 4HCO_3^- + \underset{\text{(soluble }SiO_2\text{)}}{H_4SiO_4}$$

$$\underset{\text{fayalite}}{Fe_2SiO_4} + 4H_2CO_3 \rightleftharpoons 2Fe^{2+} + 4HCO_3^- + H_4SiO_4$$

N.B.: In the case of fayalite one of the reaction products (Fe^{2+}) can react further if the water is aerobic to give an iron (III) oxide/hydroxide product.

$$2Fe^{2+} + \frac{1}{2}O_2 + 2H_2O + 4HCO_3^- \rightleftharpoons Fe_2O_3 + 4H_2CO_3$$

$$4Na_{0.5}Ca_{0.5}Al_{1.5}Si_{2.5}O_8 + 11H_2O + 6H_2CO_3$$

plagioclase feldspar

$$\rightleftharpoons 3Al_2Si_2O_5(OH)_4 + 2Na^+ + 2Ca^{2+}$$

kaolinite

$$+ 6HCO_3^- + 4H_4SiO_2$$

$$K\,Mg_3Al\,Si_3O_{10}(OH)_2 + 7H_2CO_3 + \tfrac{1}{2}H_2O \rightleftharpoons K^+ + 3Mg^{2+} + 7HCO_3^-$$

biotite

$$+ 2H_4SiO_4 + \tfrac{1}{2}Al_2Si_2O_5(OH)_4$$

kaolinite

Some of the volcanic rocks also contain significant quantities of sulphides e.g. FeS_2 which have a different mode of reaction e.g.

$$FeS_2 + 3.5O_2 + H_2O \rightleftharpoons Fe^{2+} + 2SO_4^{2-} + 2H^+$$

↓ if water is aerobic

Fe(III) oxide/hydroxide derivatives

This reaction leads to relatively high sulphate concentrations in the groundwater, unless significant quantities of suitable ions are present to precipitate the sulphate.

Within the Pacific Islands very little data is available on the composition of groundwaters having basalts/andesites as the host rock. An examination of the literature reveals a similar dearth of data for the tropics as a whole. Some of the available data is given in Table 4.

The data show some similarities as might be expected from waters in contact with similar rock types in a tropical environment and are consistent with the type of reactions expected. However, further interpretation is limited by the lack of detailed information on the composition of the host rocks and by the fact that the data have been obtained from single sample studies rather than averaged over a number of samples collected over a period of time. This problem is likely to be prevalent in the Pacific Islands as resources are frequently not available to carry out detailed long-term studies of groundwater.

The characteristics of groundwater in carbonate host rocks is explained in terms of the following equilibria

$$MCO_3 + H_2CO_3 \rightleftharpoons M^{2+} + 2HCO_3^-$$

$$\updownarrow$$

$$H_2O + CO_2 \rightleftharpoons H^+ + HCO_3^-$$

Thus the solubility of carbonates is related to the concentration of carbon dioxide in the water. For calcium carbonate ($CaCO_3$) this system has been extensively studied and the equilibrium constants determined (MILLIMAN, 1974; STUMM AND MORGAN, 1981; DREVER, 1982).

e.g. for calcite $CaCO_3$

at 25°C (298 K), in equilibrium with water and $\rho_{CO_2} = 0.05$ atm,

$$[Ca^{2+}_{(aq)}]_{eq} = 128 \text{ mg dm}^{-3};$$

if ρ_{CO_2} drops to 0.005 atm, the $[Ca^{2+}_{(aq)}]_{eq}$ '= 50 mg dm^{-3}

This relationship is well illustrated in Figure 2.

Rainwater has $\rho_{CO_2} \approx 10^{-3.5}$ atm, but groundwater usually has considerably higher values (up to about 10^{-2} atm). The solubility of carbonates is controlled by the carbon dioxide concentration and whether or not the system is open (ρ_{CO_2} remains constant) or closed (no exchange of CO_2 with the gas phase).

The solubility of carbonates (particularly $CaCO_3$) is also influenced by the presence of other cations in the carbonate structure and the ionic strength and composition of the aqueous phase. The effect of ionic strength (increased solubility with increasing ionic strength) is a well known phenomena discussed in physical chemistry texts. The influence of other ions in the carbonate structure e.g. magnesium in calcite generally leads to increased solubility (see e.g. PLUMMER AND MACKENZIE, 1974) and also a significant quantity of the other ion in the resultant solution.

Some groundwater data for Kiribati and Niue is given in Table 5 together with data from Florida where it was estimated that the groundwater was in equilibrium with $p_{CO_2} = 10^{-3.1}$ atm (BACK AND HANSHAW, 1971.

The data from Niue is relatively similar to that from Florida except for possibly a small influence of saltwater. The data from Kiribati show a small saltwater influence (as indicated by chloride levels) and a much higher level of dissolved Ca^{2+} and Mg^{2+}. The latter may be related to the composition of the host rock while the former may be an indication of high ρ_{CO_2} or the fact that the systems are not in fact at equilibrium.

Redox Conditions

In the preceeding section the behaviour of iron was shown to be influenced by the oxygen status of the groundwater. This is a particular example of the general problem of the effect of redox conditions on the equilibria, controlling groundwater composition. Only a few elements - Fe, Mn, S, C, O, N - are predominantly involved in groundwater redox reactions.

The redox reactions are most important when the water body is not in contact (equilibrium) with the atmosphere (particularly the oxygen therein). Reactions (many of them microbiological) proceed that consume the oxygen present e.g. oxidation of organic material. Then any NO_3^- or NO_2^- present will be reduced followed by MnO_2 and FeOOH. If sufficient demand for oxidation continues SO_4^{2-} and CO_2 will be reduced. Thus the redox character of the water will have a marked effect on the form in which an element is present and the concentration that is actually in solution.

Most natural waters are generally not at complete redox equilibrium and the dynamic (reversible) nature of the equilibria occurring means that it may not be possible to draw definite conclusions about the nature of the water body, although the water chemistry is frequently a good indicator of the prevailing redox conditions.

Saltwater Intrusion

In small islands a commonly encountered situation is the intrusion of sea-water into the groundwater. This is particularly common in the coastal areas and is found in both volcanic and coralline islands. The intrusion of salt water is usually indicated by high electrical conductivity and total dissolved material and confirmed by an examination of the major ion ratios, again using the constancy of composition of seawater as a reference. Care must be taken to make allowance for the presence in the groundwater of ions derived from the host rock, but usually the intrusion of saltwater is fairly obvious.

A problem occasionally arises when there is the possiblity that the salt water may not be present as a result of saltwater intrusion, but rather from a confined aquifer that has been trapped for some time. It is a very difficult problem to resolve (if the confined aquifer was of marine origin) since it is estimated that the composition of seawater has remained relatively constant (with minor periodic changes) for the past 1.5×10^9y (GARRELS AND MACKENZIE, 1971).

WHY STUDY HYDROCHEMISTRY AT ALL?

This is a valid question that is frequently encountered. Hydrochemistry is another technique that can be used in attempting to understand the evolution and properties of water resources.
Chemical information can be of use in

- o determining the extent of water movement
- o determining the degree of mixing in water bodies
- o determining whether or not water systems are in equilibrium with the surrounding environment
- o determining the extent of weathering of rocks (and hence in age determination)
- o the development of models for water bodies

It is important to emphasize the need for laboratory analyses. Electrical conductivity, pH and temperature measurements made on site, while extremely useful have limited value when it comes to a detailed discussion of the chemical characteristics of the water (e.g. electrical conductivity is a measure of the total ion concentration but does not provide direct information on the types of ion present).

CONCLUSION

Many of the properties of small tropical island waters can be explained in terms of a number of basic chemical reactions allowing for the influence of the ocean. However, only a limited amount of data is available in the Pacific islands for the confirmation of the baseline values suggested by the chemical reactions. An urgent programme involving regular good sampling and analysis is required in order to establish these baseline values for many countries. Unless we have this baseline framework it is difficult to discuss the consequences of human activities.

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TABLE 1

GLOBAL MEAN RAINWATER AND SEAWATER COMPOSITION (mg dm^{-3})

	pH	Na^+	Ca^{2+}	Mg^{2+}	K^+	NH_4^+	NO_3^-	SO_4^{2-}	Cl^-
Rainwater*	5.7	1.9	0.08	0.28	0.03	<0.1	<0.1	0.58	3.9
Seawater+	8.2	10,556	400	1272	380	0.1-2	<0.1-2	2649	18,980

* Data from GARRELS AND MACKENZIE (1971)

+ Data from MASON (1966)

TABLE 2

RAINWATER COMPOSITION DATA FOR THE SOUTH PACIFIC (mg dm^{-3})

SOURCE	pH	Na^+	Ca^{2+}	Mg^{2+}	K^+	NH_4^+	NO_3^-	SO_4^{2-}	Cl^-
WORLD AVERAGE[a]	5.7	1.9	0.08	0.28	0.3	<0.1	<0.1	0.58	3.7
NIUE[b]	6.7	3.0	15	0.05	0.5	<0.01	<0.01	9.9	7.2
TOKELAU[c]	6.4	2.0	<0.1	0.4	0.1	0.01	<0.01	<1	2.0
TARAWA[d]	6.2	2.3	2.0	<0.1	<0.1	n.d.	n.d.	<1	3.5
QUEENSLAND[e]	5.5	2.5	1.2	0.5	0.4	<0.01	<0.01	<1	4.4

a Data from GARRELS AND MACKENZIE (1971)

b Data from DSIR (NZ) (pers. comm., W.R. Dale)

c Data from DOWNES (1981)

d Data from DEPT. OF HOUSING AND CONSTRUCTION (1981)

e Data from CSIRO (Aust.) (pers. comm.)

TABLE 3

INFLUENCE OF HOST ROCK ON GROUNDWATER CHARACTERISTICS

HOST ROCK TYPE	GROUNDWATER CHARACTERISTICS
CARBONATES	pH 7.0 - 8.2 High total ion content Dominant ions Ca^{2+}, Mg^{2+}, HCO_3^- SiO_2 content low (< 15 mg dm^{-3})
BASALT/ANDESITE	pH 6.7 - 8.5 Moderate total ion content Dominant ions Ca^{2+}, Mg^{2+}, HCO_3^- SiO_2 content high (> 30 mg dm^{-3})
SEDIMENTS	pH 4.0 - 8.6 High total ion content Dominant ions Ca^{2+}, Mg^{2+}, HCO_3^-, Na^+ SiO_2 content moderate (10-25 mg dm^{-3})

TABLE 4

ANALYSES OF SOME PACIFIC ISLAND GROUNDWATERS
FROM BASALT ROCKS (mg dm^{-3})

SOURCE	pH	Na^+	Ca^{2+}	Mg^{2+}	K^+	HCO_3^-	SO_4^{2-}	SiO_2	Cl^-	Fe
Oahu, Hawaii[a]	7.7	12	24	15	5.3	156	1.6	50	15	0.43
Taveuni, Fiji[b]	7.1	9.5	17	10	1.7	134	2.9	n.d.	2.9	0.28
Upolu, W. Samoa[c]	7.6	18	21	n.d.	n.d.	120	n.d.	n.d.	31	0.16

[a] Data from WHITE et al, 1963

[b] Data from Mineral Resources Department, Fiji (pers. comm.)

[c] Data from Hydrology Department, W. Samoa (pers. comm.)

TABLE 5

COMPOSITION OF SOME CARBONATE ROCK GROUNDWATERS
(concentrations in mg dm^{-3})

SOURCE	pH	Na^+	Ca^{2+}	Mg^{2+}	K^+	HCO_3^-	SO_4^-	SiO_2	Cl^-
Florida[a]	8.0	3.2	34	5.6	0.5	124	2.4	12	4.5
Nikunau[b] (Kiribati)	7.3	7.2	105	16.8	0.2	132	n.d.	n.d.	17
Niue[c]	7.7	7.0	49	8	0.2	175	13	<1	13
Tarawa[d] (Kiribati)	7.7	9.2	74	17	<0.4	293	19.2	n.d.	14

[a] Data from BACK AND HANSHAW (1971)

[b] Data from BRODIE *et al*. (1983)

[c] Data from DOWNES (1981)

[d] Data from DEPT. OF HOUSING AND CONSTRUCTION (1981)

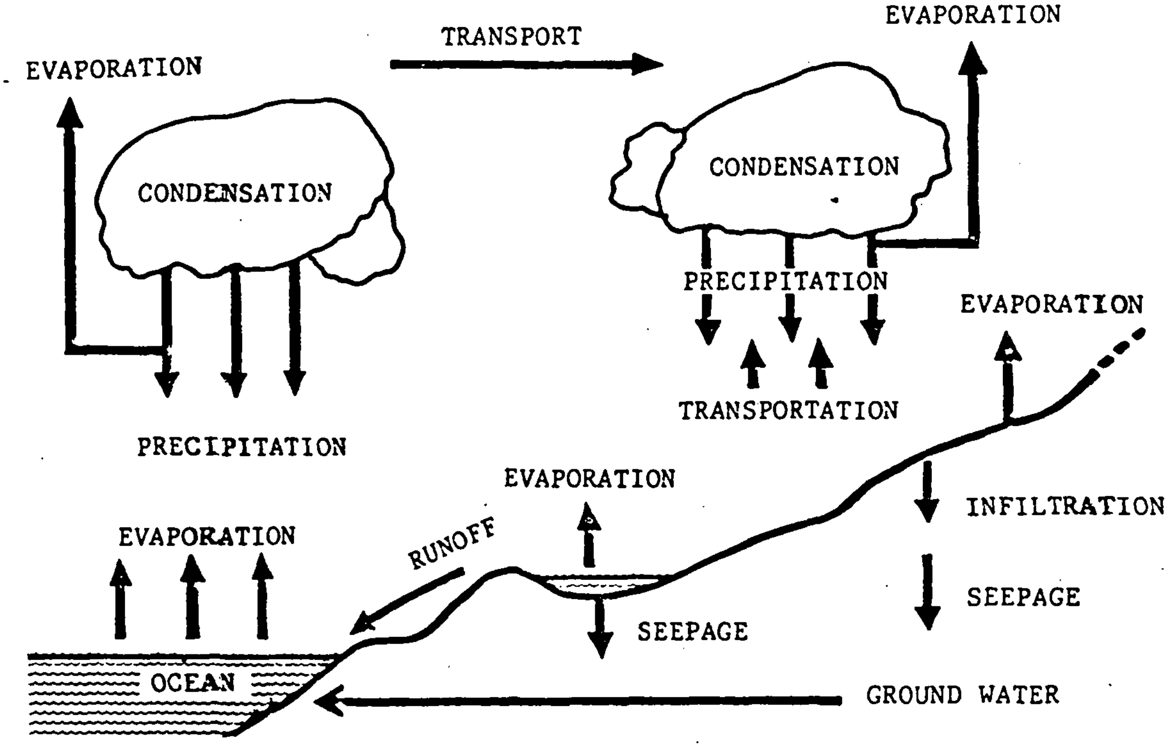

FIGURE 1. THE HYDROLOGICAL CYCLE

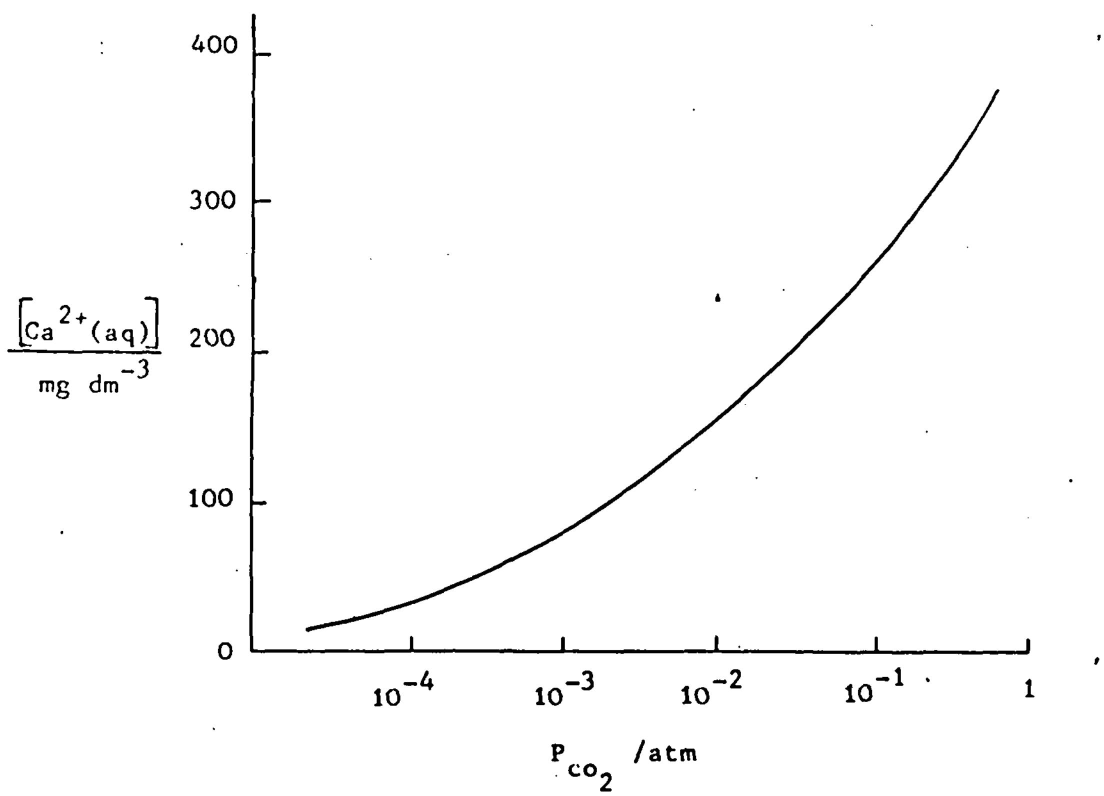

FIGURE 2. VARIATION IN DISSOLVED Ca^{2+} (FROM CALCITE) WITH PARTIAL PRESSURE OF CO_2

CLIMATOLOGY AND SMALL ISLANDS

by R.Prasad* and J.D.Coulter*

1. Abstract

After briefly reviewing the broad world climatic pattern and some special features of the southwest Pacific region and how they influence small islands, a sample group of islands will be described, with particular attention to rainfall, rainfall variability and evaporation or potential evapotranspiration.

Finally some of the implications for water resource planning will be introduced.

2. Introduction

The earth's atmosphere is subject to varying influences from the sun and the surface of the land and ocean: its physical condition is continually changing as it moves over the globe. The condition and behaviour of the atmosphere at a given time constitute weather. In order to describe or predict the weather one needs to measure the physical properties of the atmosphere both near the surface and in the upper air. These include (1) pressure, (2) temperature, (3) moisture content, (4) speed and direction of motion, (5) amount of precipitation and evaporation, (6) the state of sky as to cloudiness or the occurrence of precipitation and (7) the amount of incoming solar radiation, thermal radiation fluxes and latent and sensible heat exchanges.

Though the weather varies from day to day, it is nevertheless possible to arrive at a generalization or composite of these variations. One speaks then of the climate of a place or region.

Day to day or year to year variations in the climatic elements are best thought of as an inherent characteristic of the climate. At the other extreme the changes may cover a span of centuries or millenia - then to be recognized as "climatic change".

The operation of climatic controls tends to limit the variations in the climate of a place. The most fundamental control of both weather and climate is the unequal heating and cooling of the atmosphere at different times of day and seasons in different parts of the earth. Geographical variations occur on a wide variety of scales, the most important of which is the latitudinal variation. Other important climatic controls are altitude, the distribution and size of land and water bodies, mountain barriers, vegetation, air masses, atmospheric disturbances of various kinds and ocean currents.

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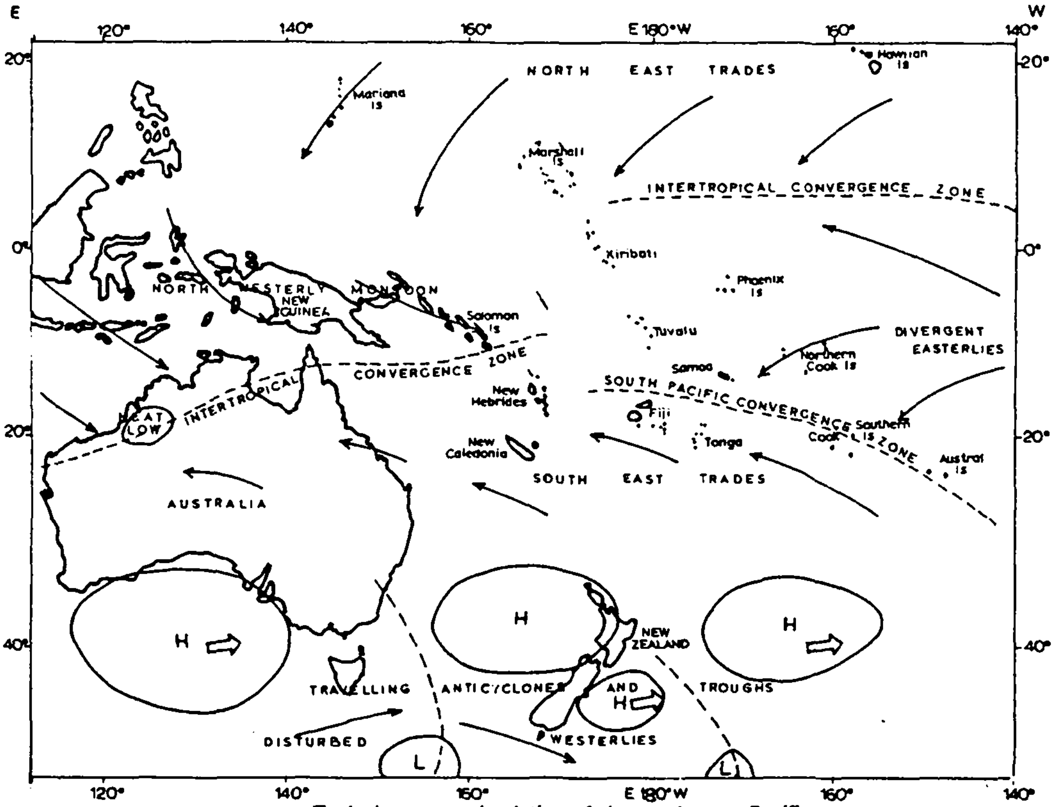
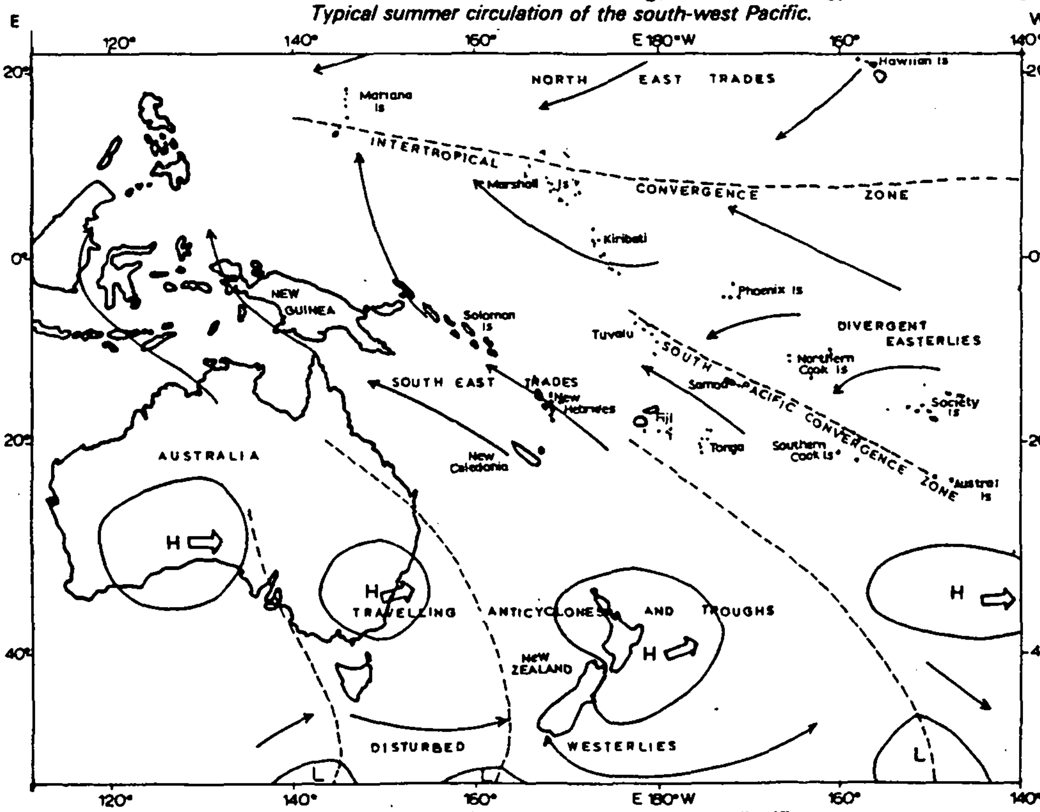


Typical summer circulation of the south-west Pacific.



Typical winter circulation of the south-west Pacific.

FIGURE 1 Typical circulation patterns of the South-West Pacific - after Steiner 1980.

For water resource considerations, the important element of climate is the rainfall - the average or expected amount at any time of the year, and its variability from place to place and from time to time. Also of importance is the amount of evaporation (from water surfaces, the soil, or as transpiration from vegetation) and potential evaporation or potential evapotranspiration, the amount of evaporation which would take place if water supply were unlimited. The rate of evaporation (and potential evaporation/evapotranspiration) is influenced by other weather elements - solar radiation, wind, humidity and temperature.

3. The General Circulation

The broad patterns of climate (the macro-climate) are controlled by the general circulation of the atmosphere. Driven by the different radiation balance of high and low latitudes, and of winter and summer, the atmospheric and oceanic motions transfer surplus energy from near the equator to the polar regions. We see the broad belt of stormy circum-polar westerlies at the surface in the middle and high latitude temperate zone, the easterly trade wind belt near the tropics, between them a broad area of relatively high pressure, with light winds and low rainfall, and the intertropic zone of convergence (ITCZ) near the equator where upward air motions often accompany widespread convergence of air flow and lead to copious rain. Fig.1 shows these and other features of the circulation and weather patterns in the southwest Pacific region in summer and winter.

Such representations of the general circulation of the atmosphere grossly oversimplify the reality. The distribution of land masses and ocean basins leads to complications - monsoon regimes develop where large land areas are a source of outward flowing cold air in winter and an area of inflow of moisture laden air in summer, thus breaking up the strictly zonal patterns. Even over the oceans the pattern is not simple. The high pressure belt and the trade winds are interrupted by transient troughs of low pressure associated with higher latitude disturbances. In parts of the Pacific there is an anomalous dry zone near the equator, while in slightly higher latitudes, 8° to 20° S or N, other areas see the formation of tropical cyclones - occasionally destructive, but contributing a significant proportion of the total rainfall in some places.

Tropical cyclones occur in the north Atlantic (west of about 30°W), the north Pacific (east of about 140°W and west of about 180°) the south Pacific (west of about 150°W) and the Indian Ocean, north and south.

Fig.2, satellite pictures from GMS 2 in the afternoon of 28 February 1983 when tropical cyclone Oscar was approaching Fiji

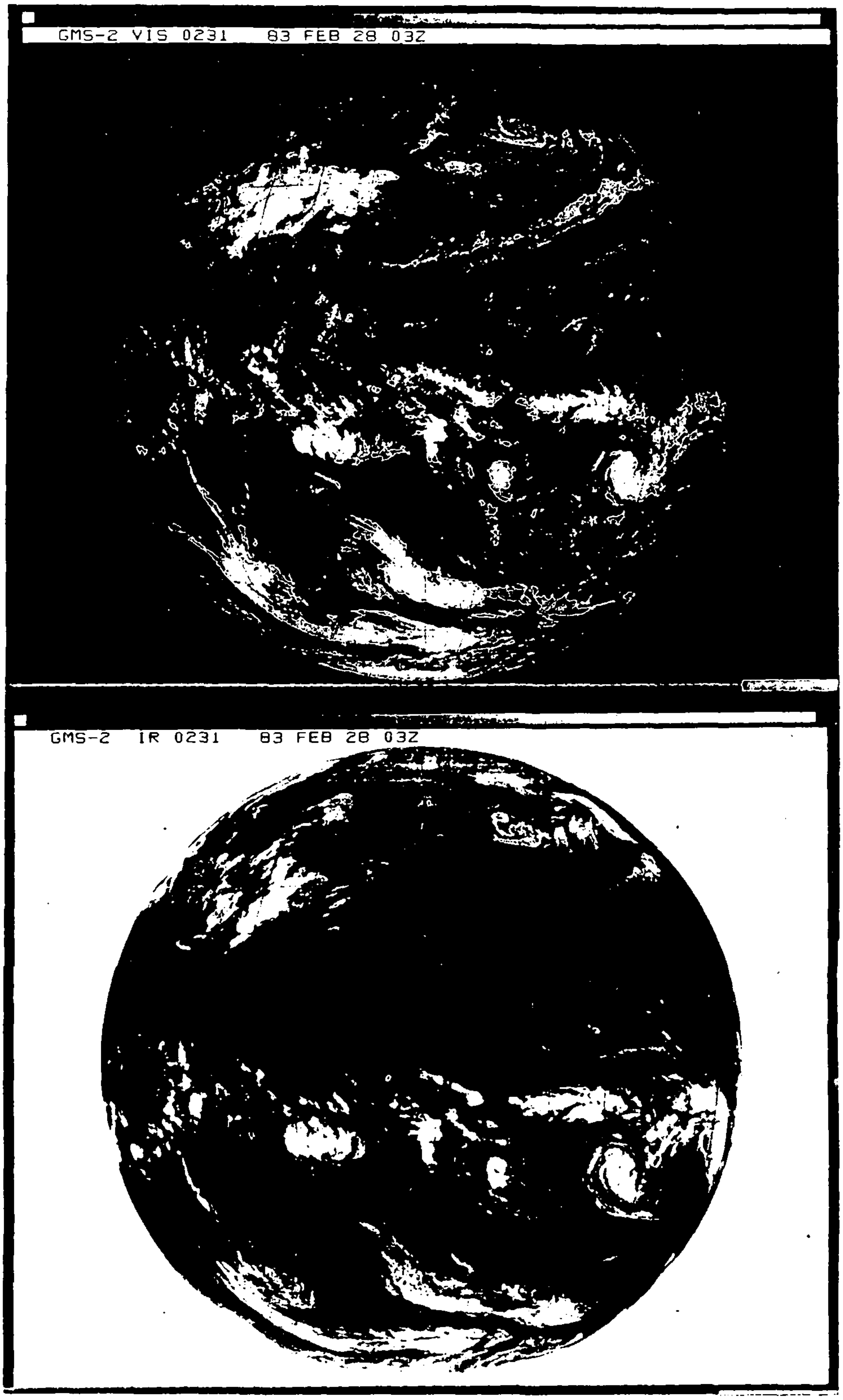


FIGURE 2 Picture of cloud cover, visible and infra-red, by Geostationary Meteorological Satellite - GMS2, located at 140° East. 0231-0300GMT 28 Feb., 1983.

illustrates some of these features. Oscar is the eastern-most of the three tropical cyclones which can be seen. Clouds associated with high latitude disturbances are present in both hemispheres. The southern ITCZ is well developed, the northern branch less so, and there is a clear area along the equator north of Fiji.

4. Climatology and Water Resource Development

Understanding of climate develops through theoretical studies and observations. Currently there is much effort world wide in developing a theory of climate and climatic fluctuations, mostly by using large computers to construct numerical models. Hand in hand are internationally co-ordinated efforts to achieve as uniform as possible a coverage of observational data in three dimensions. As well as conventional land based measurements (and measurements from ships and aircraft), remote sensing by means of satellites, and on a more local scale by radar, is now being used to give a nearly global data input to the numerical models and of course,information for immediate local use. For the first time it is now possible to get information on, for example, the patterns of cloud cover and indirectly of precipitation over the whole globe. See for example the global maps of sea surface temperature, geopotential, wind and tropical precipitation index produced each month at the U.S. National Weather Service Climate Analysis Centre. (NOAA---)

Interesting and promising as these new development are (and it is hoped of course that with further understanding of the longer lasting anomalies such as El Nino some seasonal prediction ability may be developed), it remains that for practical water resource applications, direct local surface observations and appropriate statistical summaries are all important, although radar measurement of the rainfall in an area can be very useful for water systems management.

One would like to have well distributed observations for a long period of years, basically of daily readings, with appropriate summaries of the data. Rainfall is the most variable of the weather elements, and hence requires the longest observing period and densest network. By convention, climatologists have adopted a 30 year period for climatic "normals", but in some places an even longer period is needed to give a good indication of the long term variability of rainfall.

5. Small Island Climatology

Small islands largely share the climate of the surrounding ocean, but even the smallest (of habitable size) probably undergoes some local climatic effects. In islands of more than a few tens of kilometres in extent and a few hundred metres in height, the orographic effects on weather and climate are often dramatic.

There is generally an interruption of the wind flow and a rain shadow on the lee side, and an augmentation of rainfall and cloud on the windward side and on the high ground. A somewhat wider temperature range, more sunshine and greater evaporation and potential evapotranspiration are to be expected on the leeward side of the island. The sea breeze effect is often pronounced and plays an important role in determining the local weather.

For a general account of global or regional climates there are many reference books available. (e.g. Lockwood 1979, Riehl 1979, Steiner 1980).

Detailed figures for particular places may not be readily accessible, though some comprehensive data publications do exist, with world (e.g. ESSA 1968), regional (e.g. ASEAN 1982 a, b: Brookfield and Hart, 1966; N.Z.Met.S. 1983, Taylor 1973) or national (Fiji Meteorological Service 1980; 1981) data coverage. Currently, under the sponsorship of the World Meteorological Organization's World Climate Program, much effort is being put into "data rescue" and the creation of computer data archives. Local data should be available from the National Meteorological Service of the territory concerned. There may or may not be a good record from a nearby station for a new water development study, of course.

6. Representative Small Pacific Island Climates

We present some statistics of the sort considered useful for water resource development for a number of representative small islands in the Pacific region. We include Nadi Airport and Suva/Laucala Bay, both on Viti Levu, which is not strictly a "small island" by the criterion for this Workshop, because they show the characteristics of this regional latitude, and show up well the orographical effects which would be seen on an island at the large end of the spectrum of "small" islands.

Monthly rainfall series give a fairly satisfactory definition of the longer duration high or low rainfall anomalies which are of most concern for water resources. We have tried to give fairly full details. Between them, the mean standard deviation or coefficient of variation, and extremes (or 1st and 9th decile value) give a fair picture of the frequency distribution. The gamma statistic indicates the degree of skewness in the distribution: if its value is less than about 10 the distribution is markely skewed and use of the normal distribution to establish quantiles is not appropriate (Table 1).

Wherever possible we have given average Penman potential evapotranspiration estimates (Table 1, Fig.4) as a guide to water need for agriculture or water losses from reservoirs. We also provide the monthly averages of incoming solar radiation and details of temperature as additional information to enable further understanding of the climate of these islands (Fig.5).

The most obvious point that can be noted from the figures and the table is the relatively high rainfall in many tropical islands. However there are exceptions to this as is shown by Christmas Island which is one of a group of islands near the equator (known as the Line Islands) located in a belt where divergent easterlies perhaps originating from semi-permanent anticyclones of the southeast Pacific prevail most of the time. As a result average rainfall in this belt is relatively low. It is also extremely variable. From time to time an anomalous circulation pattern brings heavy rain over periods of several months (Fig. 3). Further west, the equatorial islands have higher rainfall, but it is still highly variable. (Christmas Is. 2°N 157°W, average annual rainfall 832mm, co-efficient of variation (CV) 64%; Tarawa 1°N 173°E, 1981mm, CV 42%). At both places average monthly rainfalls are somewhat greater in the southern hemisphere summer-autumn season.

Average rainfall increases rapidly in the quasi-permanent ICTZ north and south of the equatorial dry zone, (e.g. Jaluit 6°N 170°E 4110mm; Funafuti 8.5°S 179°E 3469mm CV 19%): it decreases again with increasing latitude north (e.g., Kwajalein, 9°N 168°E 2630mm, CV 14% and more gradually to the south, e.g. Rotuma, 12.5°S 177°E 3526mm, CV 12%; Yasawa-i-Rara, 16°S 178°E, 1852 mm, CV 24%). Relative variability in monthly and annual totals is greatest at the equatorial stations, lowest at those with the greatest average rainfall (Table 1).

It is instructive to consider mean monthly potential evapotranspiration (PE) in relation to the rainfall decile values-thresholds exceeded in 10%, 20% --90% of years (Fig. 4). In high latitudes winter PE is low mainly because incoming solar radiation is low, and in most islands rainfall totals in a month are almost always considerably greater than PE in the winter spring half year. Periods of water shortages are common in the summer (e.g. Chatham Is., 44°S). Near the tropics, small islands and stations in the western dry zone of larger ones, having seasonally more uniform PE rates, and usually relatively lower rainfalls (and greater variability) in the winter season often experience periods of deficient rainfall (relative to PE) in that season. Even in summer, when average rainfall may be well above PE, because of the wide variability, water shortages sometimes occur in the normal wet season also.(See Fig.4, Suva, Nadi Airport, Niue).

Because of the high variability rather than low average rainfall, monthly totals at Tarawa are often below PE; and because of the lower average and still greater variability, inadequate monthly totals are quite frequent at Christmas Is., where average PE values are likely to be somewhat greater than at Tarawa. Some very wet periods also occur, of course.

For water resource assessment it is usually necessary to look at the longer rainfall anomalies - from 3 months to one or two years. In another Workshop paper (Coulter 1985) methods of utilising rainfall statistics for this purpose are outlined, mainly by means of statistics for consecutive months' rainfall totals, and accumulated "deficits" and surpluses" given by a simple soil moisture-water balance model using daily rainfall data.

For example, in many of the smaller Fiji islands and in the west of the larger ones, inadequate soil moisture for crops and failing domestic water supplies are experienced in perhaps most years resulting from two or three months of near normal or only slightly below normal rainfall. However, in an extreme year, 1983, a prolonged very low rainfall anomaly, extending from early March (March and April are normally "wet" months) to September caused serious water shortages. In many places this was a record low rainfall event in up to 50 years of records. In some places rainfalls in the preceding "wet season" were also below normal (Coulter 1983).

Longer anomalies may represent widely different levels of water availability over a time scale of one or two years. This is of course most marked in the equatorial islands already mentioned (note the extremely high annual CV values at Tarawa and Christmas Island, 42% and 64% respectively). The higher latitude islands in Table 1 have CV values of 15 to 25% for annual totals. The following table gives some figures for one of the small islands (Mago Is.) in eastern Fiji, showing quite high variability in 18 month and 2 year totals.

Table: Rainfall Variability in periods of 1 year, 18 months, 2 years, at Mago Is., Fiji (17^{o} 26' S 179^{o} 8'W, 12m):1928-1983

	Lowest mm	1st d mm	Median mm	Mean mm	9th d mm	Highest mm	S.D. mm	CV%	G
A	879	1558	2005	2049	2646	4593	533	26	18
B	2187	2559	3224	3366	4261	6445	738	22	24
C	1409	2064	2621	2805	3704	6083	798	28	15
D	2416	3230	4013	4104	5208	7602	867	21	26

A: calendar year
B: 18 months November to April (highest 18 months on average)
C: 18 months June to November (lowest 18 months on average)
D: two year total (January to December)

Figure 3 is a time plot of accumulated departures of rainfall from the average at Christmas Is. The curve passes through zero at the beginning and end of the reference period.

Periods of low rain rainfall are indicated between high and low turning points, e.g., Feb. 1967 and Jan. 1972. The heavy rains of 1982-1983 are shown.

In this discussion we have made no allowance for the changes of PE except for differences in average monthly values. Day to day changes can be quite large but monthly totals have very much smaller range of variation than rainfall. Calculated monthly values of "Penman" PE have a coefficient of variation of about 7 to 12% at Nadi Airport. Hence not much error is caused by using average PE rates in water balance considerations.

Geographical Note

Of the islands quoted, Kwajalein (3 sq. km), Tarawa (9sq. km), Jaluit and Funafuti (2.8 sq.km) are low atolls of small land area; Christmas Is. is a large atoll (310 sq.km).

Rotuma (44 sq.km) and Guam (550 sq.km) are hilly but mostly not very high.

Niue (258 sq.km) is a raised limestone platform as is most of Mago (20.7 sq.km).

Raoul Is. (29 sq.km) is steep and Chatham Is. (900 sq.km) has some plateau areas, but is mostly low. Viti Levu (10,350 sq.km) is mountainous.

Acknowledgements and Data Sources

To New Zealand Meteorological Service for supplementary data for Kiribati and Tuvalu stations, Niue, Raoul Is. and Chatham Is; for special computer analyses of Fiji data; and for permission to copy Figure 1. To Meteorological Satellite Centre, Japan for Figure 2 (copied from "Monthly Report"). Other data from N.Z.Met.S. publications, Taylor 1973, and NOAA "Local Climatological Data" annual summaries for Kwajalein and Guam.

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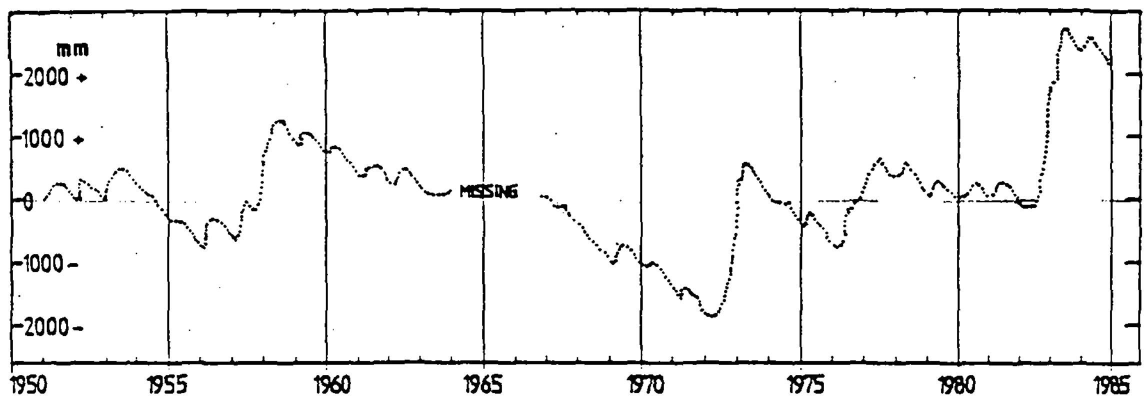

FIGURE 3. Cumulative rainfall departure at Christmas Is., Kiribati. (01°59'N, 157°29'W) 1951-1954: running total of monthly rainfall - average monthly rainfall (annual average/12). The reference period, 1951 to 1981, has annual average 762mm or 63.5 mm/month.

Note periods of generally below average rainfall from June 1958 to December 1964, January 1967 to April 1972 and March 1973 to February 1976; near average rainfall from about June 1977 to May 1982; and the marked increase from then to mid 1983.

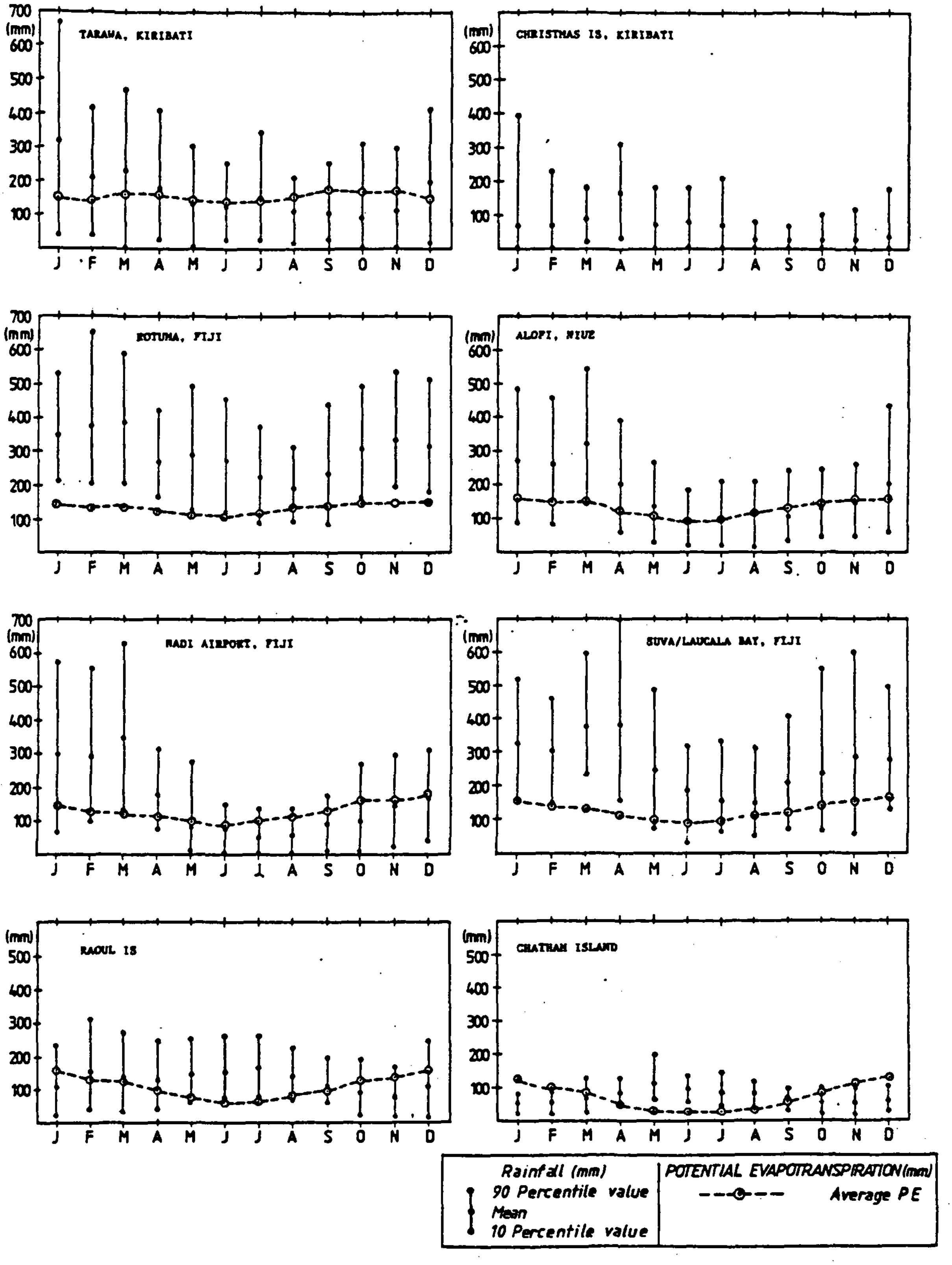

FIGURE 4 Monthly Rainfall - mm :
mean, 90 percentile value, 10 percentile value
Average "Penman" Potential Evapotranspiration (PE) - mm

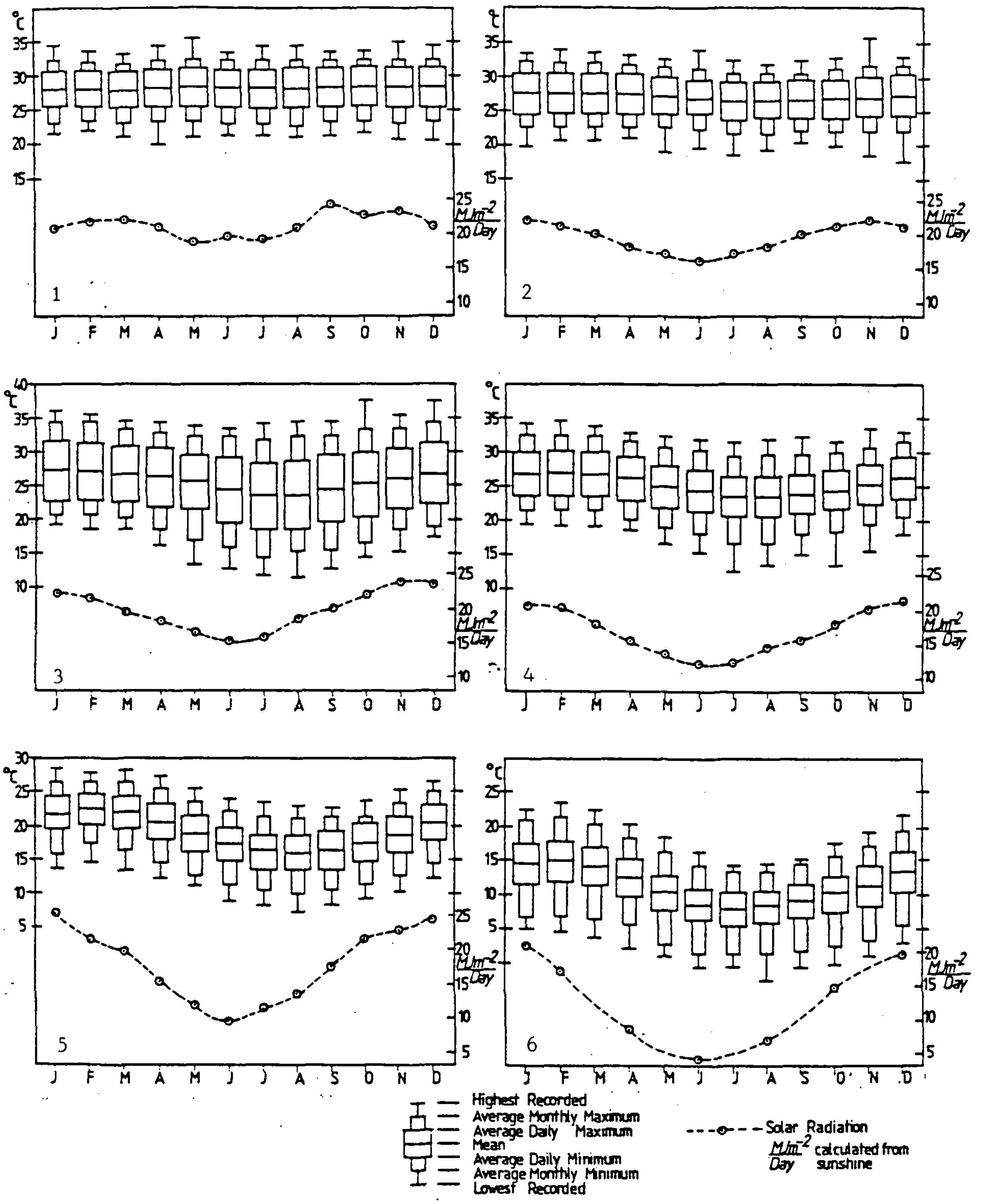

FIGURE 5. Monthly variation of air temperature; average global solar radiation.

1 Tarawa, Kiribati
2 Rotuma, Fiji
3 Nadi Airport, Fiji
4 Suva (Laucala Bay), Fiji
5 Raoul Is
6 Chatham Is.

Table 1. Rainfall Statistics for Selected Pacific Islands.

M = Mean rainfall (mm)
S = Standard deviation (mm)
CV = Coefficient of variation (percent)
G = Gamma shape parameter (for non zero values)
PE = Mean potential evapotranspiration, Penman (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1 Chatham Is.					43°57'S			176°34'W		44m			1951-1980
M	57	58	75	84	114	97	86	83	66	59	57	59	895
S	30	41	43	35	56	30	35	36	23	32	31	30	166
CV	52	69	57	41	49	31	42	42	35	54	55	50	18
G	3.8	2.5	3.0	4.4	5.6	10	5.9	5.7	7.0	2.8	3.4	3.8	58
PE	131	102	83	50	32	26	25	36	55	83	107	124	853
2 Raoul Is.					29°15'S			177°55'W		38m			1937-1978
M	111	153	138	129	144	160	160	141	113	94	77	109	1535
S	100	132	107	98	70	66	65	58	49	57	63	113	363
CV	90	86	78	76	49	41	41	41	43	61	82	104	24
G	1.3	1.8	2.0	2.2	4.7	5.8	5.6	5.3	5.6	2.5	1.7	1.1	18
PE	160	134	128	99	77	62	70	82	99	128	139	158	1337
3 Alofi,Niue					19°03'S			169°55'W		21m			1905-1972
M	272	261	304	193	124	84	102	103	108	131	141	205	2041
S	167	147	158	118	90	63	80	88	80	84	89	145	457
CV	61	56	52	61	73	75	78	85	74	64	63	71	22
G	2.5	2.9	3.9	2.5	2.0	1.6	1.7	1.6	1.9	2.4	2.8	2.0	20
PE	162	147	146	119	106	90	99	116	130	146	154	162	1577
4 Laucala Bay,Fiji					18°09'S			178°27'E		6m			1951-1981
M	329	306	377	383	243	179	155	146	204	235	283	277	3117
S	140	112	163	213	142	109	104	115	122	207	202	135	532
CV	42	37	43	56	58	61	67	79	60	88	71	49	17
G	5.5	6.5	5.2	3.9	3.0	2.0	2.7	2.2	2.4	1.7	2.0	4.0	33
PE	149	128	126	107	93	82	88	104	112	133	141	152	1415
5 Nadi Airport,Fiji					17°45'S			177°27'E		19m			1942-1984
M	308	282	353	178	85	73	49	61	84	95	138	167	1873
S	168	144	183	91	63	68	50	60	69	85	95	105	441
CV	55	51	52	51	74	93	102	98	82	89	69	63	23
G	2.6	3.6	3.9	3.7	1.5	1.2	0.9	1.2	1.4	1.3	1.9	2.2	18
PE	157	135	132	116	105	87	96	114	132	154	157	165	1550
6 Mago Is,Fiji					17°26'S			179°08'E		12m			1928-1983
M	247	222	255	230	161	103	89	105	127	147	176	183	2045
S	108	109	135	136	103	84	63	109	104	139	103	141	533
CV	44	49	53	59	64	82	71	104	82	95	58	77	26
G	4.0	4.1	3.8	2.6	2.5	1.6	2.2	1.5	1.4	1.6	2.6	1.9	18

7 Rotuma, Fiji 12°30'S 177°03'E 26m 1951-1980

M	347	375	387	264	287	268	222	187	233	307	332	317	3526
S	134	184	192	95	135	120	108	93	132	129	145	144	418
CV	39	49	50	36	47	45	49	50	57	42	44	46	12
G	6.7	5.1	4.6	7.8	4.2	5.2	3.5	4.8	3.2	6.1	7.0	3.9	76
PE	149	146	155	133	125	107	113	131	141	156	160	156	1672

8 Funafuti, Tuvalu 08°31'S 179°12'E 1m 1941-1980

M	407	353	307	247	240	231	254	267	197	262	297	407	3469
S	186	185	156	110	136	110	125	159	96	123	128	163	667
CV	45	49	52	44	56	45	47	58	47	46	44	41	19
G	5.7	5.5	5.1	5.2	3.4	5.1	5.2	2.9	4.3	4.3	5.3	6.7	29

9 Tarawa, Kiribati 01°21'N 175°59'E 2m 1946-1984

M	295	203	214	181	149	140	163	126	103	92	117	198	1981
S	215	142	169	128	110	95	130	124	93	106	118	139	831
CV	73	70	79	71	74	68	80	98	90	116	101	71	42
G	1.3	1.5	1.0	2.0	1.3	1.6	1.2	1.2	1.2	0.9	0.9	1.4	4.7
PE	157	146	166	161	145	143	145	157	176	169	173	152	1890

10 Christmas Is., Kiribati 01°59'N 157°29'W 3m 1951-1984

M	89	67	87	179	77	87	68	33	26	29	44	45	832
S	196	106	56	115	76	96	62	53	53	66	105	91	537
CV	220	158	64	64	99	110	91	161	199	224	240	202	64
G	0.4	0.7	2.1	1.8	0.9	1.0	1.4	0.7	0.6	0.5	0.4	0.4	2.6

11 Jaluit, Marshall Is. 05°55'N 169°40'E 1892-1968*

M	283	255	368	381	422	380	361	336	329	324	309	362	4110
S	151	132	136	112	163	121	102	91	112	131	73	160	438
CV	53	52	37	29	39	32	28	27	34	40	24	44	11

*(broken period)

12 Kwajalein, Marshall Is. 08°44'N 167°43'E 1945-1972

M	102	64	153	165	259	257	256	259	288	307	279	240	2630
S	80	49	146	114	130	84	75	86	102	113	109	167	378
CV	78	77	95	69	50	33	29	33	35	37	39	70	14

13 Guam WB, Marianas 13°33'N 144°50'E 1956-1972

M	141	106	113	118	158	157	286	341	401	335	241	165	2561
S	78	74	118	122	168	63	108	121	114	133	93	98	384
CV	55	70	104	103	106	40	38	35	28	40	39	59	15

(The PE values are the best estimates currently available. Most were calculated from sunshine data, the period of record being very short at several places. In a few cases the gamma parameter was calculated from a slightly shorter data period than that stated.)

Discussion - Theme III

(Keynote Speaker)

Q. Interception rates.

Rates vary with rainfall intensity.

Q. On quantifying recharge events.

Recharge modification derived from the lens model.

Q. Pump test duration. Is long time test period necessary.

Long term tests should be run to obtain specific yield but are very difficult to carry out in the dynamic island environment.

Q. Criticism of pump tests in deep wells as will induce saline intrusion.

Agreed.

(Prasad/Coulter) : Climate

Q. How many years satellite data available.

15-20 years

Q. How many rain gauges necessary.

Depends on local requirements and variability of runoff.

Q. (Malaysia) Since there are no rain gauges over much of the country, can extrapolation be used effectively.

Maybe within uniform areas.

(Barker) : Modelling

Q. (Indonesia) What is the value of modelling. Quotes some 2000 production wells with salt water intrusion problems.

It is important to realise that modelling will not always be of significant value. Under the circumstances to which the questioner refers, where a large body of data is available, hydrogeological predictions can often be made simply by reference to observations made under similar situations. However, even then modelling can be of some value; for example, by providing formulae for summarising the data and, hence, eliminating random variations.

(Manners) : Ecology

Q. (Gass) What is the effect of the depth of rooting on the ground-water reserves and is there any relationship between vegetation type and length of travel time to streams thus resulting in a temporary decrease in stream discharge due to changes in vegetation rather than relating decreased discharge due to evapotranspiration.

Not sufficient information due to short duration of the project but would expect some such relationship.

Q. Has the changing vegetation had any effect on the water chemistry.

To date answer seems to be no but would require a longer period of study.

THEME IV WATER RESOURCES ASSESSMENT

COASTAL AQUIFER MODELLING

J A Barker
(British Geological Survey)

1. INTRODUCTION

There is no doubt that the use of models is on the increase and that they can be of great value in understanding and, hence, managing water resources systems. The aim of this paper is to discuss coastal aquifer modelling in general terms covering such topics as: the variety of models in use, how to choose a model, good modelling practice, and the dangers of modelling. Such issues should be of interest not only to modellers (or potential modellers) but also to those who are involved in data collection for models and in using the results of models in the resource management process.

A glossary of terms commonly used in coastal aquifer modelling is provided as an aid to further study of the literature. Also, a short bibliography is provided for the benefit of readers who wish to study the techniques of aquifer modelling.

2. WHY MODEL?

Suppose the behaviour of an aquifer had been monitored in great detail under a very wide range of conditions; including droughts, floods, heavy pumping, no pumping and so on. And suppose all the observations were made available in an easily accessible form. Then in order to predict how the aquifer would behave under a given set of conditions it would only be necessary to look up a similar set of conditions in this vast data bank. Obviously such data is unlikely to ever be available, and it will normally be necessary to extrapolate the aquifer behaviour from very limited data. This extrapolation is best achieved by combining a few physical laws (e.g. mass conservation, Darcy's law) with the data to form a self-consistent model.

A common use of models is to predict the behaviour of an aquifer so that, once economic and other considerations have been taken into account, a choice can be made between various proposed management policies. Perhaps less obviously, a model can be used to determine the properties of an aquifer, through what is essentially a calibration procedure, using data on the response of the aquifer to natural or man-made stresses.

Models can also aid the process of data collection in a number of ways. Once a model is constructed it becomes obvious which parameters need to be measured in the field.

Also, since a model can be used to indicate the sensitivity of the required results to the quality and quantity of data, this can help in the design of a balanced programme of fieldwork. Finally, since a model (especially a computer model) will require data to be input in a consistent and logical manner, this will tend to improve the way in which observations are recorded.

3. TYPES OF MODEL

In Table I an attempt has been made to classify existing coastal aquifer models, and a general description of these various types follows. Concise definitions of the terms employed will be found in the Glossary (Section 10).

TABLE I. A classification of models.

PURPOSE	Prediction		
	Management		
	Identification		
METHODLOGY	Mathematical	Analytical	
		Numerical	Finite difference
			Finite element
			Boundary integral equation
	Analogue		
TRANSITION ZONE	Fully mixed		
	Sharp interface		
SPATIAL DEPENDENCE	Cell		
	Hydraulic		
	Hydrodynamic		
TIME DEPENDENCE	Steady-state		
	Quasi-steady-state		
	Unsteady state		

The first classification is according to the use of the model. The majority of models in use are *prediction models* which simply predict the response of the aquifer to various stresses such as pumping and rainfall. Prediction models usually form the basis of the other two types of model; namely *identification models* and *management models*, which are described in Sections 7 and 8, respectively.

The second classification used in Table I is according to methodology. Most commonly used are the *mathematical models*, which express the behaviour of the aquifer in terms of a set of equations which represent the physical laws of mass conservation and transport. In simple cases these equations can be solved analytically to give unknown aquifer parameters (e.g. heads) in terms of functions of known parameters.

Unfortunately the equations are often very complex and require numerical solution, usually using a computer. Mathematical models normally take the form of sets of differential equations and there are various methods for turning these, approximately, into a set of arithmetical equations which can be handled by a computer. (Cell models, introduced later, tend to produce arithmetical equations directly). The most commonly used of these methods has been the *finite-difference method*, which is now being superceded to some extent by the *finite-element method* which, in particular, is more convenient for problems with irregular geographical boundaries. The *boundary-integral equation method* has proved to be very effective and easy to use on some saline interface problems, but it requires a greater degree of aquifer homogeneity than the other two methods.

The equations that describe the behaviour of an aquifer are mathematically similar to those that describe other physical systems. For example, Darcy's law becomes Ohm's law when head, flow rate and hydraulic conductivity are replaced by voltage, current and electrical conductivity, respectively. Such systems can therefore be used to model aquifers and are then referred to as *analogue* models. These are not extensively used in coastal aquifer modelling, probably because the interface has few physical analogues.

Coastal aquifer models assume one of two conceptual forms depending on how the transition zone is treated. Most realistically the problem is regarded as one of mass transport (of chloride) in flowing water, giving what are known as *fully-mixed* models. The equations are then expressed in terms of water pressure (rather than head because of density variations) and the concentration. Such models have been of limited value in predicting the behaviour of real aquifers because of the difficulty in obtaining data suitable for the determination of the relevant transport parameters (notably the dispersion coefficients). However, theoretical studies using such models do give valuable insight into the behaviour of the transition zone.

Alternatively, and much more frequently, use is made of the *sharp-interface* approximation, and the equations are then expressed in terms of the freshwater and saltwater heads (which, taken together, give the interface position).

Models can also be distinguished by the way variables are assumed to vary in space. In *cell* models the aquifer is divided into a number of regions within each of which the variables are assumed constant. A simple example occurs when a water balance calculation is being performed for the whole of an island; effectively, a single-cell model is then in use. The term *hydraulic* is used to describe models in which variables are considered to vary areally but not in depth. The quantities appearing in such models therefore represent vertical averages of real quantities. Hydraulic models cannot therefore represent vertical flow, although they can approximate the vertical movement of a sharp interface. In *hydrodynamic* models no such vertical averaging is employed, so these are more realistic, and correspondingly complex, models.

In *steady-state* models it is assumed that the value of a variable at any point in the aquifer is independent of time; in other words, the variables depend only on position. This requires that the stresses (pumping, recharge, etc.) can also be regarded as unchanging. If the stresses are varying very slowly in relation to any characteristic response time of the aquifer, then it should be adequate to regard the aquifer as being in a steady state at any instant. This assumption leads to *quasi-steady-state* models. Most realistically, *unsteady-state* (or *transient*) models attempt to simulate the continuous changes of the aquifer. Unlike the other two types, transient models must include parameters representing storage capacity (e.g. specific storage, porosity).

4. CHOOSING A MODEL

Many factors must be taken into account when choosing a model for any particular application. The choice is rarely a clear-cut one but consideration of the following points should help to reduce the range of possibilities:

(i) A model must be capable of reproducing all the essential characteristic behaviour of an aquifer. So, for example, a model based on the Ghyben-Herzberg approximation, which assumes hydrostatic equilibrium, would be inappropriate when there is significant vertical flow.

(ii) A model should be compatible in detail and accuracy with the data that can be obtained. Therefore, for example, a model should not be expressed in terms of parameters which cannot be determined by field measurement or calibration. (Fully-mixed models are not favoured for this reason).

(iii) Staff with suitable training must be available.

(iv) Adequate computing facilities must be available (or obtainable within the project budget).

It is natural, from the point of view of cost, to choose the simplest model that is compatible with the above criteria. However, another good reason for choosing a simple model is that it will usually provide more insight into the behaviour of an aquifer than would a more complex model.

An option worth serious consideration is that of using a hierarchy of models of increasing complexity. Often such a hierarchy develops naturally as a result of increasing understanding of the behaviour of an aquifer (as data increases), and, sometimes, due to the improving technical ability of the modeller.

5. GETTING A NUMERICAL PREDICTION MODEL

In the previous sections some effort has been directed towards making the reader aware of the variety of models in use and encouraging a careful choice. There is little doubt, however, that the most commonly used type of aquifer model is the numerical prediction model, which will therefore be given special attention in this section and the next.

The two main options for obtaining such a model are developing or buying-in, the advantages and disadvantages of which are listed below.

The main advantages of developing a model are: (i) it will be suited to local conditions (e.g. staff and computing equipment), (ii) the assumptions made, and therefore the limitations of the model, will be well understood, and (iii) since the detailed structure of the model will be understood, it should be easy to modify (assuming continuity of staffing). There are two major disadvantages in developing a model: (i) the high initial cost (possibly including considerable staff training), and (ii) the long gestation period before a reliable model is available. This latter point becomes of particular importance if the model results are required within a short project period.

The main advantages of buying-in a model are: (i) the initial cost will be low (often only the cost of handling a magnetic tape), (ii) the model should be working quickly, (iii) benefit is gained of some of the experience of the group which developed the model, and (iv) the model will normally be reliable. The disadvantages are: (i) the code will be difficult to modify (this can be a serious problem), and (ii) some of the assumptions made in developing the model may not be clear. If a model is being bought it should be ensured that it is well documented, that there will be continuity of communication with the developer (for when things go wrong), and that the code is compatible with the local computing environment (both in terms of software and hardware).

Two further options worth serious consideration are: (i) having both the development and running of the model performed by an outside organisation, and (ii) collaborative development with an exchange of staff. The latter option has many advantages and can provide an excellent framework for staff training.

6. DEVELOPMENT OF A NUMERICAL PREDICTION MODEL

Some consideration will now be given to the actual process of developing a model, using the numerical prediction model as an example. Figure 1 provides a schematic representation of this process.

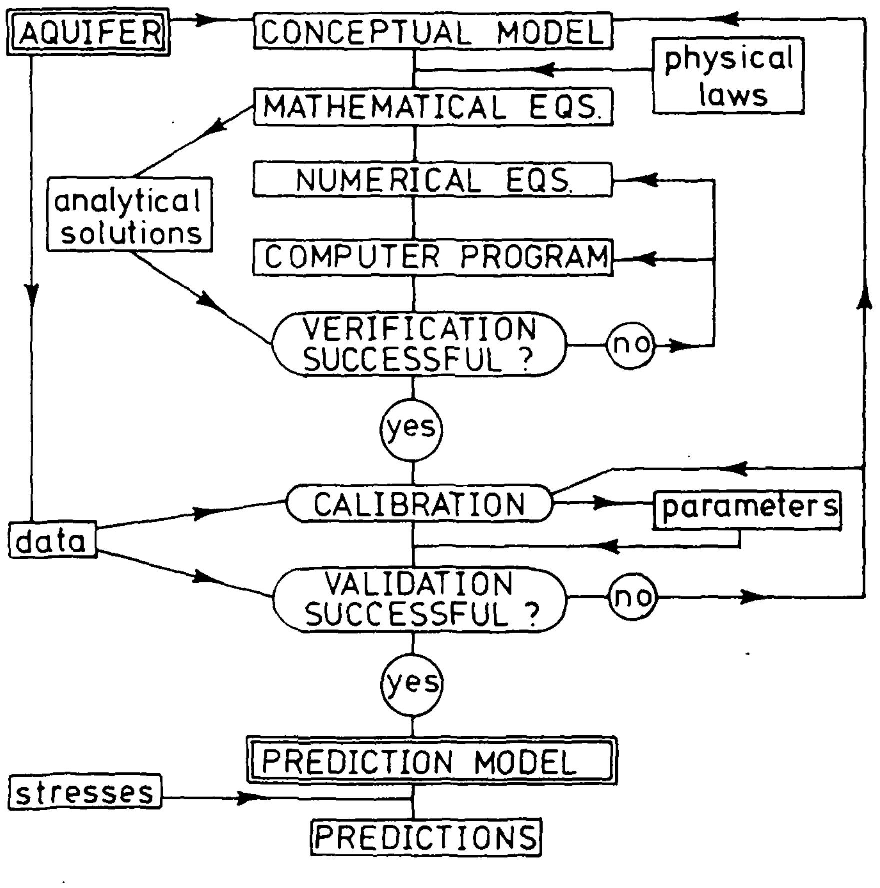

Figure 1. Development sequence for a numerical prediction model.

The first stage in any modelling exercise is to produce a conceptual model of the way the system works. This model will be based on whatever geological, geophysical and hydrological data is available. Three decisions that have to be made at this stage are: (i) whether the model is to be transient or steady-state, (ii) how many spatial dimensions are required to describe the aquifer behaviour, and (iii) what geographical boundaries to choose for the model, although the whole of a small island may reasonably be included.

The next stage is to formulate the model as a set of mathematical equations. This is achieved through the use of various physical laws (e.g. mass conservation, Darcy's law). The equations will normally take the form of second-order differential equations with a set of boundary conditions.

In order to make the solution of the equations tractable using a computer, they must be reduced to a form which involves only simple arithmetic operations. There are various methods for achieving this (Section 3), the most common being the finite-difference technique where the rate of change of a variable is replaced by the difference between the values at two points divided by the distance between the points. The resulting numerical equations are then coded in a high-level computer language such as FORTRAN, so the model takes the form of a computer program. The correct formulation of such numerical equations is the subject of an important branch of mathematics known as numerical analysis, and with which modellers should have some familiarity.

At this stage it is important to check that the program really does solve the original set of differential equations to a reasonable accuracy; this checking process is normally referred to as *verification*. Very often it is possible to consider special cases of the model where the mathematical equations become so simple that an analytical solution is possible. If the computer model does not produce results which are compatible with the analytical solutions there may be errors in either the computer program or in the numerical formulation. Some numerical formulations may only work well for a limited range of parameter values, therefore it is important to investigate a wide range of possible aquifer conditions in the verification process.

Once a model has been verified it can be applied to a real aquifer. Values for some of the parameters required by the model will have been determined from field measurements but many may be quite uncertain. The normal procedure at this stage is to take a set of data representing responses of the aquifer to known stresses (pumping, rainfall, etc.), and adjust the model parameters until the model reproduces these observed responses. This process is referred to as *calibration*, *adjustment* or *identification*; and during the process the model is effectively being used as an *identification model* (Section 8). Model calibration is not a straightforward mathematical or computational problem and often requires considerable hydrogeological judgement.

A model is said to be *validated* once it is capable of reproducing the observed behaviour of the aquifer. To some extent the validation procedure is inseparable from that of calibration, however it is advisable to validate using data distinct from that employed during calibration. If the model does not accurately simulate the observed aquifer behaviour further calibration may be required, or it may even prove necessary to reconsider the adequacy of the conceptual model. In the latter case it will often be sufficient to change only a minor element of the model description, such as a particular boundary condition. Once validated the program assumes the status of a working prediction model.

7. MANAGEMENT MODELS

Aquifer management models are used to indicate which policies are consistent with management objectives and constraints. In addition to some form of aquifer prediction model, these models will incorporate economic and legal aspects of the problem, and may also take account of ecological, sociological or other factors.

A management model must be based on some decision criterion or criteria such as: maximum net economic benefit, minimum cost, or maximum water supply. The constraints on acceptable policies can be very diverse, for example: water quality limits, maximum capital cost, maximum running cost, and minimum supply.

Essentially, two methodologies are used in management modelling. The simplest of these involves choosing the *best* (according to the decision criteria) of a set of proposed policies. The other method, which tends to be much more complex, is to find an optimal policy using the techniques of operational research (e.g. linear programming). The latter method is obviously appropriate when continuous design variables, such as abstraction rates, are involved.

8. IDENTIFICATION MODELS

An identification model is one which, roughly speaking, uses a prediction model in reverse. Given observed responses of an aquifer to various stresses, an identification model might be used to determine: unknown aquifer parameters, stresses (e.g. recharge), or boundary conditions. A simple and common example arises in the analysis of pumping-test data, where observed water levels in boreholes are used to determine the hydraulic properties of an aquifer such as transmissivity and storage coefficient.

Various techniques are used to turn a prediction model into an identification model. Most simply, a trial-and-error variation of parameters is conducted until predicted aquifer behaviour matches field data. Automatic computational procedures have now been developed to replace this techniques, but this is an area of continuing research rather than one where standard procedures are followed.

A problem that often arises in the use of identification models (and model calibration) is that various sets of derived parameters give equally good predictions of the aquifer behaviour. Considerable hydrogeological judgement is then required in order to choose the most appropriate set. The usual cause of this problem is inadequacy of the data, either in terms of quantity, quality or range of measurement.

9. DANGERS AND PRECAUTIONS

Groundwater modelling has many champions and, perhaps even more, critics. Exaggerated claims are sometimes made for what a model can achieve (not necessarily by the modeller) and when expectations are not met the modelling process is often condemned as a whole. There is a general need for a more informed view of what modelling can and cannot achieve.

Aquifer models are just one of several tools available to hydrogeologists and water-supply planners. As with any tool they should be chosen with care and used with skill, and they can only perform a limited range of tasks.

The prerequisites for successful modelling are: adequate data, adequately trained and experience staff, suitable computing facilities, and good communication between modellers, hydrogeologists and planners.

With regard to collecting adequate data, it is inadvisable to leave all modelling aspects of a project until data collection is complete. Model calibration will indicate whether or not adequate data is available, and the option to collect more should be left open as long as possible.

Model results are often computer generated to high precision and this can, incorrectly, be taken to imply great accuracy and, hence, considerable confidence in the predictions. Also, due consideration must be given to the assumptions made in formulating a model and the effects they may have on the final results. More generally, modellers must take care to present their findings in such a way that they will not be misinterpreted or given undue credence.

A problem that should always be addressed is that of the effect of errors in the input data on the final results. A techniques that can help here is that of sensitivity analysis, where the data input to a model is varied within the bounds of expected error and a range of results obtained. The modeller can reasonably be expected to give a most likely prediction, but some confidence range on the results should also be welcomed.

Finally, and by way of recommendation, the possibility of using simple models (e.g. cell models and analytical models) should not be overlooked. These can be improved in stages, perhaps in parallel with staff training and data collection, to produce a hierarchy of increasingly more complex models. The simpler models will provide insight into the aquifer behaviour while the more complex ones will have the potential to provide accurate predictions.

10. GLOSSARY

Terms used in coastal aquifer modelling.

ABRUPT INTERFACE - see Sharp Interface Approximation.

ADJUSTMENT (or CALIBRATION IDENTIFICATION) - Variation of the parameters of a model to obtain a close reproduction of observed aquifer behaviour. (Adjustment and Validation are aspects of the same procedure).

ANALOGUE MODEL - Model whose behaviour can be described by the same mathematical equations (but not the same physical laws) as the aquifer.

ANALYTICAL MODEL - Mathematical model for which the solution is expressed in the form of analytical expressions (not involving derivatives).

AREAL MODEL - Aquifer model in which the dependent variables (e.g. head) vary with geographical position but not with depth.

BOUNDARY CONDITIONS - Description (usually mathematical) of the phenomena occurring at the boundaries of an aquifer model (e.g. constant head or no flow).

BOUNDARY INTEGRAL EQUATION METHOD - (sometimes called the Boundary Element Method). Method of formulating a numerical model where the boundary of the aquifer is divided into discrete elements over each of which the dependent variables (e.g. heads) are assumed to vary in a simple manner.

CALIBRATION - see Adjustment.

CELL MODEL - Model in which an aquifer is visualised as consisting of one (single-cell) or several (multiple-cell) regions in each of which average conditions (e.g. heads, recharge) are considered adequate to characterise the aquifer behaviour. Often used as the basis of management models.

n-DIMENSIONAL MODEL - Model defined in n space coordinates (e.g. an areal model is a 2-dimensional model).

DUPUIT APPROXIMATION (ASSUMPTION) - An approximation where it is assumed that equipotential surfaces are vertical or, equivalently, that flow is horizontal. (Leads to Hydraulic rather than Hydrodynamic models).

FINITE-DIFFERENCE METHOD - Numerical model in which differentials in a mathematical model are approximated by differences over finite intervals in space and time.

FINITE-ELEMENT METHOD - Numerical method in which the aquifer is divided into elements over each of which independent variables are approximated by simple continuous functions (often polynomials).

FULLY-MIXED MODEL - Mathematical model in which a flow equation (for water) is coupled to a mass transport equation (for dissolved solids) - the diffusion-convection equation - by a density/concentration relationship. The independent variables are usually pressure and concentration.

GHYBEN-HERZBERG APPROXIMATION - Assumption that the pressure distribution in a coastal aquifer, with a sharp interface, is hydrostatic. Sometimes taken to include the assumption that the saltwater is static.

HYDRAULIC MODEL - Mathematical model expressed in terms of vertically averaged independent variables (e.g. heads). (see also Dupuit Approximation).

HYDRODYNAMIC MODEL - Mathematical model in which the dependent variables (e.g. heads) vary both horizontally and vertically. Contrast with Hydraulic Model.

IDENTIFICATION - see Adjustment.

IDENTIFICATION MODELS - Models used to determine aquifer parameters - which can then be used in prediction and resource management models.

INITIAL CONDITIONS - Values or derivatives of dependent variables (e.g. heads) given at a particular time which determine (in part) the subsequent behaviour of an unsteady-state model.

MANAGEMENT MODEL - Model which combines hydrogeological prediction with economics to provide a basis for management decision.

MATHEMATICAL MODEL - Representation of the behaviour of an aquifer by a set of mathematical equations.

NUMERICAL MODEL - Mathematical model in which the continuous variables are represented by a set of discrete numerical values and the equations are solved (approximately) by arithmetic operations (normally using a computer).

PREDICTION MODEL - Model which simulates the behaviour of an aquifer in response to various stresses (e.g. pumping).

QUASI-STEADY-STATE MODEL - Model where unsteady-state behaviour is approximated by a sequence of steady-state situations.

SECTIONAL MODEL - Model in which independent variables are assumed to be independent of distance in a particular geographical direction (normally the direction parallel to the coastline).

SENSITIVITY ANALYSIS - Study of the effect of small changes in input parameters on the behaviour of a model.

SHARP INTERFACE APPROXIMATION - Assumption that the transition zone between freshwater and saltwater is negligibly thin.

SHARP INTERFACE MODEL - Mathematical model in which an equation for the freshwater head is coupled to an equation for the saltwater head by an equation relating the interface position to these heads. (Contrast with Fully-Mixed Models).

STEADY-STATE MODEL - Model in which the dependent variables are independent of time.

TIP - see Upper-Toe.

TOE - Line along which a sharp interface intersects the base of an aquifer.

UNSTEADY-STATE (TRANSIENT) MODEL - Model in which the dependent variables are time dependent.

UPPER TOE (TIP) - When saltwater has intruded into a confined aquifer the line along which the interface intersects the upper boundary of the aquifer is known as an upper-toe. (Its existence implies that there is a net inland flow of freshwater).

VALIDATION - Check that a model accurately reproduces the observed behaviour of the aquifer against which it has been adjusted. (This is not a univerally adopted definition and sometimes the term is used interchangeably with Verification).

VARIABLE - Quantity represented by a symbol in a mathematical model or a physical measurement in an analogue model. Subdivided into: Independent Variables (e.g. coordinate, time), and Dependent Variables (e.g. head, concentration).

VERIFICATION - Process of checking that a numerical model accurately solves the intended set of mathematical equations. (Not a universally adopted definition - see also Validation).

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NEW TECHNOLOGY FOR WATER RESOURCES DATA

David Scott, Solomon Islands

Introduction

New technology for the collection, processing and storage of water resources data is being acquired by Solomon Islands in an attempt to overcome problems imposed by shortage of staff and remote sites with difficult access. The combination of pressure transducers for water level sensing, tipping bucket raingauges for rainfall measurement and solid state data loggers for data recording is expected to provide a simple and robust system. A dedicated micro-computer system will allow data transfer from loggers and will greatly extend data processing capability by the use of the micro-TIDEDA software for hydrological data storage, editing, retrieval and analysis.

A set of solid-state rainfall recorders has been supplied as part of a United Kingdom technical assistance project and installation of this equipment has begun. Further equipment will be obtained from the EEC funded Pacific Energy Programme. Tender documents and technical specifications have been completed for the required water level recorders, rainfall recorders and stream gauging equipment. A micro-computer system comprising the micro-TIDEDA software and the necessary hardware will be supplied by the New Zealand Bilateral Aid Programme. An evaluation of the equipment will be carried out as part of Solomon Islands' participation in the Pacific Energy Programme.

The Equipment

Brief profiles of the various components of these new developments are:

(i) Storage Raingauge Project (U.K. assistance)

Two types of raingauge are involved, both the result of developments at the Institute of Hydrology;

(a) A daily recording gauge comprising a moulded plastic tipping bucket mechanism, a fibreglass housing and a solid-state logger. The logger has capacity for 86 daily values and is encapsulated in plastic. A small magnet is used to operate the logger reed switches which control LCD data readout, clock timing and resetting.

(b) A variable time period recording gauge comprising a modified Rimco tipping bucket raingauge and a solid state data logger with capacity for 4096 values (approx 5½ months at 1 hour time interval). A simple field data reader provides LCD data readout for field inspection. Office data translation will use an Epson micro-computer and eventually will transfer data directly to the micro-TIDEDA system.

(ii) Hydropower Assessment Project (Pacific Energy Programme)

Four types of equipment have been described in the tender documents:

(a) Basic solid state water level recording equipment comprising:

- a water level sensor (pressure transducer) with a pressure range of approximately 0–0.2 bars and resolution within ±0.5% of full range,
- a solid state data logger able to sample at 24 hour intervals and with sufficient memory to store data from 80 days observations,
- exchangeable components and ancillary equipment as required for operation and data output.

(b) High resolution, high capacity, solid state water level equipment comprising:

- a water level sensor with a pressure range of approximately 0–0.75 bars and resolution within ±0.1% of full range,
- a solid state data logger able to sample at a range of time intervals from 15 mins to 6 hours or more and with sufficient memory to store data from 80 days of 30 min interval observation,
- exchangeable components and ancillary equipment as required for operation and data transfer using the standard RS232C interface.

(c) Solid state rainfall recording equipment comprising:

- tipping bucket raingauge,
- solid state data logger able to store daily rainfall totals and with sufficient memory to store data from 80 days observations,
- exchangeable components and ancillary equipment as required

for operation and data output.

(d) Stream flow current meters.

(iii) Micro-Computer System (N.Z. assistance)

This system includes software and hardware.

(a) Software comprising micro-TIDEDA running on the CP/M operating system with Datastar and Wordmaster. The micro-TIDEDA software is for processing time dependent data and allows editing of data, retrieval in a range of forms and enables simulation of hydrological processes.

(b) Hardware comprising:

- micro-computer, 8 bit CPU with 64k RAM and RS232C interface,
- dual 8 inch floppy disk drives,
- VDU terminal,
- low cost printer,
- low cost plotter.

Conclusion

The new system is expected to have a number of advantages over existing procedures. In particular the equipment should provide greater reliability, allow less frequent field inspection and be simple to operate. Computer storage of hydrological data will make it possible to react quickly to requests for water resources data. Since many such requests come from consultants or advisors who are visiting the country for relatively short periods this should be very useful.

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SECTION G06: SYSTEMS FOR STORING GENERAL HYDROLOGICAL DATA

"SOFTWARE FOR ARCHIVING AND RETRIEVING TIME-DEPENDENT DATA"

1. Purpose and Scope

To store hydrological data, to allow editing of the data, to allow retrieval of records in any required form, and to enable simulation of behaviour of a process.

2. Description

MicroTIDEDA is a computer software for processing time dependent data, particularly hydrological data. It stores on disc files all kinds of time series such as water level, rainfall, temperature, hydraulic gate setting, turbine output, the three components of a wind vector, and sediment concentration. Time is stored with each data point. Deletion of redundant values that can be recovered by interpolation (termed "compression") enables substantial economies in the storage volume.

Adjustments may be made when data is entered to correct for recorder maladjustments. Any part of a stored record may be replaced or deleted and additions may be inserted without disturbing the rest of the record.

Rating curves may be stored with the record. A set of rating curves which describes a relationship that changes many times may be stored. These rating curves may be revised as new measurements come to hand. Such ratings enable conversion of recorded levels to discharge.

Processing of stored data is specified using a "language" and different kinds of data, eg. discharge and rainfall, are automatically processed in the manner appropriate to their kind.

A set of mathematical statements representing a physical system can be used on the stored data to represent a physical process, with up to 15 input records and up to 15 output records. Different records may be read simultaneously and synthetic record derived from these. This may be used for making good a period of missing record. or for analysing how changes in one component of a system will affect another; eg. how developments such as hydroelctric power, irrigation or other river control works will change the flow regime.

3. Input

Original field records of water levels, rainfalls and other phenomona (typically on charts or 16-track punched tapes, or as signals from telemetry units); measurements of discharge, sediment concentration, gate settings, etc; rating curves relating two or more of these variables; language to direct processing, editing archiving and simulation.

4. Output

Archieved data are stored on magnetic discs. Data may be produced in machine readable formats as required by other computer software. Display options using a printer or screen include:

a) calendar tabulations of averages or totals for days, weeks, months or years;

b) tabulations and print-plots of value versus fraction of time exceeded;

c) plots of one time series against another;

d) mass-curves and other similar analytical aids to display simulation results;

Display options that use graphical plotters include:

a) graphs of values versus time eg, hydrographs, with the option of showing calibration measurements as symbols;

b) rating curves with the option of showing calibration measurements as symbols.

5. Operational requirements and restrictions

a) Installation: 5 man days by one technical officer.

b) Operational training: 20 man days by one technical officer, assuming recipients are familiar with hydrological practices.

c) Computer hardware and operating system: microTIDEDA and its associated programs may be run on any floppy disc microcomputer that uses a Digital Research CP/M operating system on a Zilog Z 80 or Intel 8080 processor and will exploit a high speed maths chip (AMD 9511 or Intel 8231 A) if one is installed. An Enviro-Labs model 311 paper tape reader is used to translate 16-track punched tapes.

d) System capacity: One double density floppy disc (500K can hold up to approximately 150 years of daily information, or 18 months of 15 minute information, and many floppy discs can be maintaned in a library. Alternatively, the system can be operated on hard discs with the advantages of faster access times, larger amounts of storage and multiple user facilities. Compression of data increases, typically by an order of magnitude, the amount that can be stored without loss of accuracy.

6. Form of Presentation

Manuals in English and compiled programs on floppy disc.

7. Operational Experience

The TIDEDA system has been the base of the New Zealand Ministry of Works and Development national hydrological data archive since 1972. The micro-TIDEDA version described herein has operated on microcomputers with 16 geographically dispersed hydrological field parties since installation was completed in mid 1983.

8. Originator and Technical Support

Originator: Hydrology Centre of Ministry of Works and Development.
Supply and technical support: Micro Controls and Systems Ltd.

9. Availability

From HOMS National Reference Centre for New Zealand

10. Conditions of Use

Micro Controls and Systems Ltd will charge a royalty and a fee for handling and technical support.

ASSESSMENT OF GROUNDWATER RESOURCES ON CORAL ATOLLS : CASE STUDIES OF TARAWA AND CHRISTMAS ISLAND, REPUBLIC OF KIRIBATI

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Water Resources of Small Islands, Suva, Fiji
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Commonwealth Science Council)

1. INTRODUCTION

The assessment of groundwater resources including the estimation of safe yields on coral atolls is becoming ever more important as demand for water increases. The increased demand, caused largely by population growth, has been quite significant and has led, in some cases, to overpumping of freshwater lenses. Upconing of the transition zone between fresh and seawater in the vicinity of pumping wells or galleries has generally resulted, especially during periods of below average rainfall. The salinity of the pumped water can increase during such periods to levels well above established standards (WHO, 1971) for drinking water.

Increasing pressure on existing water supplies on coral atolls has led, in some cases, to detailed investigations of the groundwater resources and alternative water supplies. Generally, alternatives such as rainwater collection, desalination or importation have been found economically non-competitive with groundwater for village water supplies. On an individual basis, however, rainwater is often preferred and used for drinking water. Other uses such as washing and bathing generally rely on groundwater either from local wells or from reticulated supplies feeding to communal tanks, standpipes or connections within houses.

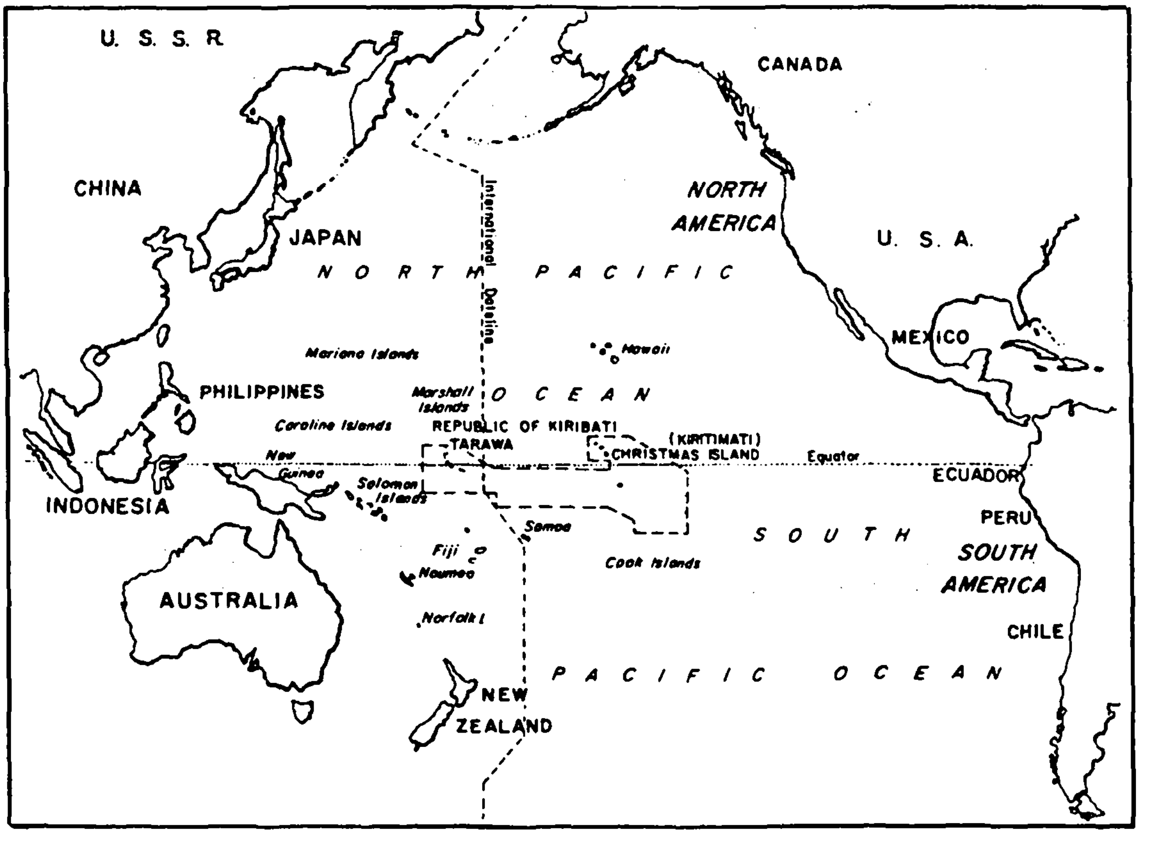

FIG 1 CHRISTMAS ISLAND & TARAWA LOCALITY MAP

In order to develop groundwater supplies from freshwater lenses on coral atolls without harming the long term viability of these resources, it is necessary to determine their location, extent and sustainable yield. This paper outlines methods used, problems encountered and solutions offered in the assessment of such groundwater resources on Tarawa and Christmas Island in the Republic of Kiribati. It also offers suggestions for future workers in this field about the usefulness of the various methods employed.

2. BACKGROUND

Tarawa and Christmas Island are both located just north of the equator and are on either side of the International Date Line ($1^\circ30$'N, $173^\circ00$'E and $2^\circ00$'N, $157^\circ30$'W, respectively) as shown in Figure 1. Tarawa atoll, the administrative capital of the Republic of Kiribati with a population of slightly more than 20,000, has a land area of about 31 km^2 (Figure 2). Christmas Island, the largest coral atoll in the world in terms of land area (320 km^2), has a relatively small population of about 1400 (Figure 3).

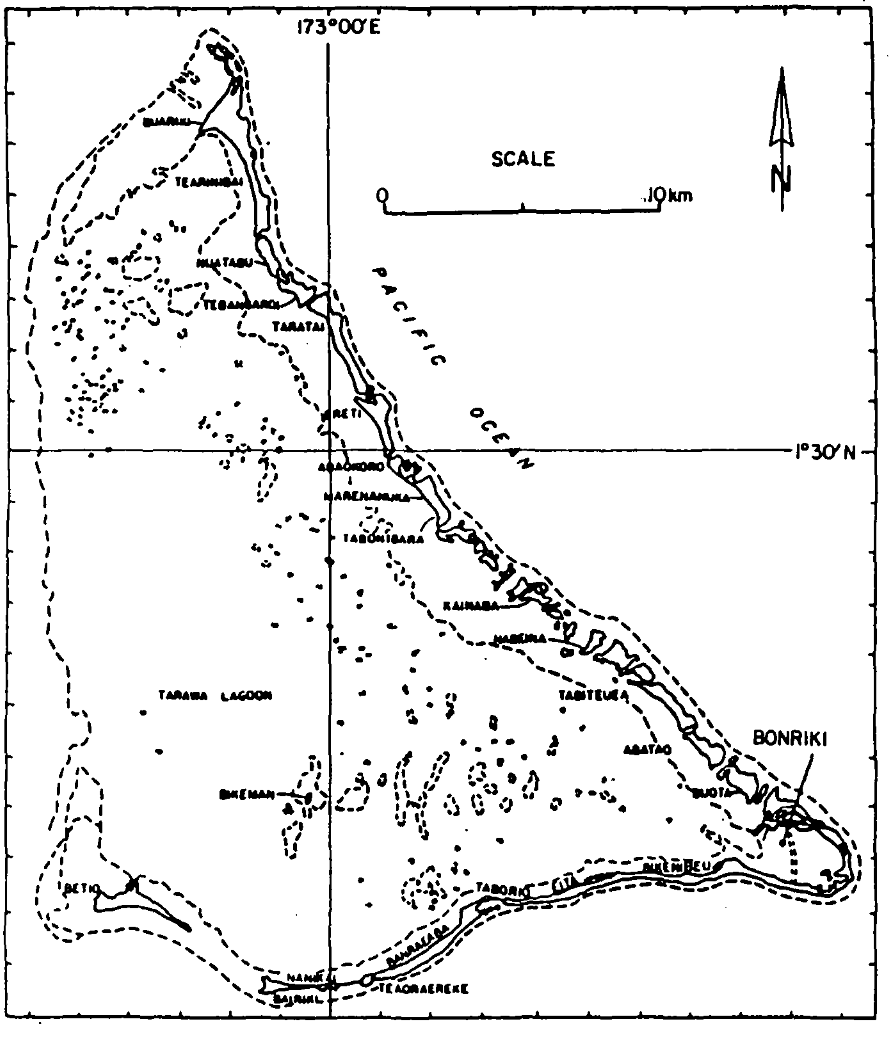

FIG. 2 MAP OF TARAWA

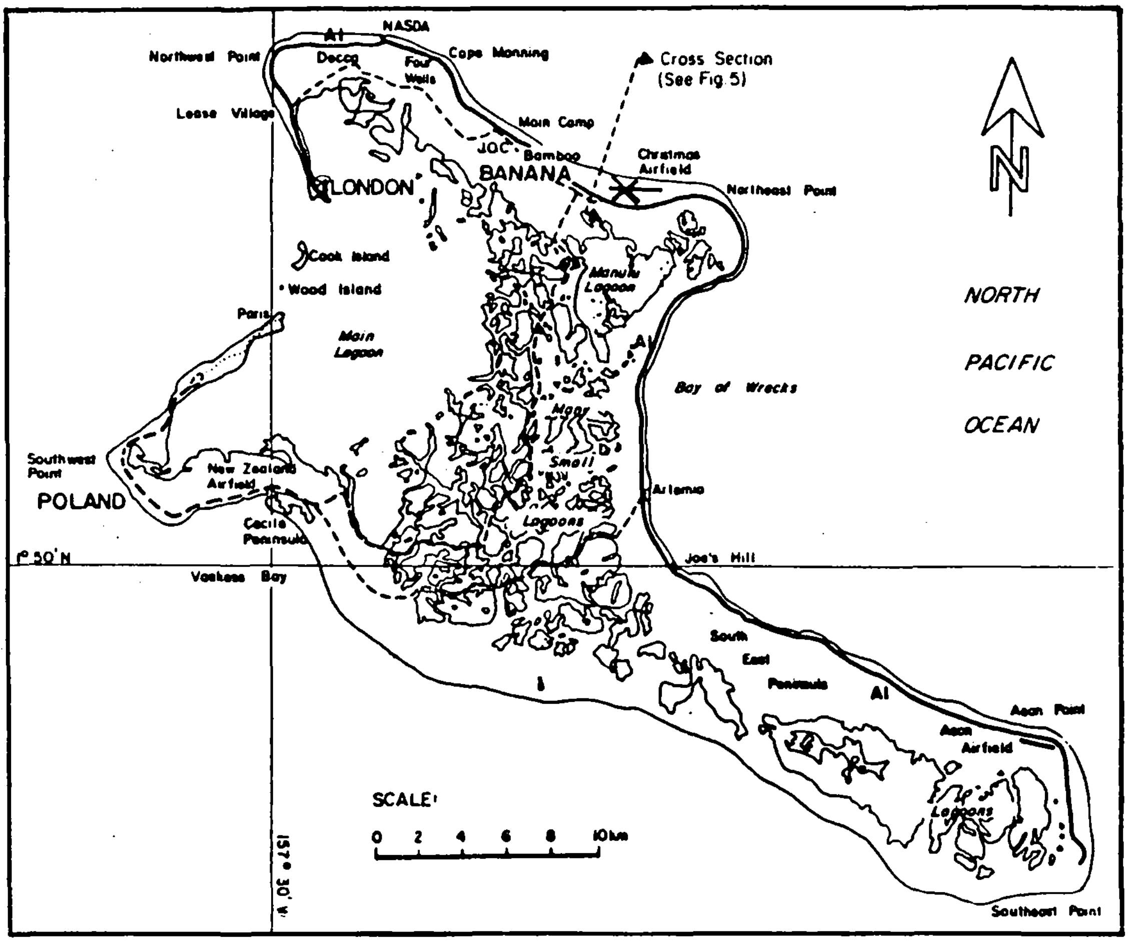

FIG. 3 MAP OF CHRISTMAS ISLAND

A number of reports and papers have been published regarding the geology, hydrology and water resources of these atolls. The more recent publications include:

(a) Tarawa Murphy, 1981 (drilling report); Jacobson and Taylor, 1981 (geology, resistivity, initial safe yield estimates); DHC, 1982 (hydrology, modelling, safe yield estimates, engineering proposals to upgrade and expand present water supplies) and Daniell, 1983 (summary of results).

(b) Christmas Island. Murphy, 1982 (drilling report); Falkland, 1983a (hydrology, resistivity, modelling, safe yield estimates, engineering proposals to upgrade existing water supplies) and Falkland, 1983b (summary of results).

It is not the intention in this paper to reiterate the above work but rather to outline the major features.

3. OUTLINE OF TECHNIQUES USED

Combined drilling and electrical resistivity programs were used on both atolls. The electrical resistivity survey combined with electrical conductivity measurements of exposed waters (wells, pits, galleries and ponds) and observations of topographical features allowed the extent of freshwater lenses to be determined. Salinity profiling of boreholes and electrical resistivity soundings established the depths of lenses.

In both investigations, water quality tests including physical and chemical analyses were undertaken. Water samples from the boreholes were tested on site for electrical conductivity and pH. Later, laboratory tests were made of the major ions, hardness, alkalinity, electrical conductivity and total dissolved solids. In the Christmas Island case, radiological tests were also carried out to determine if any residual radiation was present in the deeper lens water as a result of atmospheric nuclear tests at this location in the late 1950's and early 1960's.

Water level monitoring was conducted at a number of sites to determine the response of the groundwater to tidal and other influences and, hence, attempt to determine aquifer permeability. Cores were obtained from a number of boreholes for geological profiles to be examined and for laboratory testing of permeability and porosity. During drilling, tests were carried out to determine field values for permeability in the vicinity of the boreholes. A dye movement experiment was performed on Christmas Island in an attempt to yield another estimate of permeability. Finally, water samples from different depths were tested for tritium levels in order to provide information on residence times in the lenses.

To model the long term behaviour of the lenses once their location, extent and depth was determined, detailed analyses cf rainfall, pan evaporation, vegetation and other data were used to estimate monthly recharge values. This information was input together with different levels of artificial extraction and estimates of relevant aquifer parameters to a 'sharp interface' type computer model based on Ghyben-Herzberg theory. Estimates of sustainable yield for lenses were obtained using the model and the assumption that extraction from lenses should not exceed about 20 to 30 percent of the long-term average recharge to the lenses. Similar percentage values were previously used in studies on Guam (Mink, 1976) and on Kwajalein in the Marshall Islands (Hunt and Petersen, 1980).

During the drilling programs permanent monitoring equipment was installed to allow long term monitoring of the behaviour of the lenses in response to natural and artificial extraction (pumping) conditions.

4. MAJOR FEATURES

(a) Combined drilling and electrical resistivity program

The combined drilling and resistivity program was found to be particularly suitable to this type of water resource assessment. Salinity profiles obtained during drilling allowed comparisons of freshwater thickness estimates to be made with the electrical resistivity soundings. It was found, mainly because of the relatively uniform geological conditions on these atolls, that the latter method was a sufficiently accurate method of determining fresh water thickness especially near the centre of lenses (Falkland, 1983a). This meant that the cheaper, quicker resistivity method could be used with reasonable confidence in areas away from boreholes. In practice, a ratio of about 1 borehole to 10 resistivity soundings was used on Tarawa. This ratio was decreased to about 1 to 18 on Christmas Island where a total of 24 boreholes were drilled and 445 soundings were made.

(b) Drilling rig and methods

A most suitable drilling rig was found to be a 40 hp diesel powered JACRO 200 rotary drilling rig with N size rods and casing. The rig was well able to drill 75 mm holes to depths of about 30 metres. Drilling to this depth allowed profiles showing salinity (electrical conductivity) variations from the fresh lens water near the watertable through the transition zone to seawater to be established. An example of such profiles for Christmas Island is shown in Figure 4. A portable electrical conductivity meter costing about $300 was used for this purpose. Water samples were obtained during drilling of each hole at depth intervals of between 1.5 and 3 metres. By comparing electrical conductivity (EC) with chloride ion concentration (Cl) for a number of samples, the limit of freshwater was selected as 2500 EC units (umhos/cm). This was equivalent to 600 ppm Cl which is the maximum permissible limit for drinking water (WHO, 1971).

The drilling rig, with a total weight of 500 kg, was able to be dismantled into "two man lift" copmponents. This has definite advantages when limited lifting equipment is available. The aluminium construction of mast and frame is ideally suited to the corrosive environments on coral atolls. The cost of the drilling rig was approximately $13,000 while the associated equipment (drill rods and casing, bits, tools) cost about $5000 (Australian dollars, 1983 prices).

Boreholes were drilled in patterns both across the island to establish cross sectional shapes of lenses and along the island to determine logitudinal variations. An example of a cross section showing boreholes and lens shapes on Christmas Island is shown in Figure 5.

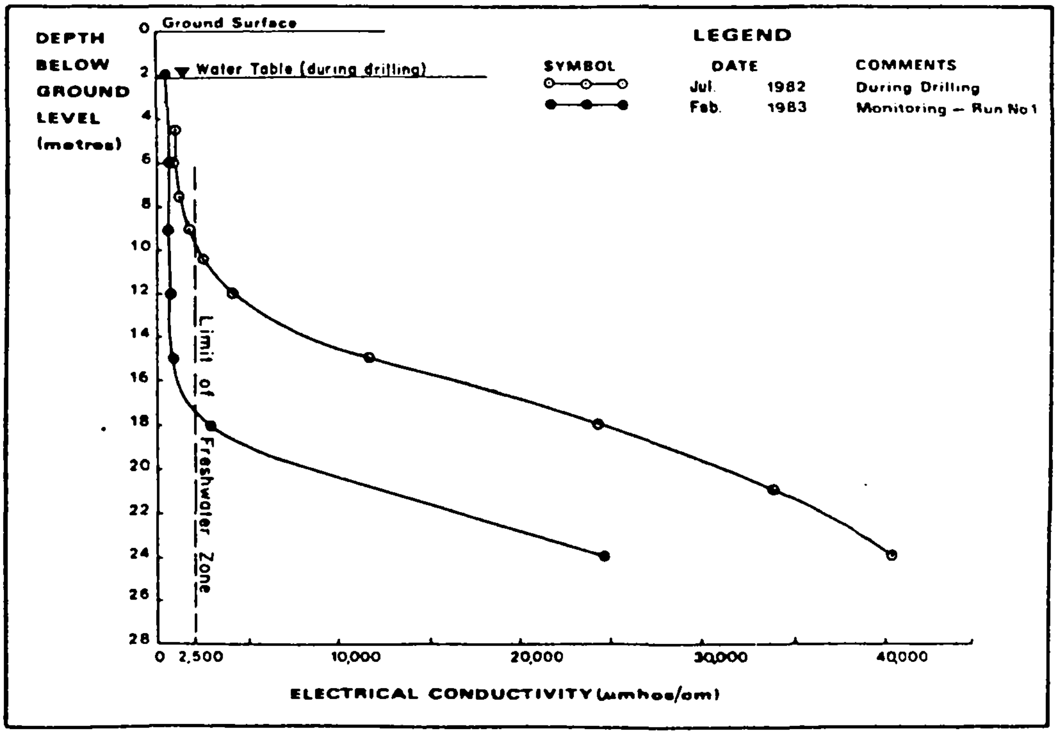

FIG.4 BORE DEPTH V. ELECTRICAL CONDUCTIVITY OF FLUID, BORE BA3

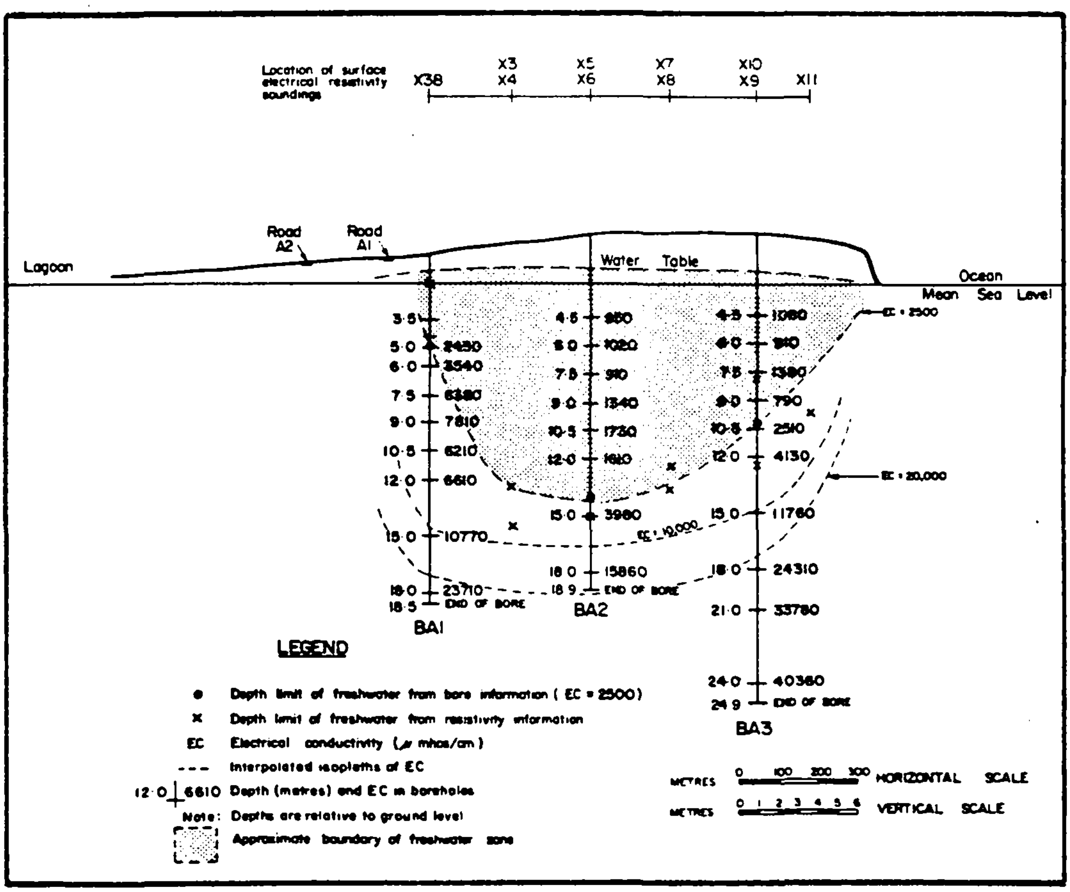

FIG.5 CROSS SECTION THROUGH BORES BA1, 2, 3 AT BANANA, JULY 1982.

(c) Permanent Monitoring System

Apart from enabling accurate salinity profiles to be obtained during drilling, the drilling program allowed the installation of permanent monitoring systems at each borehole. Regular monitoring is considered an essential element of water management of such freshwater lenses under artificial extraction conditions. Even under natural conditions monitoring provides data on the movement of the lenses which is very useful for the calibration of computer models used for the analysis of such lenses. The monitoring system at each hole consists of a set of nylon tubes terminated at different depths, between which bentonite layers have been inserted to hydraulically isolate the tube ends. Selected 6 mm diameter coral gravel (sieved locally) was installed around each tube between the bentonite layers. A typical installation is shown in figure 6. On Tarawa, the first boreholes had 65 mm diameter PVC slotted casing placed inside the holes. This was found to provide an easy flow path along the outside of the casing. This caused mixing between the various levels, as evidenced by the similarity in electrical conductivity readings. Later bores on Tarawa and those on Christmas Island indicated that the deletion of the PVC casing prevented this leakage problem from occurring. Figure 4 shows the differences between salinity profiles obtained during drilling and the first monitoring run at two boreholes on Christmas Island. A large amount of rainfall associated with the 1982 El Nino event in the intervening six months accounted for the increase in freshwater in the boreholes.

(d) Permeability and Porosity Estimates

The drilling program also allowed estimates of permeability and porosity to be obtained. Both constant and falling head techniques (Hvorslev, 1951) were used at various depth intervals during the course of drilling the holes. Using the latter method, which was considered more reliable, average permeabilities of 5 to 8 m/day were obtained in the areas where freshwater lenses occurred on Christmas Island. Slightly higher values (about 12 m/day on average) were found on Tarawa. Values were found to increase with depth particularly below about 10 to 20 metres. This is consistent with observations of the geology made during these studies and those on other atolls, for example, Enewetak (Wheatcraft and Buddemeier, 1981) and Kwajalein (Hunt and Peterson, 1980) in the Marshall Islands.

The upper recent (Holocene) sediments of lower permeability are found to overlie higher permeability Pleistocene limestone. Often a distinct unconformity is found between 10 to 20 metres. The upper sediments are those of direct importance to the establishment of freshwater lenses.

Porosity values determined on laboratory cores were found to vary between about 30 and 40 percent.

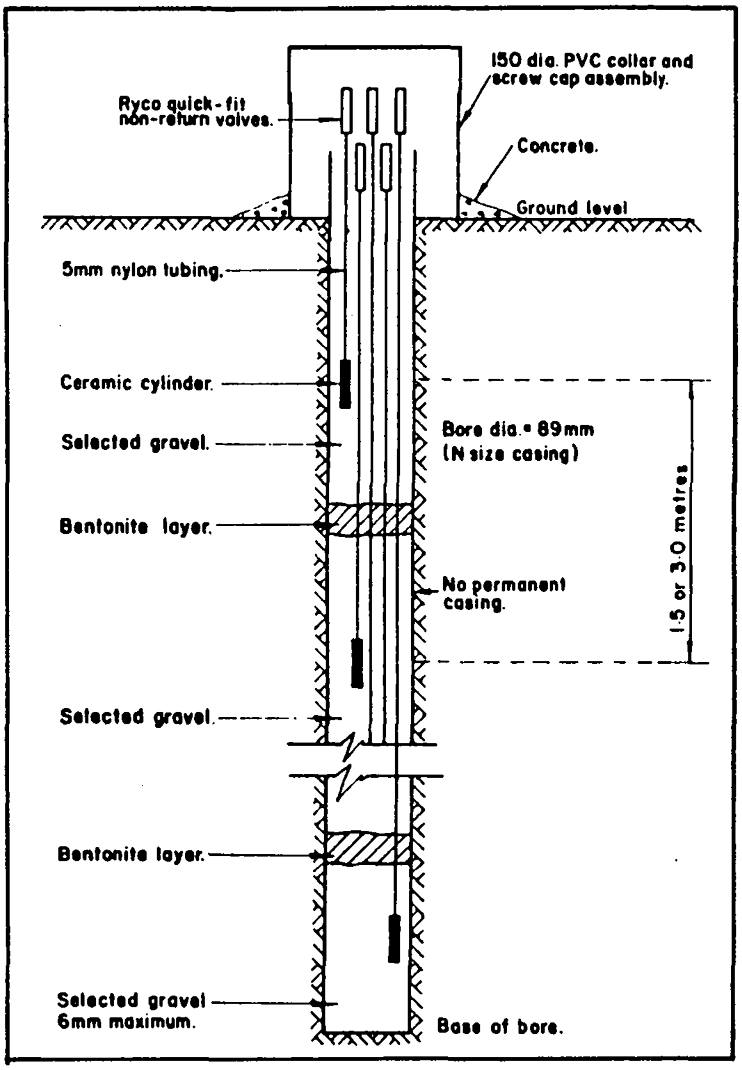

FIG. 6 BOREHOLE MONITORING SYSTEM

(e) Electrical Resistivity

The electrical resistivity program was found to be a particularly useful method for determining freshwater lens thicknesses. An ABEM Terrameter SAS 300 instrument and the Wenner electrode array were used on both islands. The Lee modification to the Wenner array, incorporating a fifth electrode, was used at many locations to check for lateral inhomogeneity effects.

Further details are provided in Jacobson and Taylor (1981) for Tarawa and in Falkland (1983a and 1983b) for Christmas Island.

Field data was analysed using a computer program called 'Inverse' (Merrick, 1977 and Davis, 1979). The computer program, while not essential for the analysis of field data, allowed quick results to be obtained. It was found that most soundings were interpreted in terms of four layer models. Such a model corresponds to the following physical interpretation: an upper soil moisture zone typically between 150 and 300mm thick overlying an unsaturated zone with a thickness on average of 2.5m. Below this is a freshwater zone typically between 5 and 15m thick which overlies more saline water ranging from slightly brackish through to seawater.

Comparison between estimates of freshwater thickness based on salinity profiles and resistivity soundings at borehole locations indicated that the latter method was reasonably accurate in areas where the freshwater thickness exceeded 5m. An example comparison for a Christmas Island borehole is shown in Figure 7. Below this thickness, estimates from the resistivity method were not particularly good. In thin lens conditions, the freshwater zone is 'masked' by a relatively thick overlying unsaturated zone with a much higher resistivity (principle of suppression, Mooney, 1980).

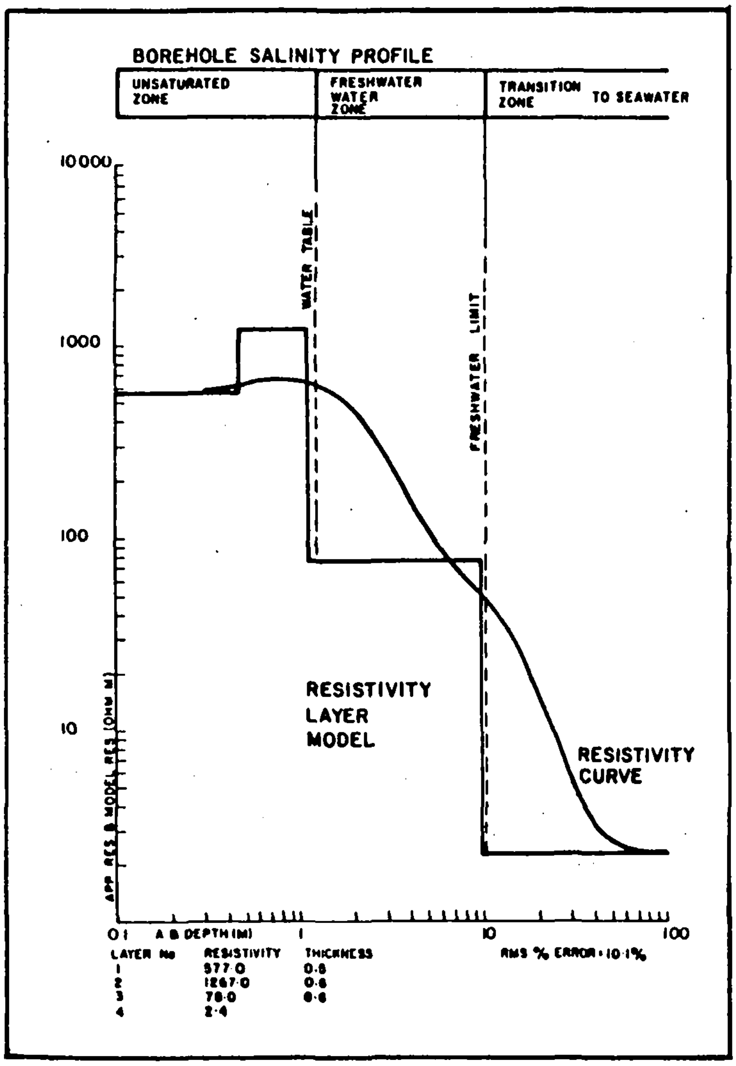

FIG. 7 COMPARISON OF BORE & RESISTIVITY INFORMATION, RESISTIVITY SOUNDING BORE BA3 AND X343.

One of the basic interpretative rules employed was not to rely on any one single sounding but rather to view its results in relation to nearby soundings. In this way an overall picture of lens thickness was established. Topographic features and electrical conductivity readings of exposed water were also used as a guide. Contour plans of freshwater thickness were thus developed.

(f) Water Table Measurements

Surface water level recorders (Leupold-Stevens F type) were set up at locations across lenses in both studies. It has been suggested (for example, Cox, 1951 and Anderson, 1976) that such observations can allow estimates of the bulk hydraulic conductivity or permeability to be made. A method has been proposed by Carr and Van der Kamp, 1969 for this purpose. In practice, it was found that unless the tidal fluctuations on the lagoon side were significantly less than those on the ocean side it was difficult to calculate permeability by the method proposed. It is suggested that permeability estimates are probably better obtained from borehole tests (but not large scale pump tests) as described earlier. While these tests are much more localised in their extent an overall picture can be built up of the aquifer permeability from repeating the tests at all boreholes.

Measurements of water level were used in conjunction with survey data to determine average heights of the water table above mean sea level at various locations. Under theoretical sharp interface (Ghyben-Herzberg) conditions the depth of freshwater below mean sea level is 40 times the head measurement (height of water table above mean sea level). Under actual conditions on coral atolls, however, sharp interfaces do not exist but rather transition zones develop between fresh and seawater. The concept of a modified Ghyben-Herzberg (GH) ratio can be introduced to describe the actual conditions. Modified GH ratios relate the head above mean sea level to the thickness of freshwater between mean sea level and a lower limit defined by a selected value of electrical conductivity or some other suitable water quality parameter. For Christmas Island, the average of modified GH ratios was about 1:20 while for Tarawa the ratio was about 1:30.

A note of warning is given at this stage regarding the use of head measurements for estimating freshwater lens thicknesses. It was found in some locations, particularly on Christmas Island, that erroneous predictions of freshwater lens thickness would be made using such measurements. For example, at two sites approximately 1 kilometre apart, heads were found to be very similar (average value of about 0.45m above mean sea level) yet the thickness of freshwater, as determined from adjacent bores, were, respectively, about 8m and 1m. Thus, at the former site reasonable estimates of freshwater thickness would be made using the head measurements but at the latter site the estimated thickness would be considerably in error. It is, therefore, suggested that extreme caution be exercised if using head measurements as a basis for determining freshwater thickness and results should be viewed as preliminary only. Alternative methods such as drilling and sampling and geophysical techniques including both electrical resistivity and electromagnetic methods should be used wherever possible.

(g) Dating of Freshwater Lenses

Tritium analyses of water samples from three bores on Christmas Island confirmed that the age of the freshwater is relatively young. Residence times are less than about 20 years even in the deepest lenses on this atoll. Such data confirms simple flow calculations based on the amount of average annual recharge compared with the total volume of lenses.

(h) Modelling

Modelling of the lenses was undertaken to determine safe yields or extraction rates. Firstly, a recharge model was used to determine what proportion of rainfall actually recharged the freshwater lenses. The model accounted for both shallow and deep rooted vegetation. The latter vegetation, predominantly coconut trees, was found to have a very significant effect on recharge. The roots of these trees not only intercept moisture from the upper soil moisture zone but also transpire water directly from the capillary zone above the freshwater lenses. These deeper roots enable them to survive extensive drought periods during which shallow rooted vegetation, such as grass, dies off. Inputs to the recharge model included monthly rainfall and evaporation data and estimates and measurements of soil moisture zone thickness, field capacity, wilting point, ratios of shallow to deep rooted vegetation types, the proportion of roots for deep rooted vegetation which penetrated to the water table and appropriate crop factors. Full details for Christmas Island are contained in Falkland (1983a) and for Tarawa in DHC (1982) and Daniell (1983). The effects of different proportions of coconut trees, as a percentage of the total area of lenses, and average annual recharge is shown in Figure 8 for Christmas Island.

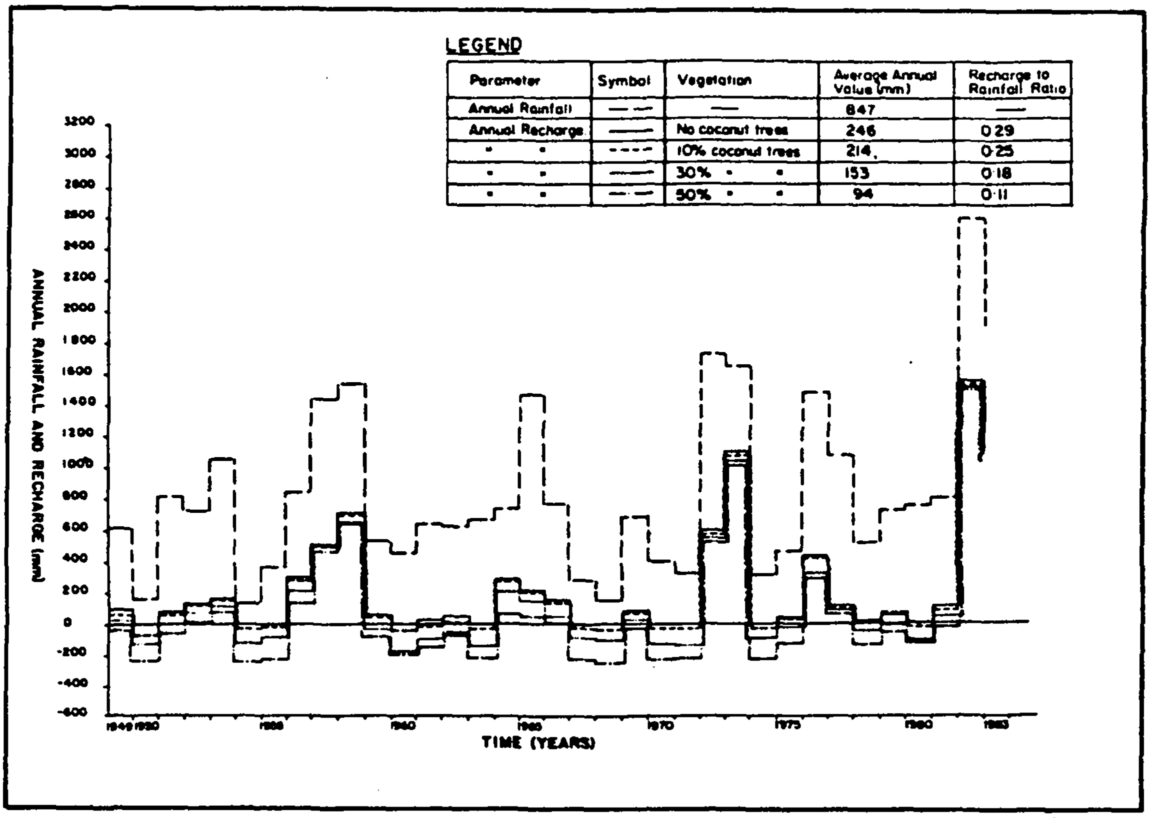

FIG. 8 COMPARISON OF ANNUAL RAINFALL & RECHARGE, 1949—1982.

The second stage was to input recharge estimates on a monthly basis to a lens model. The model used was a sharp interface one, based on that outlined by Chidley and Lloyd (1977). Other required inputs were lens shape as defined by an array of 100m by 100m nodes, permeability, porosity and modified GH ratio. The model was calibrated using known freshwater thicknesses in mid 1982 and early 1983 in the case of Christmas Island.

One of the major findings, after calibrations were done and test runs were conducted using the full period of recharge data, was the significant influence of coconut trees on the sustainable yield. For Christmas Island, where four major lenses were modelled, the effect is shown in Figure 9. This is not surprising due to the same significant influence of this vegetation on recharge. It can be seen for a given lens area the sustainable yield is approximately halved if 30 percent of the area is covered by coconut trees. It is, therefore, in the interests of maximising water resources to remove coconut trees from lens areas. This may conflict in many situations with other objectives or priorities and is not necessarily a socially acceptable strategy.

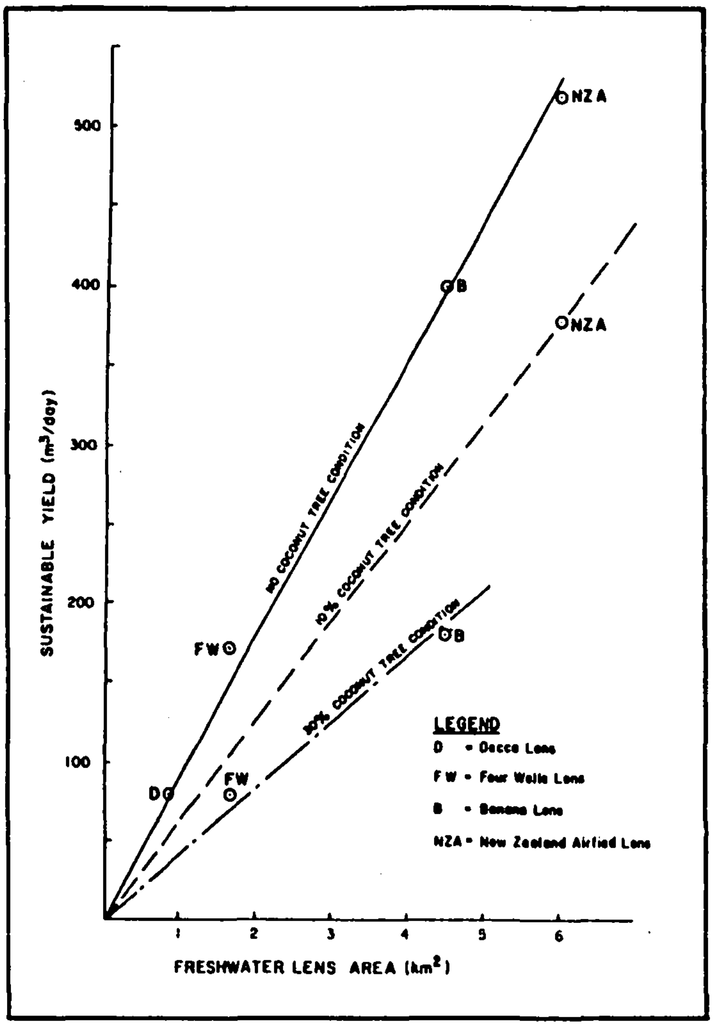

FIG. 9 RELATIONSHIP BETWEEN LENS AREA & SUSTAINABLE YIELD FOR VARIOUS VEGETATION CONDITIONS.

5. CONCLUSION

A number of the techniques employed for the assessment of groundwater resources on coral atolls have been outlined. It is hoped that some of these experiences may be of benefit to other workers in similar situations.

6. ACKNOWLEDGEMENTS

The work outlined above was carried out on behalf of the Australian Development Assistance Bureau (ADAB) by the Department of Housing and Construction (DHC) for the Government of the Republic of Kiribati. The author wishes to thank DHC for allowing the use of material prepared within the Department and ADAB for providing finds for attendance at the Workshop. The efforts of the typing staff who typed this paper at short notice are gratefully acknowledged.

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ASSESSMENT OF SURFACE WATER RUNOFF AND DETERMINATION OF GROUNDWATER RECHARGE ON SMALL 'HIGH' ISLANDS : A CASE STUDY OF NORFOLK ISLAND, AUSTRALIA

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(Paper for presentation to the Proceedings of the Workshop
On Water Resources of Small Islands, Suva, Fiji,
2 - 9 July 1984; sponsored by the
Commonwealth Science Council)

1. INTRODUCTION

Surface water resources on small islands can be divided into two categories:

(1) rainwater collected from roofs or other catchments,
(2) surface runoff in the forms of streams or rivers.

Rainwater can be and is a useful resource in many locations especially where mean annual rainfall is high. This water resource is applicable to both 'high' and 'low' islands where economic considerations justify their use in comparison to other water supply options. In many cases the relatively high cost of materials for collecting and storing rainwater has caused this water resource to be used for domestic drinking water only while groundwater or surface runoff are used for most water supply purposes including commercial, agricultural and other domestic uses. Many case histories of, and design methods for, rainwater collection system are outlined in the Proceedings of the International Conference on Rainwater Cistern Systems held in Hawaii in 1982. Some papers are of particular relevance to the small island situation including Stephenson et al (1982), Romeo (1982) and Diamant (1982).

Surface runoff occurs only on those islands where the climatic, topographical and geological conditions are favourable. The 'high' islands of the South Pacific and other oceans generally have such favourable conditions. Annual rainfall is normally moderate to high, and the islands are typically mountainous and consist of relatively low permeability volcanic rock. In the 'low' islands, typically coral atolls, where the topography is flat and the geology consists of relatively high permeability coral sediments, no surface runoff occurs. Instead, rainfall infiltrates directly to the soil moisture zone, and subsequently is released by evapotranspiration to the atmosphere or percolates to groundwater. An assessment of surface runoff may be necessary for a number of reasons including:

(a) determination of safe yield of a stream or river for water supply purposes,
(b) design of flood mitigation works,
(c) design of hydroelectric schemes,
(d) assessment of groundwater recharge using a water balance equation.

This paper outlines methods used to determine surface runoff on Norfolk Island. In addition, the use of surface runoff and meteorological data to assess groundwater recharge on the island is described.

2. LOCATION AND LANDFORM

Norfolk Island, politically part of Australia, is situated at latitude 29°2'S and longitude 167°57'E (Figure 1). It is approximately 1700 km northeast of Sydney, Australia, 1100 km northwest of Auckland, New Zealand and 1600 km southwest of Suva, Fiji. It has an area of 35 km^2 and consists of a raised plateau about 100 m above sea level with a higher ridge rising to over 300 m in the northwest. In the southeast (Kingston) the land slopes to the sea. The island is the erosional remnant of a volcanic complex (Abell and Taylor, 1981) and is deeply incised by a number of streams or creeks.

3. CLIMATE

Norfolk Island's climate can be described as sub-tropical. Average annual rainfall for the period of record 1890 to 1982 was 1318 mm with a maximum of 1934 mm in 1955 and a minimum of 785 mm in 1976. On average the wettest month is June (148 mm) while the driest is November (68 mm). Pan evaporation data collected between 1976 and 1981 indicates an annual average of 1604 mm. December has the highest monthly average (178 mm) while June has the lowest (86 mm).

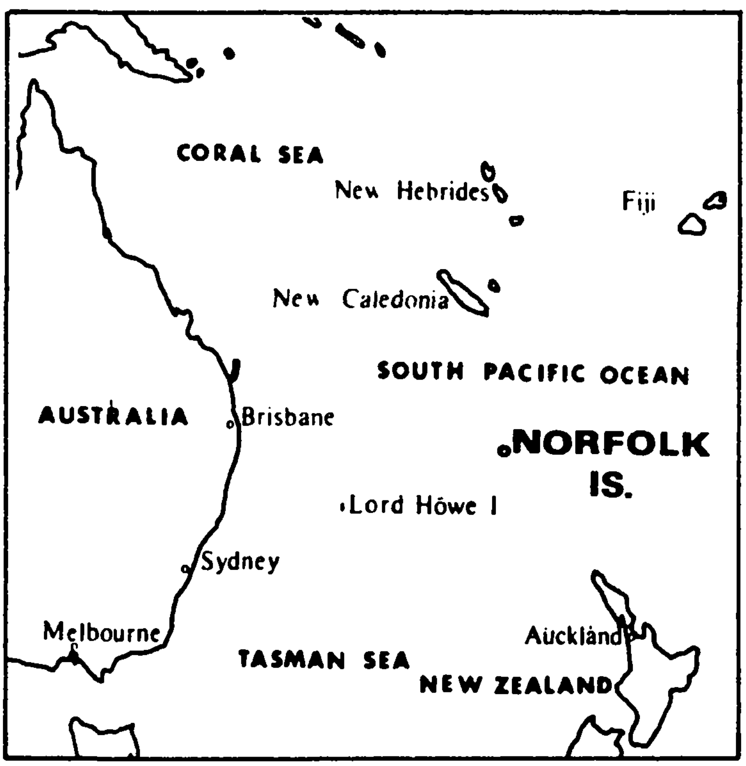


FIG. I LOCALITY MAP

4. WATER RESOURCES

Presently, the island's population (consisting of about 1700 permanent residents and an average annual tourist turnover of about 20,000) relies on a combination of rainwater collected from roof catchments and pumped groundwater for its water supply. All water collection and extraction is done on an individual basis. Groundwater exists as perched aquifers in the weathered mantle and as a basal lens below sea level (Abell, 1976). These groundwater storages are connected through a complex set of fractures beneath the weathered mantle (Abell and Taylor, 1981). The creeks, in most cases, develop from spring seepages on the raised terrain and discharge either over the rim of the island plateau or at sea level in the south.

5. SURFACE WATER INVESTIGATIONS

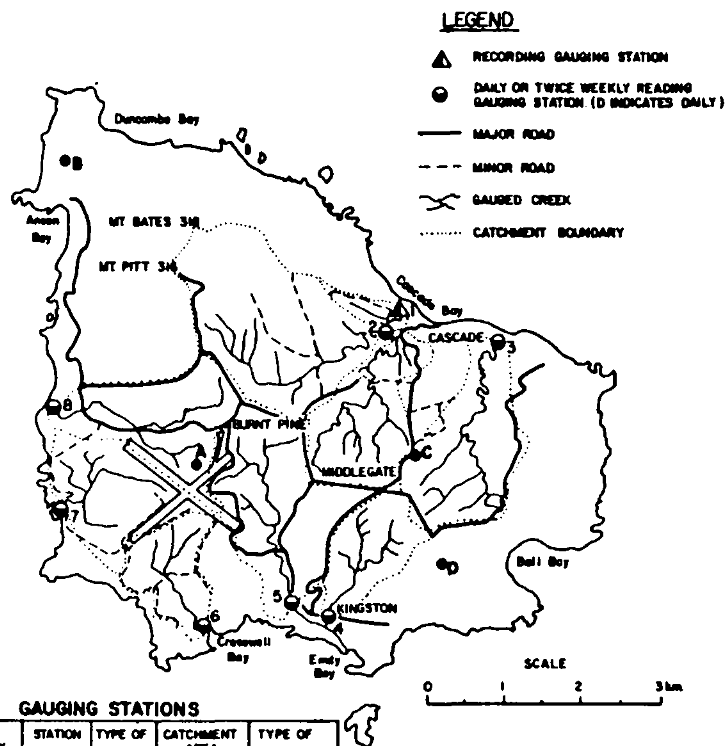
5.1 Stream Gauging Station Network

There are eight major creeks on the island. These and their respective catchments are shown in Figure 2. Gauging stations were constructed on each of the major creeks as close as practicable to the edge of the island. Full details are presented in Fitzgerald and Falkland (1981) and Falkland (1982). The gauged catchments represent about 54 percent of the island's total area. The remaining 46 percent of the island consists of small areas in all gauged catchments downstream of the gauging stations and other areas, mainly in the northwest and eastern portions of the island, where there are no or only minor creeks. From a water balance viewpoint discharges from the eight major creeks represent nearly all of the surface runoff component.

5.2 Gauging Station Features

The design of the gauging stations was influenced by two major considerations. Firstly, the stations were to be built at minimal cost and secondly, they were to be largely operated and maintained by local relatively unskilled staff. Hence, the gauging stations had to be cheap and simple. At the same time they were required to provide accurate streamflow data.

The station on the creek with the largest catchment area (Cascade Creek) was equipped with a continuous recorder. A Leupold Stevens F-type chart recorder, set to record at the rate of 1.2 inches per day, was mounted in a locally fabricated box made of galvanised sheet steel. This was fixed on top of a float well made of semi-circular corrugated steel sections (Figure 3). The float well, located within the creek, can be reached via stepping stones except during relatively rare large flow events.



GAUGING STATIONS

CREEK	STATION NUMBER	TYPE OF STATION	CATCHMENT AREA (HECTARES)	TYPE OF CONTROL
CASCADE	1	▲	628	ROCK BAR
BROKEN BRIDGE	2	● D	393	ROCK BAR
STOCKYARD	3	●	249	ROCK AND CONCRETE
TOWN	4	● D	133	CIPOLETTI WEIR
WATERMILL	5	● D	306	CIPOLETTI WEIR
ROCKY POINT	6	●	124	ROCK BAR
HEADSTONE	7	● D	197	ROCK AND CONCRETE
MISSION	8	● D	237	ROCK AND CONCRETE

RAIN GAUGES

PLAN REFERENCE	NAME	LOCATION
A	METEOROLOGICAL STATION	AIRPORT
B	J RYVES	ANSON BAY
C	G. DUVALL	CASCADE RD.
D	W WILKINS	COLLINS HEAD ROAD

FIG. 2 PLAN AND HYDROMETEOROLOGICAL DETAILS

All other gauging stations were equipped with staff gauges constructed from locally available wooden posts and concreted into position. Gauge plates graduated in metric units were attached to the posts. Natural controls were used wherever possible for the control sections. Six stations have natural controls while the other two, in the low flat area around Kingston have artificial controls (weirs). Gauge height (or 'stage') at each station is read either daily or twice weekly, and more frequently during high flow events. Details are tabulated in Figure 2.

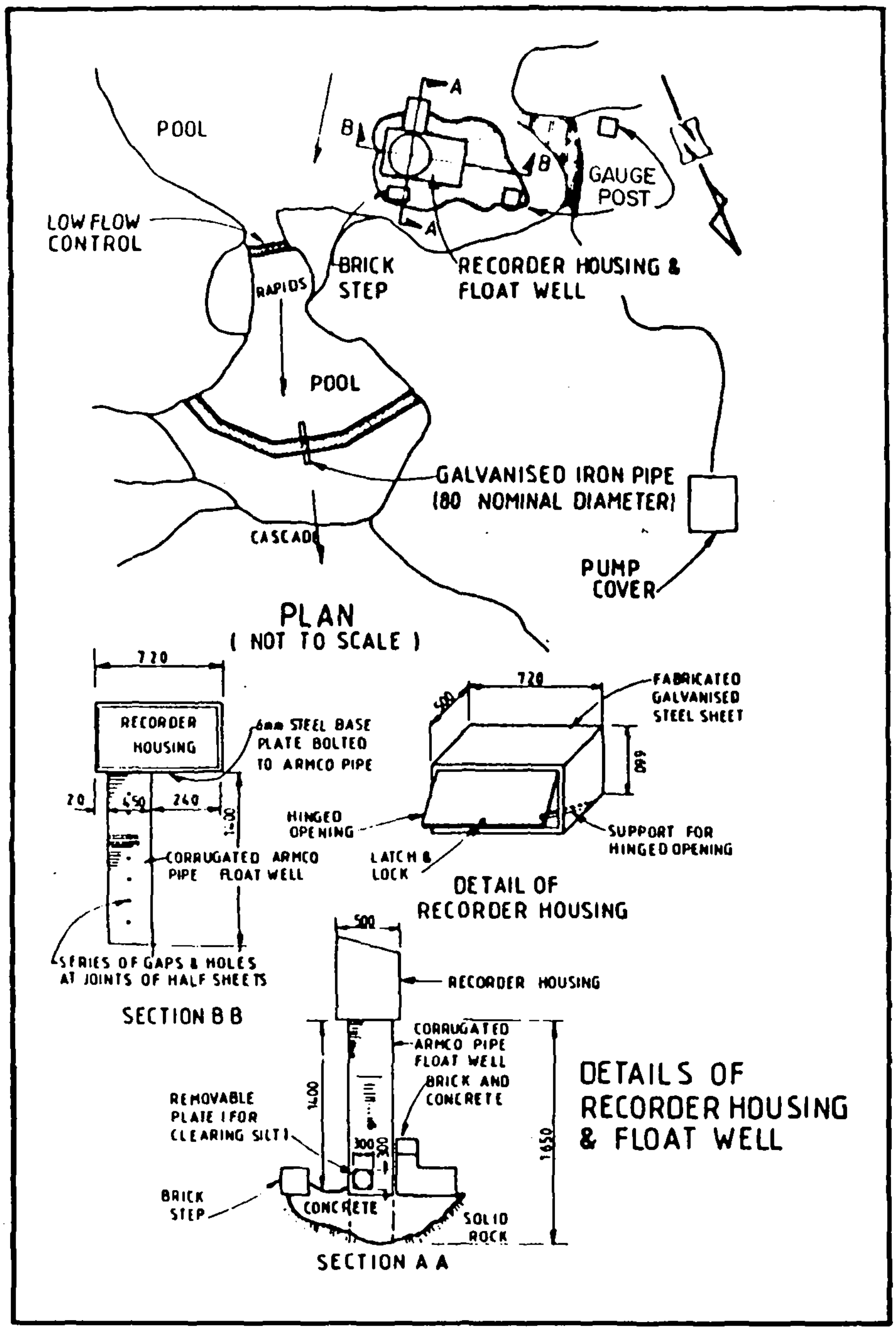


FIG. 3 CASCADE CREEK STREAMFLOW RECORDER.

Flow measuring devices were installed at all creeks in order to establish stage-discharge relationships and hence to compute flow data from the stage records. It was decided early in the investigations to dispense with the use of conventional current metering equipment for two major reasons. Firstly, most of the flows are relatively small and, thus, difficult to measure except by special miniature current meters. Secondly, in order for current meters to be used effectively in the larger flows, a higher level of training for the local personnel than was possible would have been necessary. The selected flow measuring devices consisted, where possible, of two types:

(a) small diameter pipes concreted into small weirs in the creek close to the gauge section. The outlet ends of the pipes were positioned to allow a bucket to be placed underneath. Flows can be determined volumetrically by timing how long it takes to fill a measured volume in the bucket. Such a method can be used with sufficient accuracy for flows up to about 3 litres per second (l/s).

(b) steel weir plates, fabricated locally according to design specifications for calibrated Cipoletti (trapezoidal) weirs (Bos, 1978), were concreted into position on all creeks as close as possible to the gauge section. The weir dimensions varied according to site conditions but were typically 300 mm wide and 200 mm deep. The maximum flow that can be recorded by such a weir is about 50 l/s. The formula relating flow Q (in l/s) to length of weircrest L and flow depth H (both in mm) is:

$$Q = 5.96 \times 10^{-5} L H^{1.5}$$

At the beginning of the investigation program in early 1981, a transportable V-notch weir was used in some of the creeks. The intention was that this weir plate be positioned in one creek for a period of time until a suitable stage-discharge relationship was established. It would then be moved to the other creeks and the process repeated. Leakage under the plate, however, prevented the recovery of reliable data especially at the higher flows. In some cases the plate was washed downstream after relatively large flows. This method of flow measurement was, therefore, abandoned in favour of relatively permanent weirs concreted into position. The Cipoletti weir type was selected in preference to the more common V-notch weir because it has less chance of being fouled by debris such as tree branches and weeds.

On the relatively rare occasions that flows exceed the capacity of the weir plate, estimates of flow are made from an extrapolation of the stage-discharge rating curves. Initial extrapolations were done by extending a straight line through the data on double logarithmic paper. Later extrapolations took account of the cross sections at the gauging stations.

5.3 Operation and Maintenance of Stations

Local personnel were trained in procedures necessary to operate and maintain the stations. A number of redundant features were built into the operation procedure as a method of checking results. These included measurements on both side of weir plates to determine the depths of flow at the weirs, measurements of both gauge height and weir flow depth at each station, and double or triple time and volume measurements when using the pipe and bucket method for low flow measurement. During periods of low flow both the volumetric method and the weir method were used for determining flow. Differences between the two methods were generally less than 20 percent. The volumetric method would normally be considered more accurate for low flow measurement because slight imperfections in the weir plate edge can have considerable effect on the flow depth over the weir at low flows.

Necessary maintenance of the stations includes clearing controls, weirs and pipes of debris or sediment before taking readings and noting whether any backwater effects are present at weirs. Weeds downstream of a weir, if allowed to grow too large, can cause raising of the downstream water level. This 'backwater effect' can tend to prevent the weir from flowing as it should. At all times there should be a zone of aeration between the weir plate and the overflow. If this is not present the efficiency of the weir deteriorates with the result that incorrect flow measurements are made. Weeds should, therefore, be cleared at regular intervals to prevent such occurrences.

In addition to the above, clearing of silt and other debris from the base of the floatwell is a maintenance requirement.

Rusting of mild steel weir plates and gauge plates has caused some problems due to over three years of exposure to the relatively corrosive oceanic environment. Cleaning with wire brushes on the edge of weir plates can help to alleviate the problem. Stainless steel weir edge profiles can be used if the stations are required for long periods of time.

5.4 Processing of Records

During the last 3 years water level recorder charts for Cascade Creek and other data consisting of gauge height, weir and 'pipe and bucket' measurements for each station have been forwarded from Norfolk Island to the Department of Housing and Construction in Canberra, Australia for processing.

All data can be processed manually if so desired. Hence, methods such as described above are applicable to small island nations where more sophisticated methods of processing are not available. In practice, the data has been processed by a combination of manual and computerised methods.

The water level trace from the F-type charts for the Cascade Creek station is transferred to a continuous strip chart. This is subsequently converted from analogue to digital form on a RIMCO digitiser. The digital information consisting of a set of times and gauge heights is stored on computer. Using the stage-discharge rating curves, the stored information can be converted to flow records. These flow records can be output in tabular or graphical form. An example of the graphical type is shown in Figure 4.

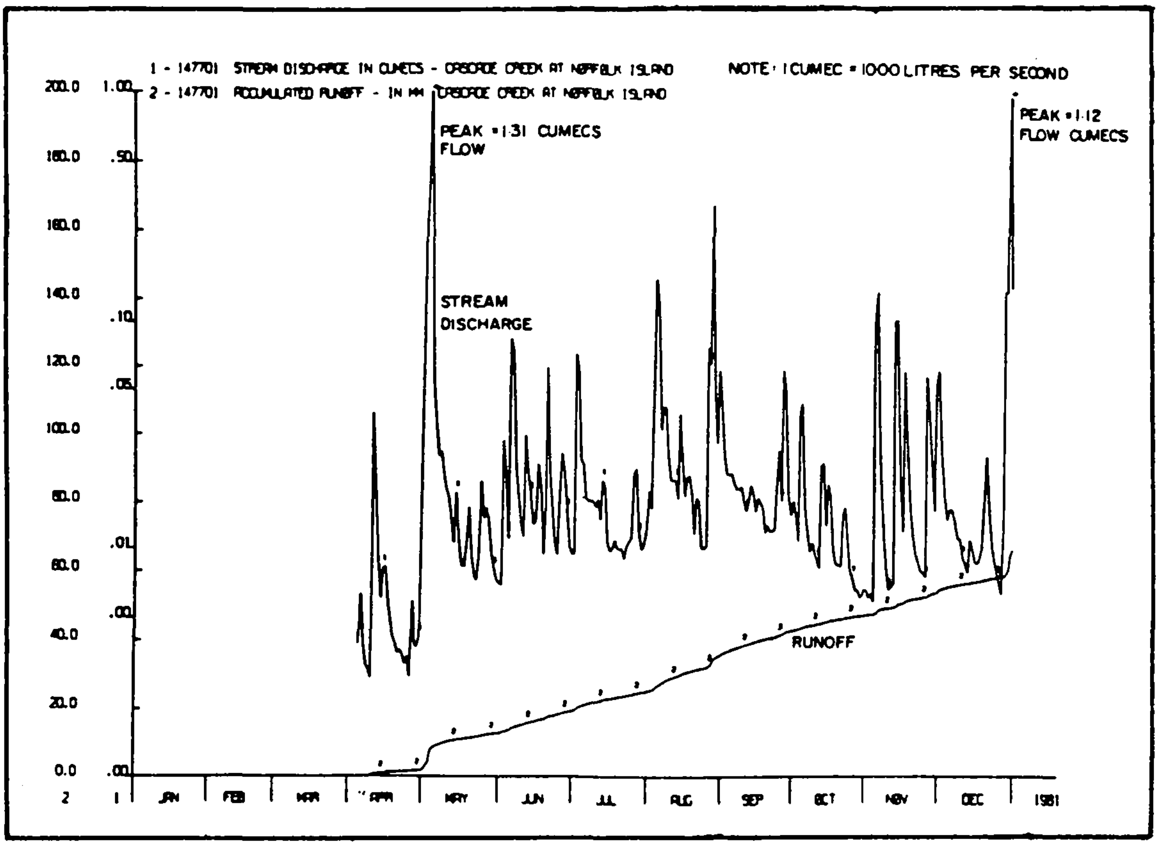


FIG.4 GRAPHICAL RECORDS, 1981.

Data from the daily and twice weekly read stations was initially converted by hand to average daily flows. Later a computer program was written to analyse and output results using a microcomputer. As with the digitiser, such relatively sophisticated technology is not absolutely necessary to process results: it merely lowers the manual input required and quickens the delivery of processed results.

The end result of the collection and processing of data from the eight gauging stations is a set of flow or surface runoff data for each creek which is available on an instantaneous, average daily, average monthly or average annual basis.

6. USE OF SURFACE RUNOFF DATA

6.1 General

Surface runoff or streamflow data can be used, as indicated in the introduction, for a number of purposes. On Norfolk Island the data has been used for the determination of groundwater recharge using a water balance equation. At present, there are no plans to utilise surface water runoff for water supply purposes. Normally, the construction of dams would be required in order to store surface runoff if such a requirement arose. It is not certain whether geological conditions are suitable for large storage dams. Also, economic considerations do not favour such a water supply system compared with a central groundwater extraction system.

The method used for determination of groundwater recharge is briefly described below. Further details are provided in Falkland (1982) and Falkland and Daniell (1983).

6.2 Water Balance Equation

The water balance equation, in terms of groundwater recharge (GR) is:

$$GR = P - Ea - SR$$

where P = rainfall
Ea = actual evapotranspiration
SR = surface runoff

A water balance was done for each catchment using monthly time increments.

6.3 Rainfall (P)

Rainfall has been recorded almost continuously since 1890. Until 1939 rainfall was recorded in the low lying Kingston area and since then near the present airport on the plateau (Figure 2). Monthly rainfall figures indicate very similar patterns for both locations.

In addition to the official rainfall records, a number of daily read rain gauges have been kept by private landowners in recent years. For the 27 coincident months of record from January 1979 to March 1982 correlation coefficients of 0.95 or better were obtained from linear regression analysis between three private and the official records.

It can be concluded that monthly rainfall is relatively uniform over the island and, hence, data from the official station only was used in water balance analyses.

6.4 Evapotranspiration (Ea)

Evaporation data from a U.S. Class 'A' pan at the official station has been collected since January 1976. A number of stages were involved in converting pan evaporation (Epan) to actual catchment evapotranspiration (Ea). Firstly, Epan was related to the potential evapotranspiration of a 'reference crop' (ETo) defined as 'an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water' (Dorrenbos and Pruitt, 1977) by the equation

$$ETo = Kp. Epan$$

where Kp is a function of climatological factors and pan position. A value of 0.7 was calculated for Kp for each month of the year. Secondly, ETo was equated to potential evapotranspiration of the actual vegetation (ETcrop) by

$$ETcrop = kc. ETo$$

where kc is a 'crop coefficient' dependent on the actual vegetation. Norfolk Island was divided into three main vegetation types with kc estimates as follows; grassed areas (0.8), closed forest (1.0), open forest (1.2). Finally, ETcrop was related to actual evapotranspiration (Ea) using the water balance procedure.

6.5 Surface Runoff (SR)

The results of eight months of streamflow recording from May to December 1981 (Falkland, 1981) are summarised below. It should be remembered that predictions on the basis of eight months of record can only be regarded as tentative.

(a) no simple relationship between catchment area and volume of runoff exists, indicating other factors such as porosity and permeability of rock and soils, and vegetative cover may be important determinants of runoff volume.

(b) in general rainfall and runoff on a monthly basis are not significantly correlated. Using linear regression, correlation coefficients for the eight stations ranged from 0.53 to 0.89.

(c) monthly runoff for the daily read stations correlated well with the continuous recording station. Correlation coefficients ranged from 0.84 to 0.99.

(d) percentage runoff (ratio of runoff to rainfall) tended to be highest for catchments on the southern side of the island. Baseflows followed this trend also. These higher percentage runoffs most likely result from a combination of lower evaporation (grass cover rather than forest), soils and geological conditions being less conducive to recharge, possible subsurface movement of water from adjacent catchments into these ones and the fact that the gauging stations on these catchments are lower in elevation and, hence, the flows presumably reflect a higher degree of seepage than on the catchments to the north. The lowest percentage runoff occurs on catchments on the southern edge of the higher ridge (Mt Pitt) area. This tends to indicate a significant recharge area, as has been independently assessed from geological and geophysical studies (Abell, 1976; Abell and Taylor 1981). The lower runoff is also due to higher evapotranspiration from the forested areas in these catchments.

6.6 Groundwater Recharge (GR) Estimates

As mentioned earlier the water balance study was done using monthly time increments. The following assumptions were made:-

(a) maximum soil moisture content is 100mm for grassed and 400mm for forested areas.

(b) evapotranspiration reduces linearly from the potential rate at field capacity to zero at wilting point.

(c) excess water after subtraction of evaporation from rainfall is used to fill the soil moisture zone to field capacity before recharge commences.

For eight months of coincident rainfall, evaporation and streamflow records, the following typical results, expressed as percentages of rainfall, were obtained:

(a) Grassed catchments: SR = 10%; Ea = 43%; GR = 45%
(b) Forested catchments: SR = 3%; Ea = 56%; GR = 35%

The residual percentage figures are due to changes in soil moisture during the eight months period.

The estimates for recharge are higher than can be expected on average as the rainfall for the eight month period was 25 percent higher than the mean. For the period 1976-1981, assuming that streamflow reflected rainfall patterns, the annual recharge for a typical grassed catchment ranged from 8 percent (1976) to 41 percent (1981) with an average of 27 percent. The corresponding average value for a typical forested catchment was 14 percent. Since about 35 percent of the island can be considered forested (Abell, 1976) the average estimated recharge for the whole island for the period 1976-1981 is 22 percent. As the rainfall in this 6 year period was only 83 percent of the long term mean, the long term recharge estimate is about 25 percent.

An independent method of calculating recharge using the ratio of chloride concentration in rainwater and shallow groundwater (Abell and Taylor, 1981) gave a value of 18 percent.

7. CONCLUSION

The methods described for determining surface runoff on Norfolk Island are considered to have direct relevance to other 'high' islands. The relatively simple methods, which have been described for obtaining streamflow data, are considered to be well within the resources and capabilities of small island nations. Such data is of considerable importance for the assessment of safe yields of streams, for the determination of groundwater recharge, or for the design of flood mitigation works or hydroelectric schemes. The use of surface runoff and other data for determining groundwater recharge on Norfolk Island using a water balance approach has been described. Recharge was found to be about 25 percent of rainfall.

8. ACKNOWLEDGEMENTS

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INITIAL ASSESSMENT OF
GROUNDWATER RESOURCES ON SMALL ISLANDS

by

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Summary

Most of the common methods of groundwater development are time-consuming and costly. If they would be applied consistently, hydrogeological exploration in large archipelagoes would probably take centuries. In many cases it is possible to get an approximate idea of the groundwater situation with simpler methods in a shorter time. Although such an approach can not substitute for exact and detailed investigations as a basis for large investments it will make it possible to provide potable water on many islands at a much earlier time than could be expected ordinarily. Examples of this procedure from the Pacific region are presented.

* * *

There are numerous publications on groundwater development which give the impression that the only way to come to an assessment of groundwater resources is through extensive geophysical investigations, test drilling and pumping, groundwater modelling, chemical analyses, etc.

However, on many islands it is possible to get an approximate idea of the groundwater situation with simpler methods in a shorter time. This approach is particularly appropriate in cases where it can either be assumed that the water resource is substantially larger than the prospective consumption or where the financial risk is small. Large investments generally have to be based on detailed investigations.

In this connection the term "initial assessment" is being used for a first assessment within a period of not more than 2 months and based on very limited information. During such a short time it is generally not possible to monitor changes in groundwater storage or groundwater quality. In 3 out of the 4 examples presented, the objective has been to investigate if the local demand can be met in a part of the island.

Assessments of this kind usually comprise the following steps:

- Find aquifer
- Investigate quality of groundwater
- Estimate recharge
- Compare intended withdrawal with estimated groundwater recharge
- Decide on the feasibility of the project.

1. Peleliu (Palau Islands)

The island of Peleliu is 10 km long and has a maximum width of about 3 km (Fig. 1). It consists mainly of coralline limestone the oldest part of which forms a mountain ridge in the northern half. Most of the remaining parts of the island are less than 3 m above sea level.

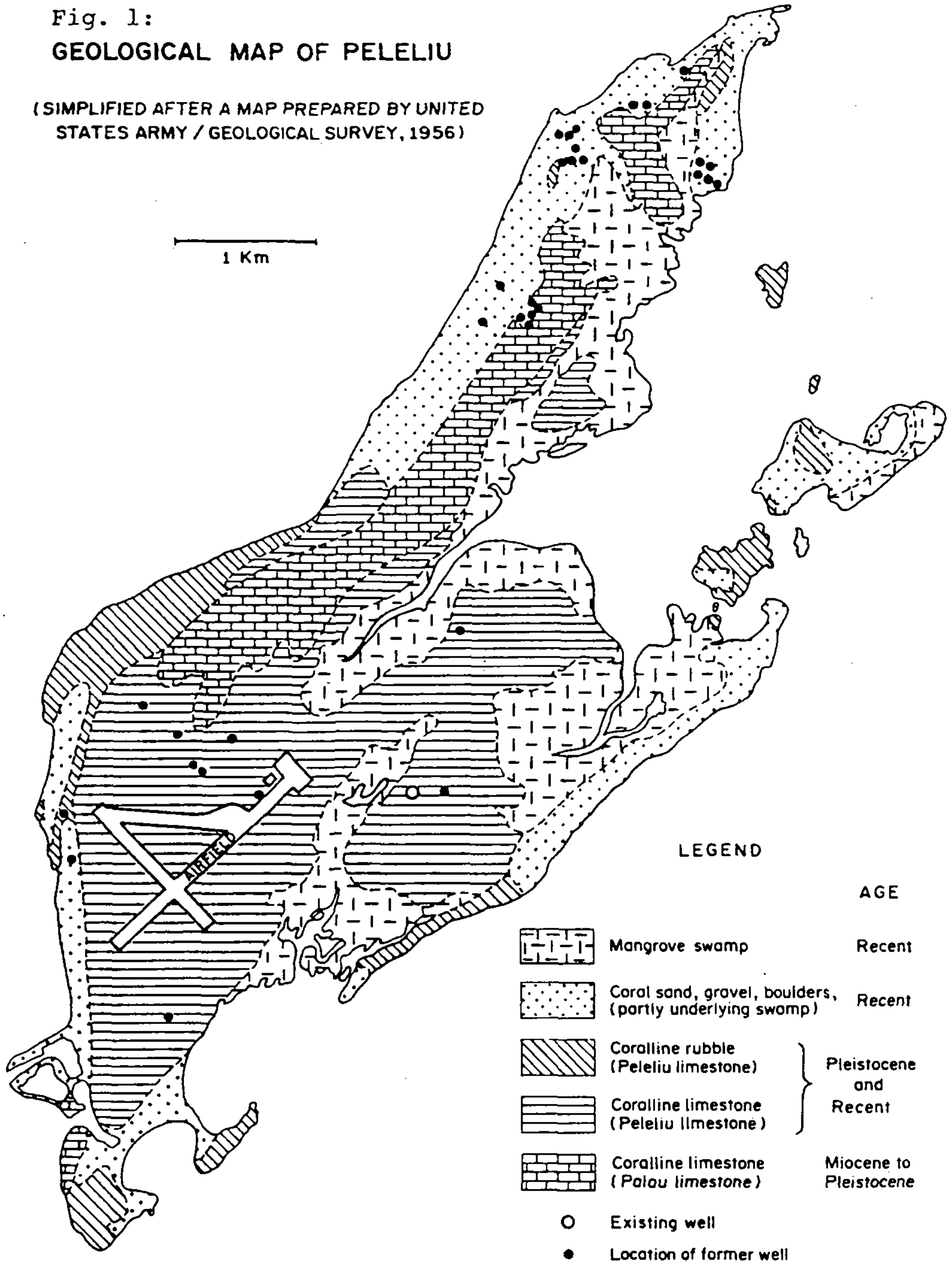
From 1945 to 1948 Peleliu served as an US airbase. About half of the wells situated within a distance of 400 m from the shoreline were reported to be brackish at that time, probably due to overpumping. This indicates that the aquifer has a good hydraulic connection to the sea.

In 1949/50 the mean water levels in wells on Peleliu and Angaur (situated 14 km southwest of Peleliu) were up to 0.75 m above mean sea level. The tidal range is about 1.3 m. Tidal fluctuations in wells were up to 0.6 m with a lag up to 4 hours. The reaction of wells was generally high near the sea and lower inland. According to the Ghyben-Herzberg relation the theoretical maximum depth of

Fig. 1:

GEOLOGICAL MAP OF PELELIU

(SIMPLIFIED AFTER A MAP PREPARED BY UNITED STATES ARMY / GEOLOGICAL SURVEY, 1956)



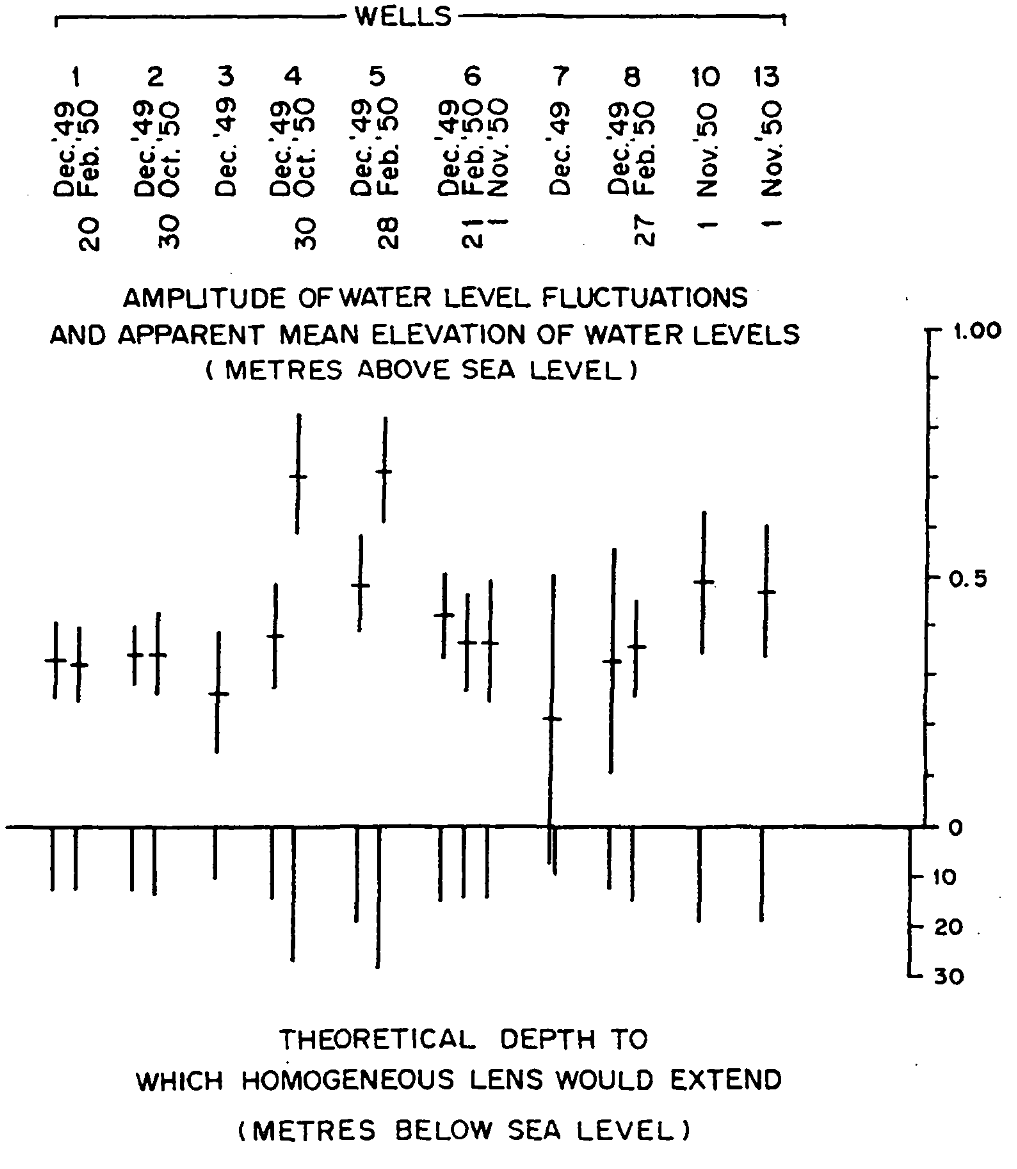


Fig. 2: Water level fluctuations on the island of Angaur (from: US Army/Geological Survey, 1956).

the fresh water lens would be 30 m. However, measurements which were made in the period 1949/50 on Angaur show that some water levels (wells No. 4 and 5 in Fig. 2) drop significantly within a few months in times of poor recharge. This indicates that the Ghyben-Herzberg relation does not apply to this area, i.e. that the fresh water resources are smaller. As the situation on Peleliu is probably similar to the conditions on Angaur it was assumed that the maximum thickness of the fresh water lens on both islands is less than 20 m.

With regard to the position of brackish wells between 1945 and 1948 the best area for groundwater development on Peleliu is probably near the airfield.

The volume of a body of fresh groundwater in this area is estimated as follows:

Average thickness of the fresh water lens:	5 m
Circular catchment area (radius 400 m) situated at a distance of more than 500 m from the sea and from brackish lakes:	0.5 km^2
Average effective porosity of limestone:	30 %

The volume of fresh groundwater contained in a body of this size would be about 750.000 m^3.

There is practically no surface run-off on Peleliu but groundwater levels are high in most of the area. Evapotranspiration may therefore be well over 2000 mm/a. If groundwater recharge would be only 20% of the mean annual rainfall at Koror (3.759 mm) this would amount to about 376,000 m^3/a in a catchment area of 0.5 km^2. Assuming that 25% of the recharge is recoverable a volume of 94,000 m^3/a remains which is almost twice the present consumption of Peleliu (50,000 m^3/a).

2. Male (Maldives)

The study of M.J.H. West and D.J. Arnell (1975) on water resources development on Male does not exactly meet the definition of an "initial assessment" given above. Although the field work was completed within a period of only 2 months great efforts were made (e.g. 50 auger holes drilled) to collect a large amount of data. Nevertheless, the results obtained may be relevant to similar cases in the Pacific.

The island of Male has a maximum length of 1.6 km, and is about 0.8 km wide. With the exception of a few small areas ground levels are less than 1.5 m above mean sea level. The tidal range is about 1.6 m.

A hardpan layer 0.05 to 0.3 m thick exists within the tidal limits of groundwater levels over much of the island. Although this layer is relatively impervious it is penetrated by some hundreds of wells. Below the hardpan there is coarse to medium coral sand with some larger fragments of corals and shells. The thickness of these uncemented layers is 4-5 m or less near the shore, but reaches 12 m or more near the centre. Below this there is generally coral reef structure.

The tidal variations (Fig. 3 and 4) show an unusual pattern with maximum reaction near the centre of the island and little reaction around the perimeter. This suggests that there is a relatively impervious zone between the aquifer and the sea around the perimeter of the island and that there is hydraulically a more direct connection through the centre of the island. This is consistent with the pattern of chloride contents and also with the water level contours which suggest some flow towards the centre as well as outwards (Fig. 5 and 6).

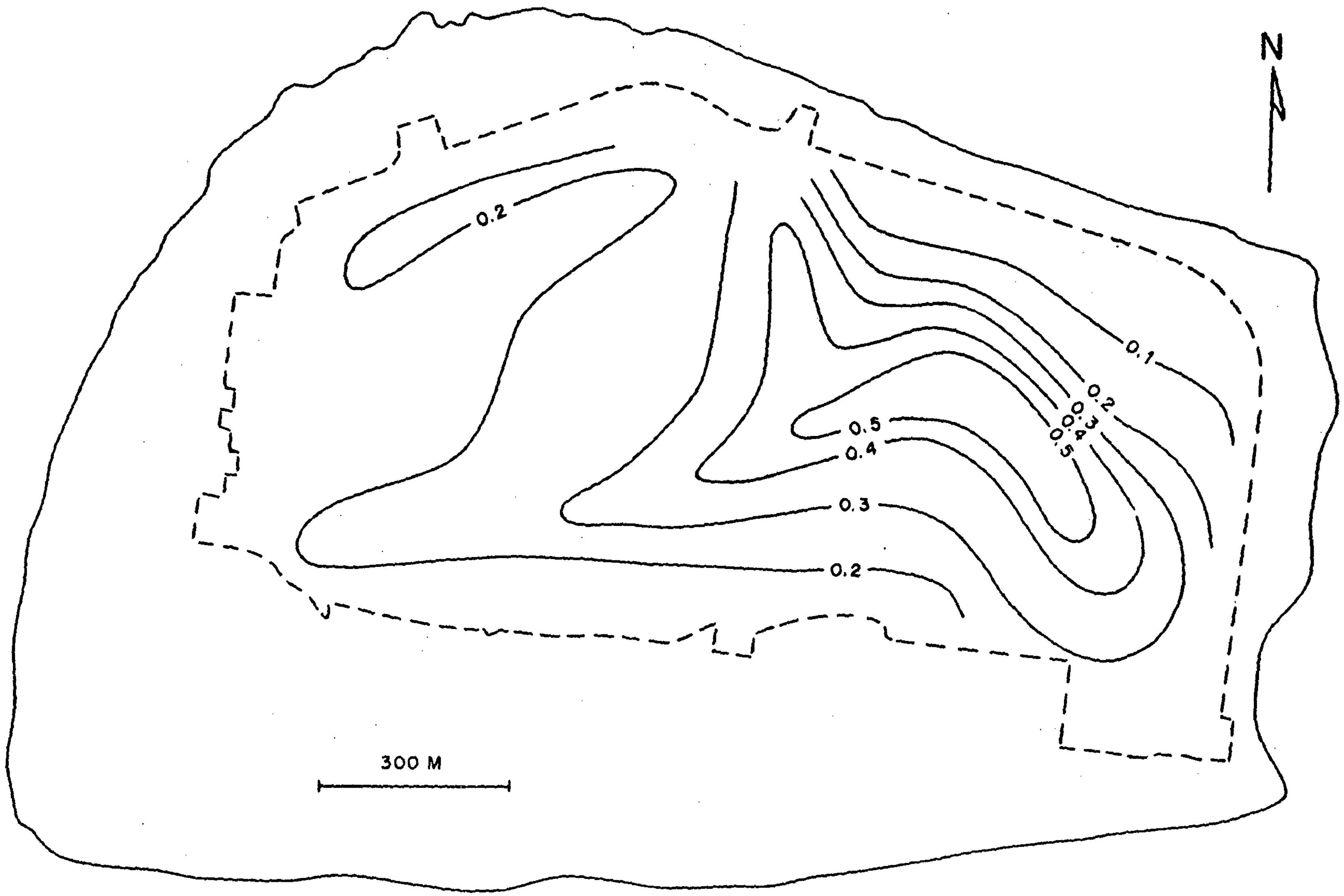


Fig. 3: Apparent tidal efficiency (in metres) on the island of Male (from M.J.H. West and D.J. Arnell, 1975).

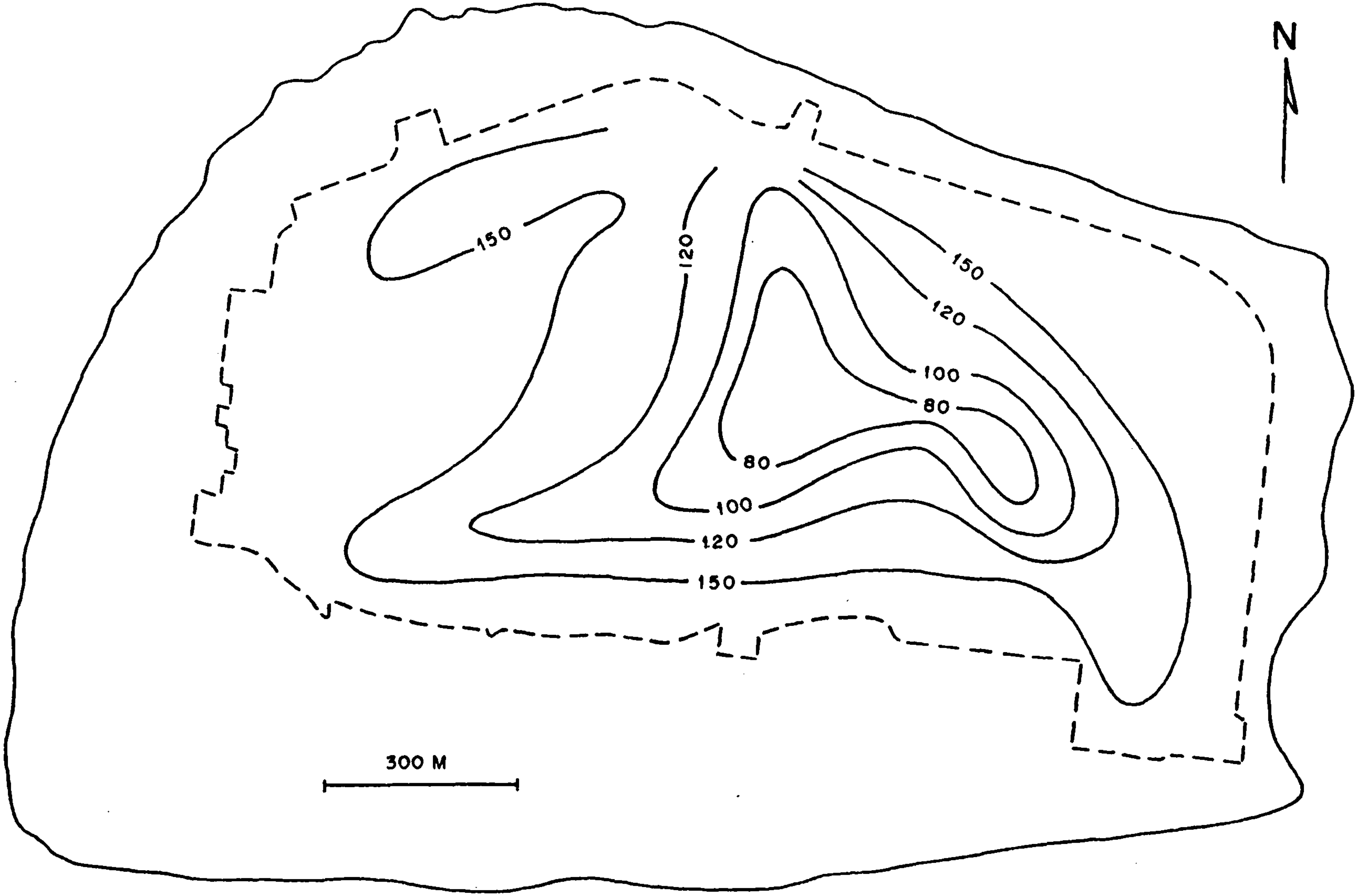


Fig. 4: Mean tidal lag (in minutes) on the island of Male (from M.J.H. West and D.J. Arnell, 1975).

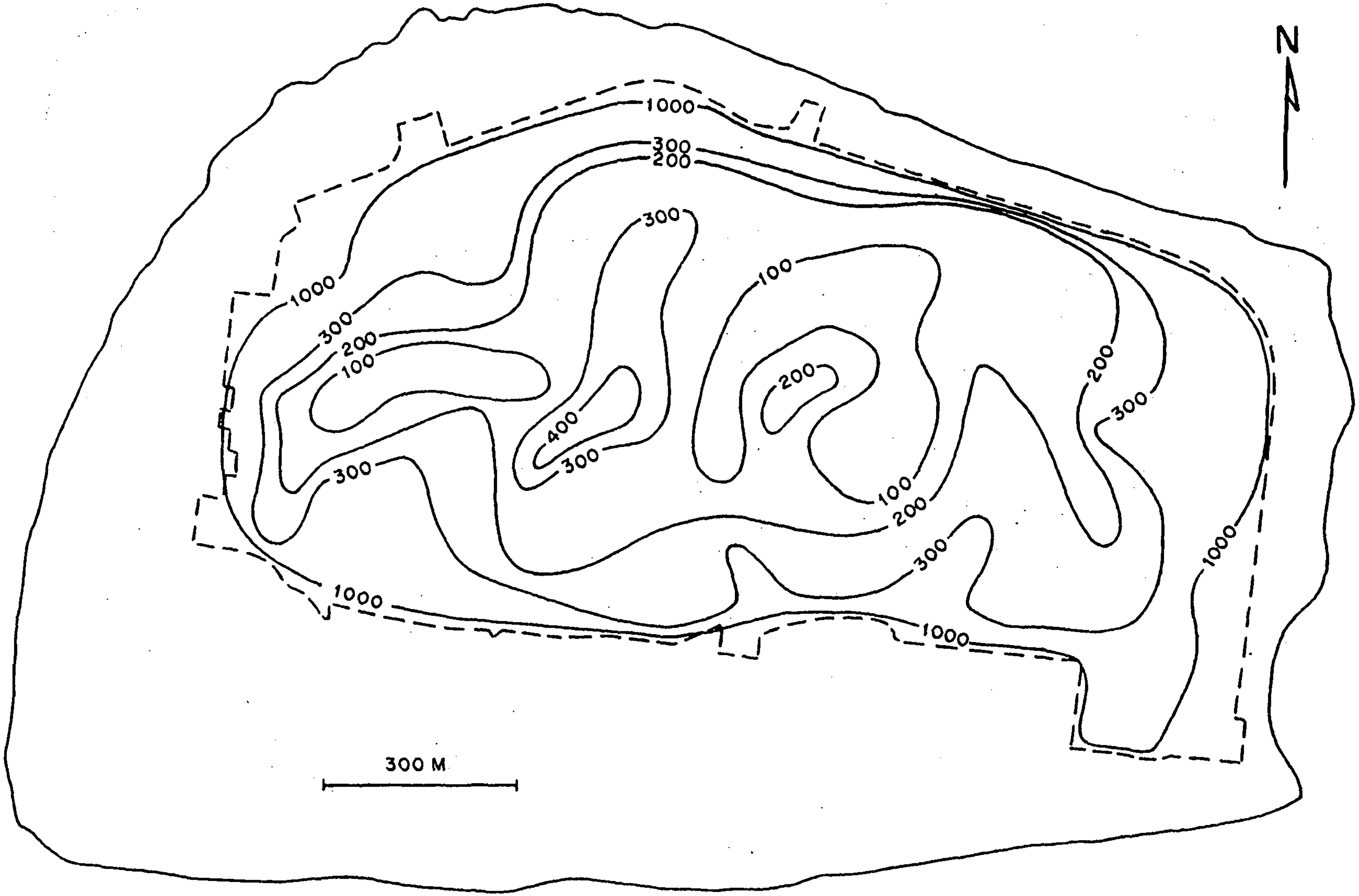


Fig. 5: Chloride contents (in ppm) in wells on the island of Male (from J.H. West and D.J. Arnell, 1975).

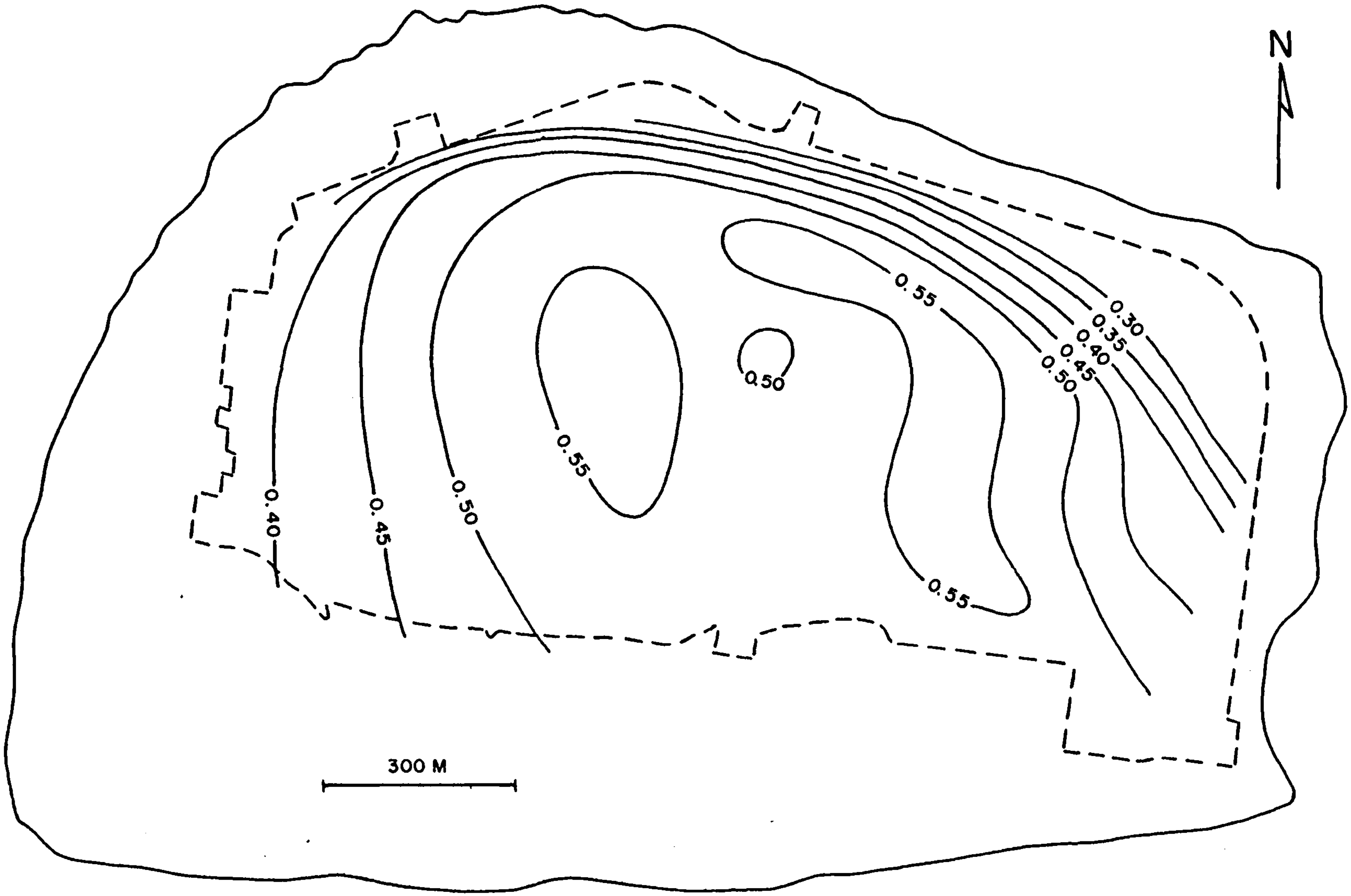


Fig. 6: Water table on the island of Male on 24/25 March 1974 in metres above mean sea level (from J.H. West and D.J. Arnell, 1975).

Aquifer characteristics were determined through tidal variations. The derived values of permeability of 0.0072 to 0.0097 cm/s are consistent with figures obtained from constant head permeability tests.

The tentative water balance for Male was established as follows (data in mm):

Mean rainfall	1,897
Surface runoff	38
Evaporation from roofs	45
Evaporation from soil	983
Recharge to groundwater	788
Interflow	33
Transpiration	571
Abstractions	124
Outflow to sea	70

From these data it follows that a further increase of abstaction would lead to a decrease of fresh groundwater stored.

Investigations made after 1980 confirmed this assessment.

3. Babelthuap (Palau Islands)

The island of Babelthuap is about 44 km long and has a maximum width of 16 km. It consists mainly of volcanic breccia, tuffs, volcanic flows and intrusives which on the whole may be classified as poor aquifers althouth it appears that flows and breccias generally have a higher permeability than tuffs. The highest elevation is 242 m.

Mean annual rainfall at Koror was 3,759 mm in the period 1948-1980. Baseflow measured in March 1973 in four rivers was between 1.4 and 6.6 $l/s/km^2$ (1 to 5.% of rainfall). As could be expected the highest rate occurred in the catchment with the highest percentage of relatively good aquifers.

Incomplete run-off records and meteorological data indicate that evapotranspiration and surface run-off may account for more than 90% of rainfall. As the mean groundwater recharge has to be higher than the rate of base flow (assumed as constant discharge over one year) groundwater recharge on Babelthuap is probably about 6% of the precipitation, i.e. 226 mm.

Water consumption in the Koror-Airai area is 2.2 million m^3/a at present. Even if the total volume of recharged groundwater could be withdrawn, a catchment area of about 10 km^2 having a recharge of 226 mm would have to be found in order to meet this requirement.

Due to the lack of identifiable extensive aquifers of sufficient thickness it was decided that it would be unprofitable to supply the Koror-Airai area with groundwater.

4. Efate (Vanuatu)

The island of Efate extends about 47 km E-W and 33 km N-S. It consists mainly of submarine volcanics overlain by subaerial lavas with a few intrusions. The gradual uplift of the island has left a series of reef limestone terraces at elevations up to 130 m above sea level. Their thickness is mostly less than 60 m. Unconsolidated sediments are preserved in areas where major downfaulting has taken place.

The best aquifers known so far are reef limestones and the alluvium. Clayey tuffs are almost impervious but other parts of the volcanics may have a moderate permeability. Due to the poor accessibility of the area there is little information on the volcanics in the central part of the island. Aquifer positions near the coast are essentially the following:

A) Aquifer partly below sea level. Groundwater brackish or endangered by seawater encroachment.

B) Base of limestone above sea level. Aquifer generally well drained.

C) Alluvium mostly above sea level with large parts of the limestone draining into the alluvium.

Although there are possibilities of groundwater development in some of the low-lying limestone areas the preferred conditions for the abstraction of large quantities of groundwater seem to be those mentioned under C. The mean annual rainfall at Vila (coastal area)is 2,267 mm (period 1953-1982). Scarce base flow data from 2 mountainous areas with about 3000 mm of rainfall (La Colle and Teuma rivers) is about 40 $l/s/km^2$. The catchments consist of volcanics and limestone.

Baseflow rates of 40 $l/s/km^2$ suggest that groundwater recharge is higher than 1,260 mm/a. However, this does not apply to the coastal area, which receives less rainfall and where a maximum recharge rate of 1000 mm may occur only under very favourable conditions. The average is estimated at around 800 mm. Assuming that only 20% of the recharge is recoverable, a catchment area of about 19 km^2 will have to be made available in order to meet the future demand of Vila (3 million m^3/a), which would be possible.

The four examples presented above show that it is possible in some cases to decide with very limited data on the feasibility of groundwater development projects. However, it is obvious that the reliability of assessments generally increases with the amount of specific information.

Estimations of this type are essentially made in order to provide safe drinking water much earlier than could be expected ordinarily. As time is regarded to be the most important factor if would be logical to look for other means which could speed up a project. One possibility is the collection of data by local authorities, well before any investigation of this kind would start.

Data qualified for this purpose would be

- Rainfall (daily)
- Location of existing wells
- Location of sources of pollution
- Electric conductivity in wells at the end of the dry season
- Run-off in streams at the end of the dry season (baseflow)

The availability of this data at the beginning of groundwater resources assessments would not only save time it would also increase the reliability of the study.

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HYDROLOGICAL NETWORKS ON SMALL ISLANDS

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1. INTRODUCTION

The establishment and operation of surface water resources networks in the tropics often presents additional problems to those encountered in the temperate zones upon which most of the literature, experience and equipment development are based. These problems may be compounded on tropical islands which are often rugged and mountainous resulting in many short streams of steep slope and high stream velocities. Usually of volcanic origin, the young geological formations have shallow soils leading to comparatively low volumes of baseflow. Combined with small drainage areas the streamflow on tropical islands varies considerably from wet to dry seasons and it is only on the larger islands that perennial streams exist.

Water and water data are vital to the further development of most countries. Although rainfall and streamflow tend to be less variable in tropical areas (ie. from one wet season to another), permanent streams are few and they are still subject to drought and large and devastating floods. Those areas subject to tropical cyclones tend to be the worst affected by these two extremes.

Due to the temporal and areal variability of rainfall and streamflow many decades of these data at numerous sites and a quantitative understanding of the hydrology of each region/island are necessary to meet the important needs of surface water information. The requirement to collect data many years in advance of its eventual use emphasises the importance of developing well designed networks that are in balance with the future needs for information.

2. SURFACE WATER INFORMATION REQUIREMENTS

Although the requirements for surface water information are both broad and diverse,they are amenable to solution through hydrologic study if there is a well planned basic set of data available and a quantitative understanding has been developed of the hydrological response of the region. The AWRC (1982) considered these data needs within the type of hydrologic study involved in providing the required answer. These hydrologic studies can be grouped into the following broad categories:

- Water Quantity
- Flood
- Water Quality

2.1 Water Quantity Studies

Water quantity studies can be related to:

- the assessment of the quantity and variability of the surface water resources of individual streams or river basins
- the assessment of inflows to, and level variations within, wetlands, or natural water bodies for environmental studies
- the recharge of groundwater systems
- the yield of aquifers or man made storages
- the changes in runoff that occur as a result of natural or man caused changes in basin condition or landuse.

The range of possible studies is large. For example storage yield studies can be for a single surface reservoir, an integrated system of surface reservoirs, a surface storage and groundwater aquifer used conjunctively, a groundwater aquifer that is recharged by riverflow or rainfall and river flow, a small run of river scheme, an offstream storage system, etc, and can vary from major water supply schemes to individual farm supplies.

For water quantity studies some or all of the following activities are necessary:

- study of the available historic flow and rainfall record
- development of a long sequence of daily or monthly flows (using modelling and stochastic generation methods)
- development of an associated sequence of rainfall and evaporation data to calculate net losses by evaporation or evapotranspiration or recharge to aquifer systems
- development of a quantitative understanding of past or likely future changes in basin runoff due to changes in vegetation conditions or land use to allow modification or correct interpretation of the yield modelling study
- development of chemical quality loads, sediment loads and an understanding of other water quality characteristics of inflow such as turbidity, colour, pH, temperature, or toxic chemicals.

Data requirements for the water quantity category of hydrologic studies can be summarised as:-

- reliable daily flow records for a range of hydrologically significant basins and of sufficient length to allow synthesis of longterm data through correlation, basin modelling and/or stochastic generation,
- daily rainfall records at sufficient sites to represent the rainfall across the basin or region and at any specific sites of interest for basin modelling, basin water balance calculations and storage water balance calculations,
- data on changes in basin land use or vegetation condition that could effect hydrologic response and,
- data sufficient to allow a reliable estimate of evaporation and/or evapotranspiration.

2.2 Flood Studies

Design flood estimation is a primary and critical step in the design of all hydraulic structures and works used in floodplain management. In terms of money invested by countries the amounts involved are of considerable national significance. The estimated average annual expenditure in works sized by design flood estimates in Australia in 1979 is equivalent to roughly US$40 per person in 1984 values (Cordery and Pilgrim, 1979).

The collection of hydrologic data during periods of extreme floods is always difficult and sometimes impossible if the floods occur during tropical cyclones. The concern for public safety, the stress on communication and transport systems, and the usually flashy nature of the small streams of tropical islands during cyclones are responsible for the hydrographer's difficulties.

The steps in planning for flood data collection, data collection during the flood event, post-flood data collection and the preparation of reports on a tropical island are discussed for Puerto Rico (8,900 km^2) by Cobb and Barnes (1981). Flood data/information are provided for Puerto Rico in several types of reports:

- Areal reports describing the water-resource characteristics of a specific basin or area of study.
- Floods resulting from a specific event. Rainfall, peak discharges, flood hydrographs, areas of inundation, and frequency of recurrence data are presented in tabular and plotted form for individual stations and are analysed on a regional scale.

- Frequencies of floods of various magnitudes throughout the country. Regression analyses are presented for floods of specific recurrence intervals. This provides a bases for transferring flood-frequency information to ungauged sites throughout the island.
- Hydrologic Atlases, showing in map form, areas which have been inundated by historical floods. A brief text, with some analyses of the floods shown, is included in these reports. Hydrologic Atlases may also be prepared showing areas which are predicted to be inundated by a flood of a specified recurrence interval.
- Flood insurance studies are made showing areas inundated by floods having an average recurrence interval of 100 and 500 years. Flood profiles are also prepared for these and other recurrence-interval floods.

For rivers with very long records and stable basins simple flood frequency studies based on annual peak discharge or peak height can be carried out. Then, if there are many stations on an island with long records that represent the full range of basin size, relief and vegetation types, regional flood frequency relationships can be developed simply from the peak flow data alone.

However, in practical terms this length of record is rarely available on islands. It is not economically feasible to gauge every major stream and a large proportion of the medium and small sized basins need to be gauged for a very large number of years. (These size terms are relative to the size of the island itself). Thus, it is necessary to adopt an approach based on a selective network of gauging stations being fully utilized through the application of advanced hydrologic techniques.

Many studies need flood volume and hydrograph shape in addition to the flood peak. In these situations and when extreme estimates are required, studies based on rainfall-runoff modelling become necessary.

Data requirements for the flood category of hydrologic studies can be summarised as follows (AWRC, 1982);

- many years of annual peak flow data on the major rivers and a representative set of minor rivers and small basins, both rural and urban,
- an adequate sequence of continuous flow records on major rivers and on catchments that represent the full range of catchment sizes, relief and land use,
- rainfall records at a recording interval appropriate to the catchment size for the same set of catchments,
- regional meteorological data for rainfall depth duration studies and probable maximum precipitation studies.

2.3 Water Quality Studies

With increasing development involving population growth, land use changes (particularly forest clearing), industrialisation, tourism, the deterioration in water quality and pollution are some of the critical problems facing water management on many islands. Often a major contributing factor to this situation in the past was the lack of appropriate and reliable water quality data. Network designers now have the responsibility of ensuring that lack of appropriate data is not the cause of similar very costly errors in future.

Water quality is of importance in all regions, however the quality parameters of critical importance can vary from region to region and sometimes from stream to stream. Also the intensity of monitoring that is required to adequately quantify the important quality parameters varies. To be effective, the design of the water quality component of the assessment program must be based on studies of data already collected and tailored to the hydrologic conditions of each particular region. However, reliable base line data are essential for all regions.

To be meaningful, water quality samples for surface streams must have an associated flow rate and sampling at any site must take place through all seasons and flow rates. For many quality parameters monthly or annual load is required in addition to the concentration at a limited set of times. For many quality parameters monitoring through flood events is of critical importance.

Also of critical importance is the development of a quantitative understanding of the factors that affect the quality of catchment runoff so that future trends can be anticipated.

Water quality data are important in relation to the use or potential use of water (human consumption, domestic, stock, irrigation, industrial, construction), its instream or storage effects (e.g. eutrophication of lakes, estuaries, storages) or as a reflection of excessive deterioration of the water catchment (e.g. high sediment loads).

Due to variations in quality characteristics and issues from region to region there will be some variations from the following summary of data needs (AWRC, 1982):

- For major rivers and for gauged catchments sampling a full range of climate, soils, vegetation and land use history, the following data are required for a full range of years:
  - T.S.S. concentrations and loads,
  - pH, temperature, colour and turbidity concentrations,
  - Nutrient concentrations and loads (for disturbed catchments),
  - major ions for samples that cover the full range of hydrologic conditions,
  - metals for a limited but representative set of samples and,
  - substantial sampling of any problem parameters.

- For a typical set of catchments a measure of monthly and annual sediment loads through a full range of years (wet, average, dry) is required.
- For significant water resources where quality is changing due to changes in land use or vegetation, on going sampling is required to reliably monitor the important quality properties that are changing.

The sampling frequency must be carefully selected so that the results truly represent the variation in the parameter being measured and, where indicated, allow loads to be calculated.

For pollutants, specifically designed data collection programs are necessary. However, pollution monitoring is outside the scope of the assessment program and this report.

3. NETWORK DESIGN

3.1 Integration

3.1.1 Integration of networks

To provide the information identified in Section 2 in a cost effective manner, an integrated hydrologic data collection program must be developed that incorporates the following (AWRC, 1982):

Streamflow	- continuous flow
	- water quality including sediment
	- peak flow or low flow partial records
Natural Water Bodies (Lakes)	- level
	- water quality
Rainfall	- daily
	- pluviometer
Meteorological	- evaporation, dewpoint and other meteorological data
Catchment	- relief, geology, soils and natural vegetation
	- history of landuse and vegetation condition

Depending on the institutional arrangements within the country, the meteorological agency may be separate from the water resources agency. Meteorological agencies usually operate a general network of rainfall and climatological stations which are essential to the water resources network.

Detailed monitoring of rainfall within gauged basins to provide basin rainfalls is exceedingly important to the integrated surface water network. Where the meteorological agency does not require this more spatially intense monitoring, the river gauging authority should operate the necessary rainfall stations. These data should be provided to the meteorological agency to enable a national meteorological data bank to be established.

Water quality assessment of surface waters should be fully integrated with the streamflow assessment program. The stream gauging network design must therefore reflect water quality data needs as well as water quantity and flood flow data needs.

3.1.2 Integration of activities

Network design is not a once only activity that has intrinsic value of itself. It forms a small part, albeit an exceedingly important part, of an integrated Hydrologic Information System. A schematic representation of this System from Whetstone and Grigoriev (1972) is presented as Fig. 1.

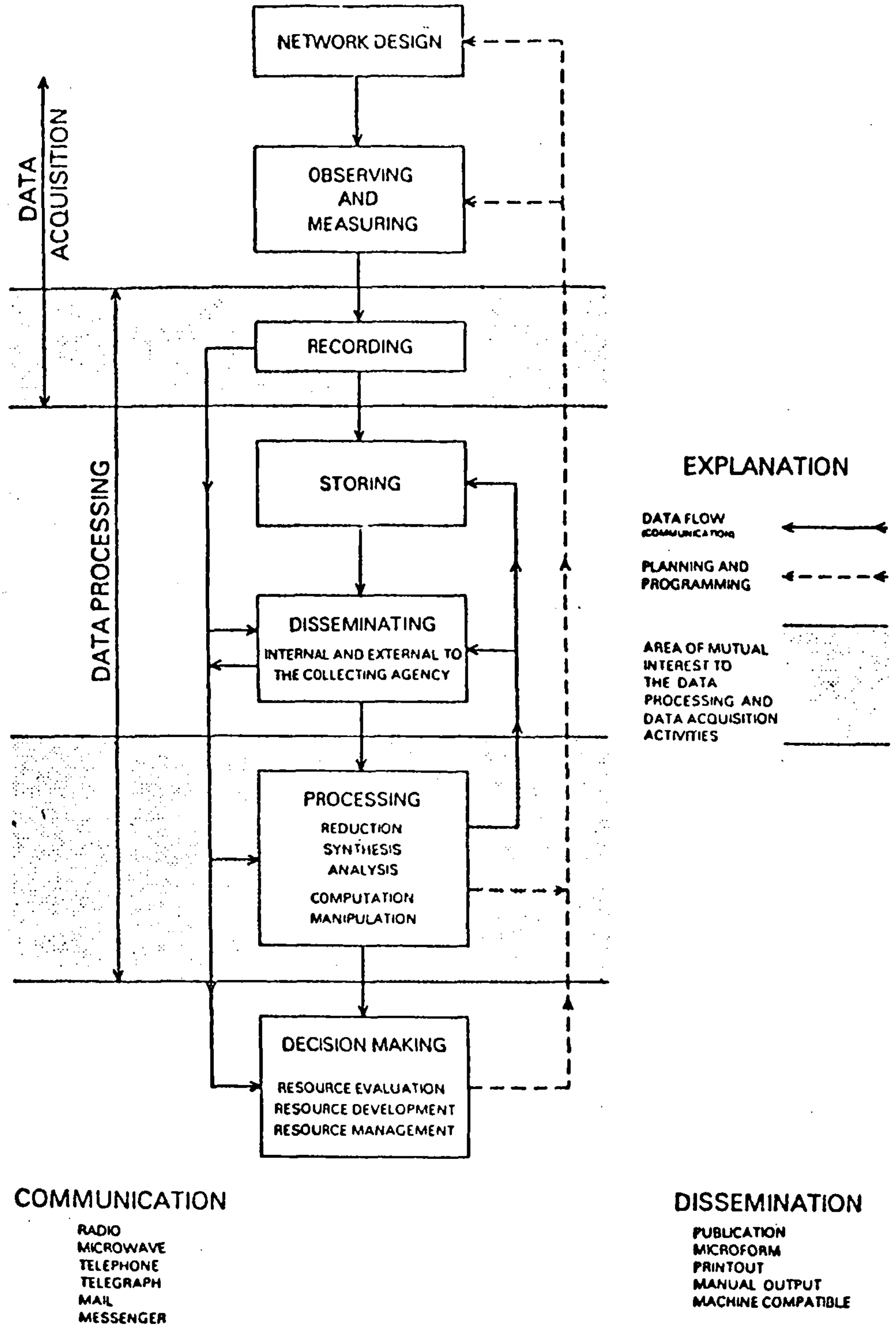
Network design is an ongoing iterative activity which operates on information feedback from the other components (subsystems) of the total Hydrologic Information System. The network must be considered as a dynamic, evolving, information gathering system that is responsive to improvements in understanding of the hydrology of the various regions and to changes in the perceived longterm needs for information.

3.2 Network Design Concepts

The considerations and concepts to be kept in mind in designing a hydrologic network are discussed in some detail in Langbein (1965), Carter and Benson (1970), Davis and Langbein (1972), Hofmann (1976), Rodda (1972), WMO (1972, 1981), Moss (1978, 1982), Brown (1970), AWRC (1982) and others.

For the larger islands there may be two main classes of networks; the national multi-purpose network (Water Resources Network) and the user-specific network (Specific Purpose Network). The former provides information on the water resources of a region, drainage division or country for general planning and design, the detection of long-term trends and provides information for the many unanticipated data demands. The latter provides information for specific projects. Langbein (1965) also saw hydrologic networks as serving these two basic roles:

> "One division of the network would appraise the basic hydrology, with density of coverage that reflects chiefly the hydrologic diversity and the potential hydrologic significance of the data to water development. The second division would be responsive to present and imminent project needs. The first division is a basic network, the second is a project network. The basic network explains the regional hydrology; the project network provides point data. The basic network looks to the future, the project network serves the present."



FROM Whetstone G.W. and Grigoriev V.J. 1972 "Hydrologic Information Systems" UNESCO/WMO Studies and Reports in Hydrology 14 72p

FIGURE 1 Schematic chart of the major elements of water data acquisition, transmission and processing systems.

The Specific Purpose Network, or project network, is an ad hoc network with stations established at the time of need for a particular project and not for their value in a general network. The network of prime concern to this paper is the national multi-purpose network (the Water Resources Network) that must be in place and operating for many years prior to the use of the data.

The Water Resources Network must be designed to provide a quantitative understanding of both the temporal and spatial variability. This is most efficiently achieved by having a mix of primary stations that operate for a very long time (or indefinitely) and additional secondary stations that operate for a finite period to sample the spatial variability. When a secondary station has sufficient record to allow satisfactory correlation with the primary network,it is closed and moved to sample a different basin type or size. The terminology refers to the duration of the recording period and not to the importance or value of the hydrologic data obtained.

3.3 Network Design Process

3.3.1 General

The ideal network is described by the AWRC (1982) as one which provides at least cost, sufficient information to adequately satisfy all justifiable needs at the time that these needs for information arise.

Surface water data must be collected over many decades for it to satisfy most information needs. This long lead time makes network design a very challenging and important activity. The network design team must include or have ready access to experienced hydrologists who have a good working knowledge of the hydrologic characteristics of the region under consideration. The team must also have ready access to advice from water planners and other potential users to better understand the possible scope of future data needs and the possible timing of these needs.

However, because it is impossible to accurately predict future specific data requirements the network must be designed to provide multipurpose data and to provide a quantitative understanding of the factors that affect the hydrologic response of the region.

3.3.2 The Design Process

Design of the network must be based on the best current understanding of the various factors that are likely to affect the hydrology of the region. This requires compilation of information in map form of various aspects including:

- climate and rainfall distribution
- geology)
- soils) or landforms
- topography)
- natural vegetation
- land use and land use history

If appropriate, geomorphological regions are then delineated and grouped into areas considered to have similar hydrologic characteristics to provide a guide to spatial variability.

Available rainfall, climatological and stream quantity and quality data are assessed together with any available hydrologic studies to gain an understanding of temporal variability and a first estimate of the likely minimum record length required for the development of reliable statistics or for various correlations.

The major rivers are identified and their likely hydrologic behaviour assessed in order to estimate the number of mainstream basins required in the network to quantify these major resources. As these basins may be too large or too complex to provide information about runoff characteristics which could be transferred, areal basins to sample the environmental factors also need to be identified.

Existing stations are classified and assessed for suitability in any ongoing network.

With all available information relevant to the hydrology of the island absorbed by the designer, gauging sites are identified to provide a balanced sampling of the major rivers and the various hydrologic regions. Care must be taken to ensure that a full range of basin sizes are represented together with all major relief, land form, vegetation and climate types.

Station density will depend on spatial variability and the relative information needs of the area. This is discussed further in Section 3.4.

Station types should be identified according to a suitable classification system (eg AWRC, 1982). For well developed networks it should be possible to identify the primary and secondary stations in the network. However for embryonic networks virtually all stations may be primary or longterm.

The design must take cognizance of any practical problems involved in establishing and operating stations in the area under consideration. The selective use of nested basins should also be considered from the viewpoint of maximising information gained for resources expended.

A number of alternative network designs should be developed and compared as the design team searches for the most cost effective network. The network adopted must be the best synthesis of current understanding.

The level of understanding required for network design is well summarised in the following quotation from Benson & Carter (1973):

> "Planning the surface water information system cannot be done by formula. It must be done by hydrologists who are familiar with the hydrology of the region, the needs for information, the information currently available, and methods of hydrologic analysis."

3.4 Network Density

As discussed in the previous section there are many variables that must be considered when deriving the appropriate density of stations in the design network for each region. These variables include (AWRC, 1982):

- volume of information and level of hydrologic understanding already available
- hydrologic diversity of the region (spatial variability)
- level of development of available resources that will be necessary in future decades (a measure of the level of understanding that will be required)
- level of social and economic development in the region
- special regional characteristics or problems that will demand hydrological data.

The network design team is best placed to establish the appropriate network density for a given region after they have studied all available information.

However there still remains a need for an independent guide as to the minimum density that could be tolerated without causing undue economic loss or restriction to the future development of that region.

The only known general guide to network densities is that provided by the World Meteorological Organisation (WMO, 1981) in the publication 'Guide to Hydrological Practices'. For small tropical islands less than 20,000 km^2, with very irregular precipitation and very dense stream network, the following ranges of norms for a minimum network are given:

	Area in km^2 for one station
Precipitation	25 (100-250 for mountainous regions if the rainfall is irregular)
Evaporation	50 000
Streamflow	140-300

At least 10 per cent of the precipitation gauges should be recording gauges. Sediment sampling should be carried out at a minimum of 15 per cent of the streamflow stations. The chemical quality of the water should be assessed at a minimum of 5 per cent of the stations.

As a general guideline networks developed to these criteria will help evolve a minimum network which will avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development of the country.

One approach to the design of precipitation networks is based on examining the correlation structure of precipitation between gauges. The initial work has been more recently described by Body and Hall (1978) and has been confirmed theoretically by Eagleson (1967). It was found that, provided the precipitation gauges are well distributed, the number of gauges required to assess storm precipitation remains constant and is independent of basin area (from 100 to 10 000 km^2). Using the above approach, as a general guide 4 or 5 gauges will adequately assess storm precipitation, 4 gauges will adequately assess monthly rainfall and 2 gauges will adequately assess annual rainfall. Thus even on small islands a minimum of 4 gauges is desirable.

Appendix 1 is an update of the information contained in WMO (1977), Statistical Information on Activities in Operational Hydrology,and other information of current networks on small islands. The network densities reflect a number of the points made earlier, but do show a general trend of decreasing density in relation to increasing area, Fig. 2. That is, in terms of streamflow stations, the island size will tend to reflect the density of the stream network and the number of stations required to cover these. This also indirectly supports the finding that the number of precipitation gauges is more dependent upon the number of basins than area.

3.5 Network Evaluation

All networks must be evaluated at regular intervals and modifications made to improve the effectiveness of the network as necessary.

There is no one simple test that can be applied to ensure that a station is adequately serving its purpose or to indicate that a given secondary station should be closed.

An essential starting point is to have all data collected in the island reliably processed and readily available. Also it is highly desirable that these data should have been analysed to improve the general understanding of the hydrological characteristics, particularly spatial and temporal variability, of the region.

With this improved understanding, the previous network design should be reviewed and revised as necessary or a new network design produced as discussed in the previous section.

Each station is then reviewed with the following aspects considered:

- percentage data capture
- accuracy of processed data
- reliability of the record generally
- consistency of data collected through the years
- any operating difficulties
- is the station reliably serving its purpose within the network?

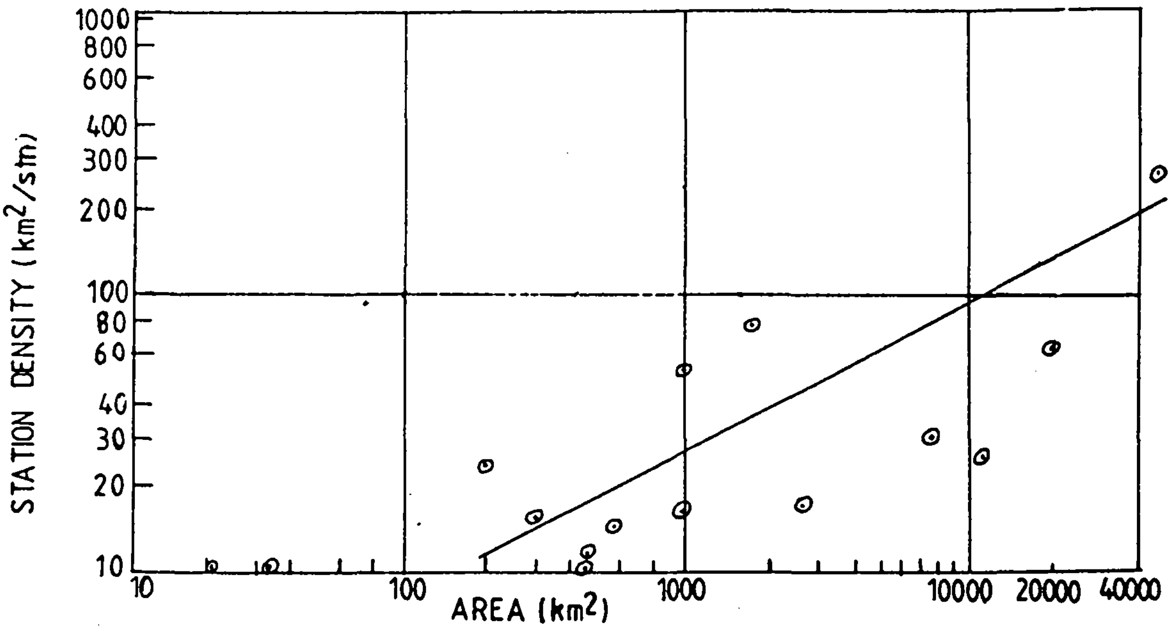


FIG 2(a) RAINFALL STATION DENSITIES FOR TROPICAL ISLANDS

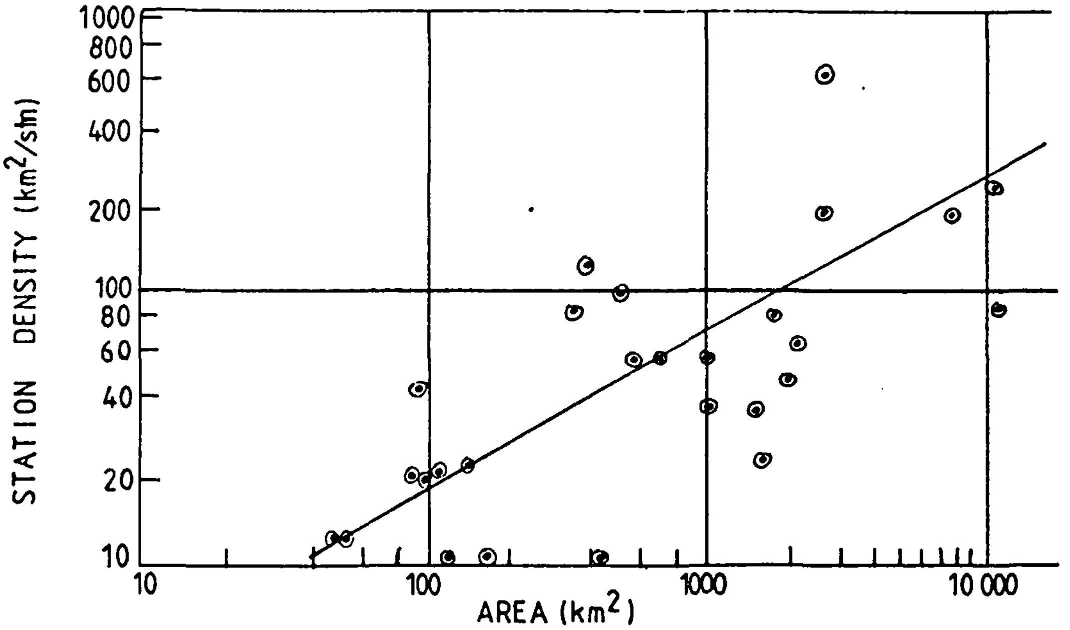


FIG 2(b) DISCHARGE STATION DENSITIES FOR TROPICAL ISLANDS

FIGURE 2 HYDROLOGICAL NETWORK STATION DENSITIES - FOR SMALL TROPICAL ISLANDS

For secondary stations as well as reviewing the adequacy of the data collected the need for further record must also be reviewed. This is best done by attempting to correlate the monthly or daily flows (and water quality characteristics if important) at that site with a nearby primary station and/or attempting to model the flows (and quality) using other available hydrologic records. If the perceived data need is to simulate a longterm distribution and this can be achieved by correlation of appropriate accuracy, the station can be closed, unless there are other important data requirements still unfilled. There will be situations where further operation of a gauging station will be required to support the water quality monitoring program,even though the station could be closed as far as quantity statistics are concerned.

4. PROCESSING AND ANALYSIS

With the decision to expend funds on the design and establishment of a station within the Water Resources Network goes the responsibility to collect data of an appropriate accuracy and reliability, to process and analyse these data and to make the data readily available to all users.

As discussed in Brown (1980), for example, it is a "hydrologic information system" that is required and not simply a set of stations. The raw data has no intrinsic value, the data only becomes valuable when it has been processed, analysed and put to work. Prompt analysis of the processed data is also essential to review the quality and value of the data and provide timely feedback to the field so any necessary corrective action can be taken.

The following activities are considered important to ensure an efficient and cost effective surface water data collection activity (AWRC, 1982):

a. The records for all Water Resource Network stations should be processed and readily available on computer media and as hard copy or microfiche within 12 months of the end of each water year. The form of output to include daily flows, daily rainfalls (where appropriate) and a summarised presentation of all water sampling analysis results.

b. Collecting authorities should make every endeavour to carry out simple hydrologic analyses of the data collected at each station every five years, or preferably more frequently. This study should assess the adequacy and value of data collected, highlight any improvements necessary or show that the station could be closed.

   Stream-stream correlations and/or basin rainfall - runoff modelling studies utilizing daily or monthly data may be appropriate together with a general study of the water quality characteristics and trends.

c. Gauging authorities should move towards development of the ability to reliably fill in missing record utilizing modelling and correlation techniques appropriate to their regions. Both the uncorrected and corrected records should be readily available.

5. CONCLUSIONS

Surface water resources information requirements have been defined, generally in the context of larger tropical islands. Network design concepts to define, establish and operate the networks to meet these requirements have been discussed, including suggested network station densities. The importance of network evaluation and data processing as part of the hydrologic information system have been emphasised. For smaller tropical islands where surface water is an important resource, many of the principles enunciated for larger islands will also apply.

6. ACKNOWLEDGEMENTS

The material contained in this paper is largely based on the Australian Water Resources Council's Surface Water Committee's discussion paper Surface Water Information Network Design.

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APPENDIX 1

HYDROLOGICAL NETWORKS ON TROPICAL ISLANDS

Island	Area km²	Number of stations					Station density km²/stn				
		Precip.	Record. Precip.	P+ RP	Evap.	Dis- charge	P	RP	P+ RP	E	D
REGION I (Africa)											
Canary Islands	7230	237	3	241	4*	38*	31	2410	30	1808	190*
La Reunion	2510	124*	28*	152	3*	15*	20	90	17		200
Mauritius (Total)	2045	257*	6*	263*	6*	38*	8	341	8	341	54
(4 basins)	416	52	7	59		40	8	59	7		10
REGION IV (North and Central America)											
Bahamas (Total)	13935	134	1	135	3	0*	104	13935	103	464	
Barbados	430	42	3	45	3	0*	10	143	10	143	
Dominican Republic	47939	133	56	189	34	51	360	856	254	141	940
France											
. Guadalupe	1700	22		22	2	21	77		77	850	81
. Martinique	1000	4	15	19		18	250	67	53		56
Jamaica	10990	430	14	444	14	129	26	785	25	785	85
Netherlands Antillas											
. St. Maarten	37	3	1	4	1		12	37	9	37	
. Bonaire	288	18	1	.19			16	288	15		
. Aruba	193	7	1	8			28	193	24	193	
. Curacao	444	38	1	39	1		12	444	11	444	
. Saba	13	3		3			4		4		
. St Eustatius	21	3		3			7		7		
REGION V (South-west Pacific)											
Australia											
. Norfolk Is. (Extra-tropical)	35	3	1	4		8	12	35	9	4	
Fiji (Total)	18234	156	97	253	5	89	117	188	72	3647	205
French Polynesia											
. Tahiti	1000	45	17	62	3	27	22	59	16	333	37
United States											
. Hawaiian Is. (Total)	18227	231	73	304	2	241	79	250	60	9113	76
. Guam	560		4	4		10		140	140		56
. Hawaii	10460					42					249
. Kauai	1437	5	2	7		40	287	719	205		36
. Kosrae	109	5	1	6		5	22	109	18		22
. Mariana	375		2	2		3		188	188		125
. Maui	1890		4	4		41		473	473		46
. Molokai	676	2	1	3		12	338	676	225		56
. Oahu	1575	4	12	16		66	394	131	98		24
. Palau	485		3	3		5		153	153		97
. Ponape	334		4	4		4		84	84		84
. Truk	91					2					46
. Tutuila	137	1	2	3		6	137	69	46		23
. Yap	98		1	1		5		98	98		20

* Figures from WMO (1977).

Note: Individual Hawaiian Islands climatological stations numbers are thought to include only those operated by the USGS and do not include the NWS Stations shown under the Hawaiian Islands (total).

Workshop on Water Resources of Small Islands, Fiji, 1984

THE ASSESSMENT OF GROUNDWATER RESOURCES ON SMALL OCEANIC ISLANDS

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Abstract

A simple scheme for the assessment of the groundwater resources of small islands is based on hydrogeological appraisal and a field data census of bores and wells. A study of available hydrological and climatic data leads to an estimate of groundwater recharge and the derivation of a water balance. Groundwater exploration is necessary to define aquifer geometry, especially the freshwater/saltwater interface, and for this the electrical resistivity depth probe technique is a powerful tool. The safe yield of an island aquifer can be calculated as a first order approximation using Mather's (1975) method, which assumes that abstracting groundwater is equivalent to reducing vertical recharge.

Introduction

Nearly all small islands have water supply problems, and most depend on groundwater to supplement their water supplies. The assessment of the groundwater resources of a small island requires consideration of available geological, climatic, hydrological, and water bore data.

Stages in an assessment program

A schematic outline of a water resources assessment program for small islands is shown in Figure 1. Small oceanic islands range from low coral atolls through limestone islands (raised atolls) and limestone-capped volcanic islands to volcanic islands. Each of these island-types has characteristic hydrogeological conditions and there is a basic distinction between the atolls and limestone islands on the one hand, where surface runoff is negligible, and the volcanic and more complex islands where surface runoff is appreciable. Hydrogeological maps which integrate geological and groundwater information can be developed for the more geologically complex islands.

A field data census of bores and wells is required for a groundwater resources assessment program. This should include details of bore and well locations, geological and geophysical logs, aquifers, water levels, bore yield and other hydraulic parameters,and water chemistry. Bore and well data should be stored on index cards (Fig. 2), which is a convenient method for up to 1000 bores. Above that number of bores a computerised bore data storage system is desirable.

Climatic and hydrological data are needed for the assessment of groundwater recharge, and derivation of a water balance. An analysis of long-term rainfall trends, rainfall distribution, and drought periods is necessary to estimate water demand. Figure 3 shows the long-term annual rainfall for Tarawa; it is evident that there are long periods of drought despite the fact that the mean annual rainfall is more than 1900 mm.

Groundwater discharge points such as springs and seepages also require measurement and evaluation, both as possible water sources and as components in the water balance. Springs may discharge above or below sea level. Elucidation of the groundwater flow system is done by plotting water levels in bores and wells and deriving a flow net; groundwater flow is normal to the water-level contours (Fig. 4).

There are certain problems in using water-level data on small islands. Water levels in bores and wells are commonly subject to considerable tidal fluctuations (Fig. 5), which depend on the permeability of the island rocks and the depth of the bore or well. Also it may be difficult to establish a satisfactory datum for levelling as mean sea level fluctuates considerably (Fig. 6). Thus direct application of the Ghyben-Herzberg relationship, which depends on determination of mean sea level,requires caution.

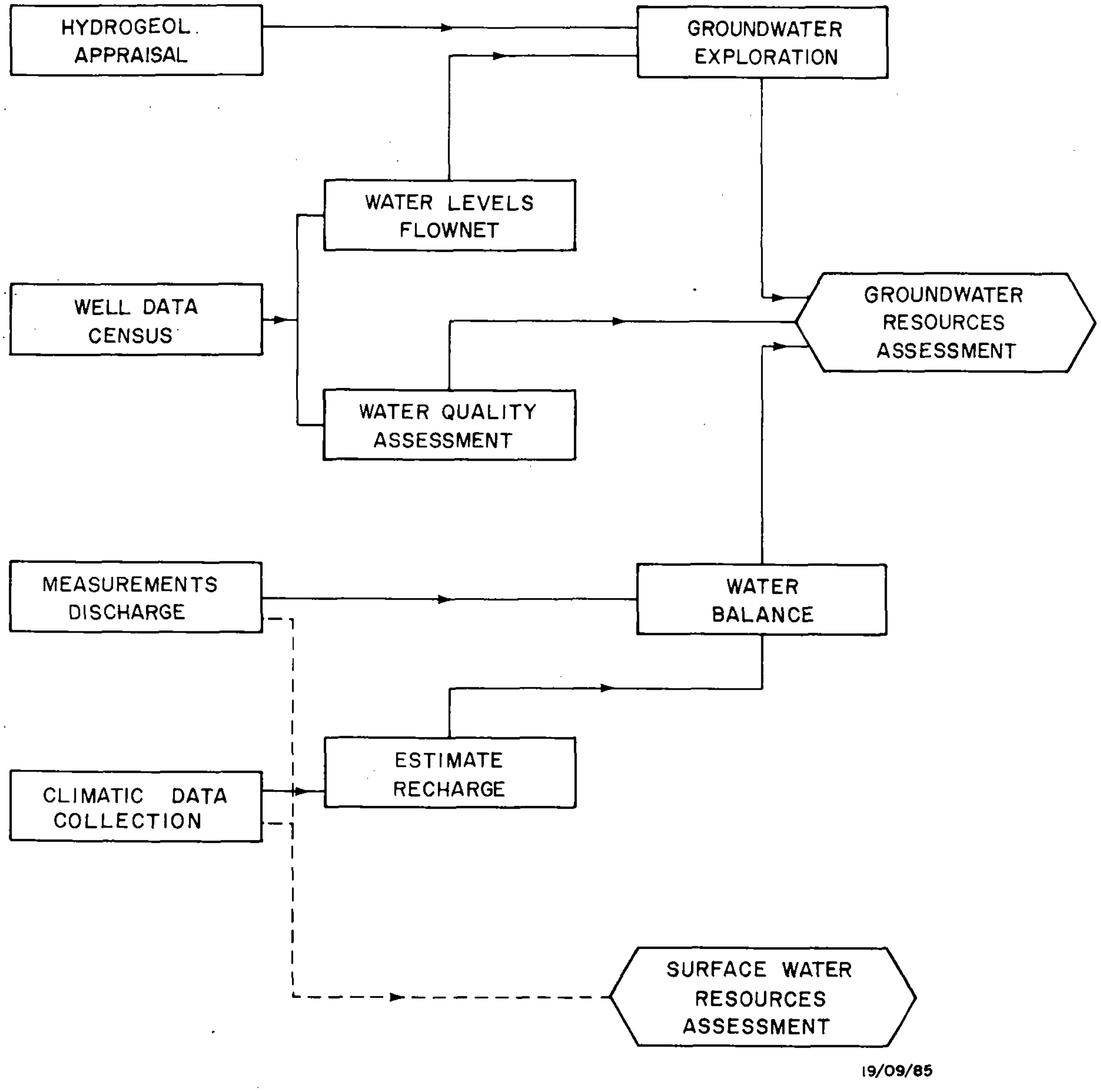

Figure 1 Groundwater resources assessment, small islands.

REGD No.	WATER BORE RECORD—BUREAU OF MINERAL RESOURCES	LOCATION SKETCH N

Bore Name and No. ______ State ______ Basin ______

Recorded by ______ Source ______ Date ______

File Ref. ______

Location: 1:250,000 ______ 1:50,000 ______

Land Division ______

Lat. ______ Long. ______ Grid Ref. ______

Air Photo Ref. ______

Elevation: ______ Datum: ______ Method: ______

Situation: Gully, rise, level ground ______ Sited by: ______

Owner: ______ Address: ______

Driller: ______ Address: ______

Drilling commenced ______ completed ______

Type: Driven, Percussion, Rotary, Jetted, DugWell, Spring

Depth reported ______ ft., measured ______ ft.

Diameter: surface ______ in., bottom ______ in.

Casing: diameter ______ in. from ______ to ______

Slotted, perforated, screen ______

Development: ______

Water Level: ______ ft. above/below surface estimated/measured __ / __ /19__

Capacity: ______ gph. estimated/measured ______

Drawdown: ______ ft. after ______ hrs. pumping @ ______ g.p.h.

Specific Capacity: ______

Transmissibility: ______

Storage Co-efficient: ______

Pump type: ______ Capacity ______ g.p.h.

Suction depth: ______ ft. Power ______

Surface equipment: ______

Status: Operating, abandoned, collapsed, capped ______

Use: Domestic, stock, town, irrigation, industry, recharge, effluent, observation, ______

Estimated Pumpage: Daily ______ Annually ______

Quality: Colour ______ Odour ______ Taste ______

pH ______ Method ______

Field Conductivity: ______ Temp. ______ °C ______

DEPTH IN FEET FROM	TO	ROSE TO (FEET)	SUPPLY G.P.H.	E/B/M*	QUALITY	TEMP. °C	LITHOLOGY	Sealed X

REMARKS ______

*E:Estimated / B:Bailed / M:Measured

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Figure 2 Index card for bore data storage. The obverse side has space for chemical analyses and strata logs.

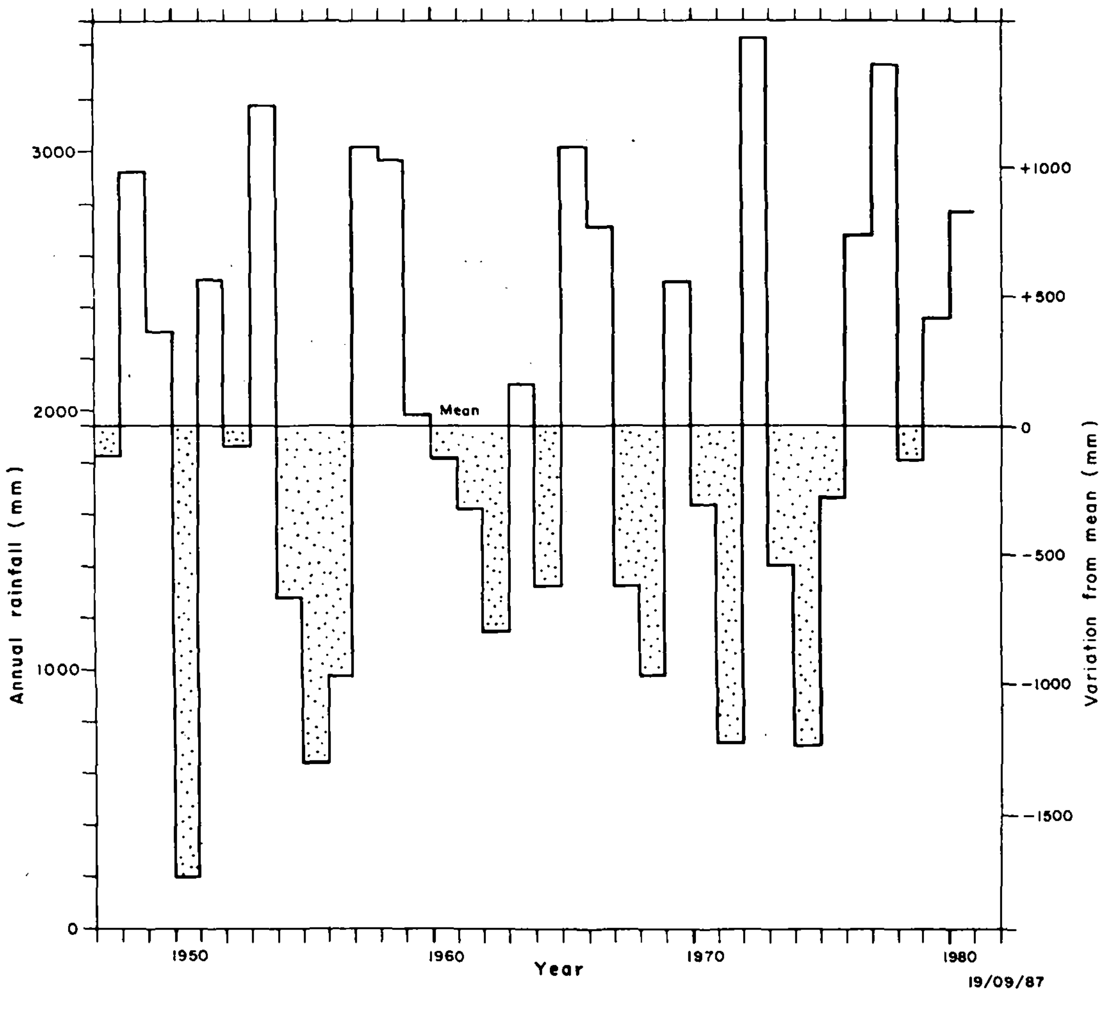


Figure 3
Annual rainfall and variation from the mean,
Tarawa atoll, Kiribati, 1947-1980

Groundwater exploration includes geophysical investigation, exploratory drilling and aquifer testing. Access for drilling rigs is often difficult in the island situation which makes surface geophysical techniques particularly useful. Of the various techniques (Table 1) the resistivity depth probe technique is a powerful tool for delineating the freshwater-salt-water interface on small islands. Results of resistivity surveys on atolls and limestone islands compare well with results obtained by drilling and analysing actual water samples (Fig. 7). A statistical comparison by Falkland (1983) on Christmas Island, Kiribati, showed good correlation between estimates of freshwater lens thickness based on resistivity depth probes, and estimates based on measurements in boreholes, provided that the lens was more than 5 m thick, and that resistivity measurements were not affected by edge-of-lens conditions or by buried cables (Fig.8). An example of a resistivity field curve and layered model for the freshwater lens in a small island is shown in Figure 9. Estimates of freshwater lens thickness in a small island can be readily contoured (Figure 10) and can also provide a quantitative assessment of aquifer porosity and freshwater storage (Jacobson & Hill, 1980). Resistivity surveys on higher volcanic islands require deeper current penetration and wider electrode arrays.

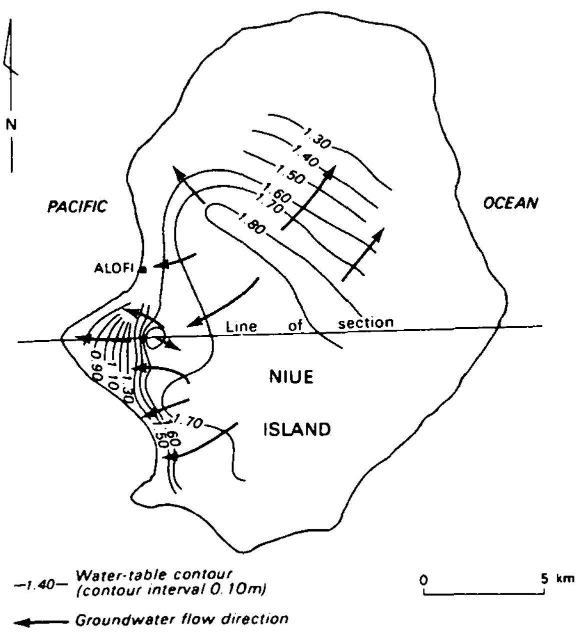


Figure 4 Water-table contours and groundwater flow directions, Niue Island, South Pacific Ocean.

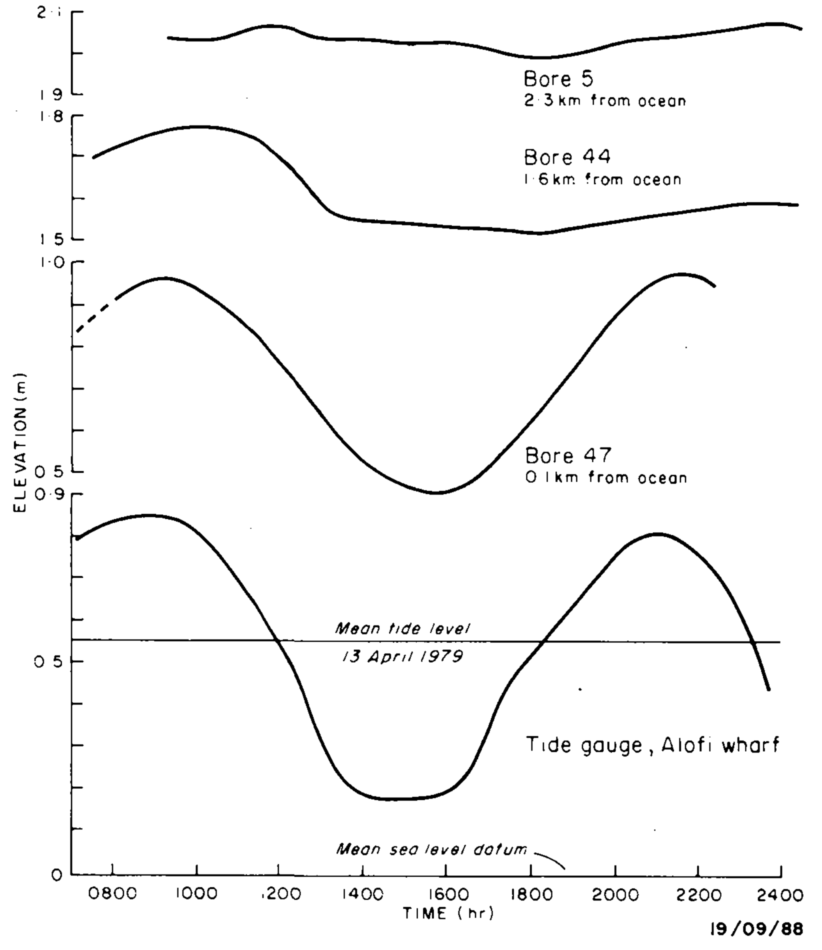


Figure 5
Tidal fluctuations in groundwater levels,
Niue Island, 13 April 1979

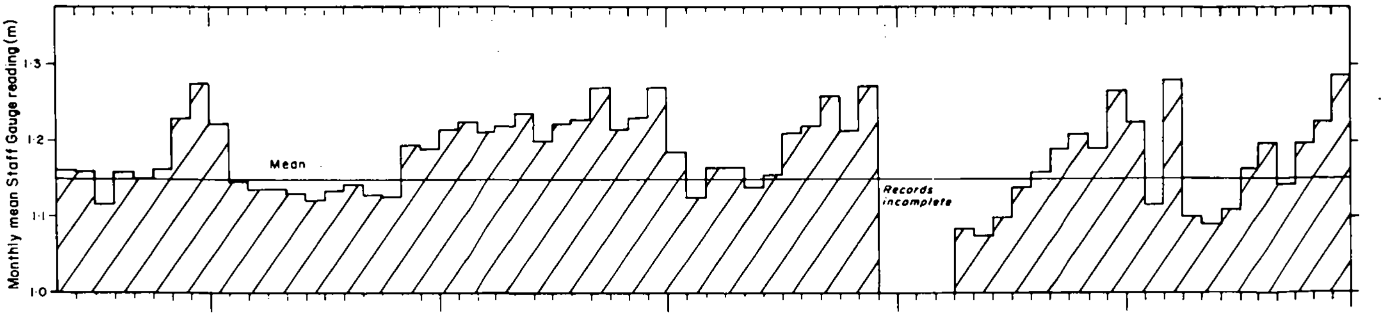


Figure 6
Variations in monthly mean sea level at the Tarawa tide gauge, 1974-1979. (Information supplied by Department of Oceanography, University of Hawaii)

Table 1. The application of geophysical techniques in small island groundwater investigations

Location	Aquifer Type	Technique and Application
Christmas Island, Indian Ocean[1]	Limestone overlying volcanics	Gravity used to identify rift zones in volcanics and cavities in limestone.
		Magnetic surveys indicated that major structures control cave directions.
		Several different resistivity methods used to indicate thickness of phosphatic soils, depth to volcanics, and limestone/volcanics contact.
		Seismic techniques indicated depth of weathering in limestone.
Niue Island[2]	Limestone-raised atoll	Gravity and magnetic used in combination to determine the limestone/volcanics contact and underlying structure of the volcanics.
		Resistivity depth probes with wide electrode spacing were used to determine depth to freshwater/saltwater interface.
Norfolk[3] Island	Volcanics	Resistivity traverses determined depth of weathering in volcanics, and depth to freshwater/saltwater interface in coastal areas.
		Magnetic surveys indicated structures in volcanics.
Tarawa, Kiribati[4]	Coral atoll	Resistivity depth probes used to determine fresh water/saltwater interface.

[1]Polak (1976); Pettifer & Polak (1979)
[2]Jacobson & Hill (1980); Hill (1983)
[3]Abell & Taylor (1983)
[4]Jacobson & Taylor (1981)

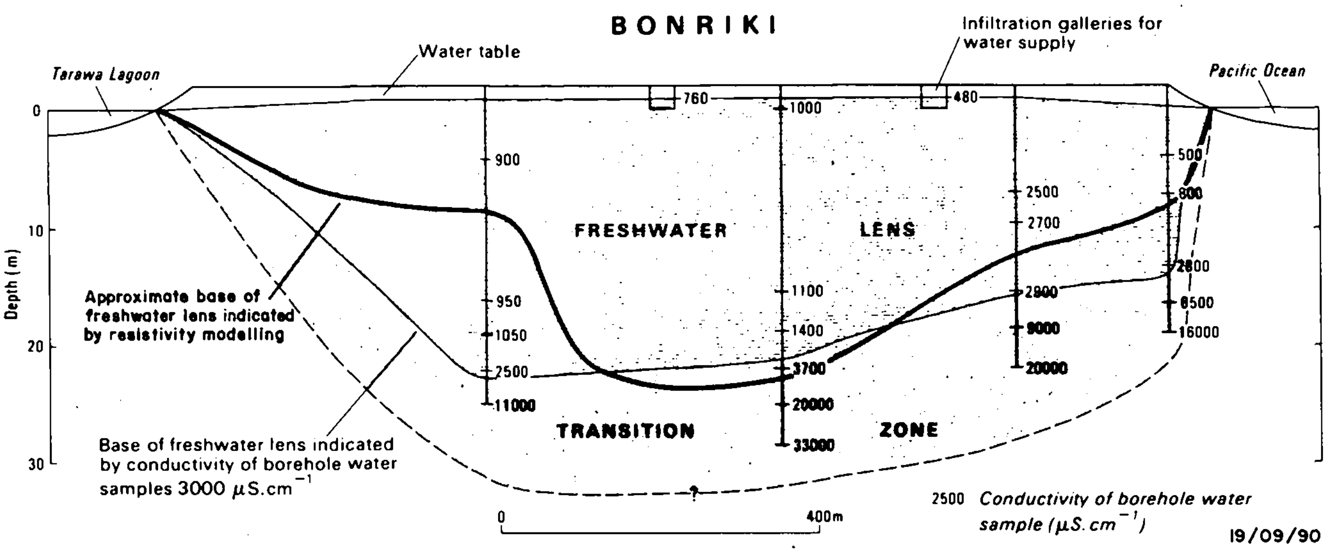


Figure 7

Cross-section of the Bonriki freshwater lens, Tarawa, as determined by conductivity of borehole water samples, and by resistivity modelling

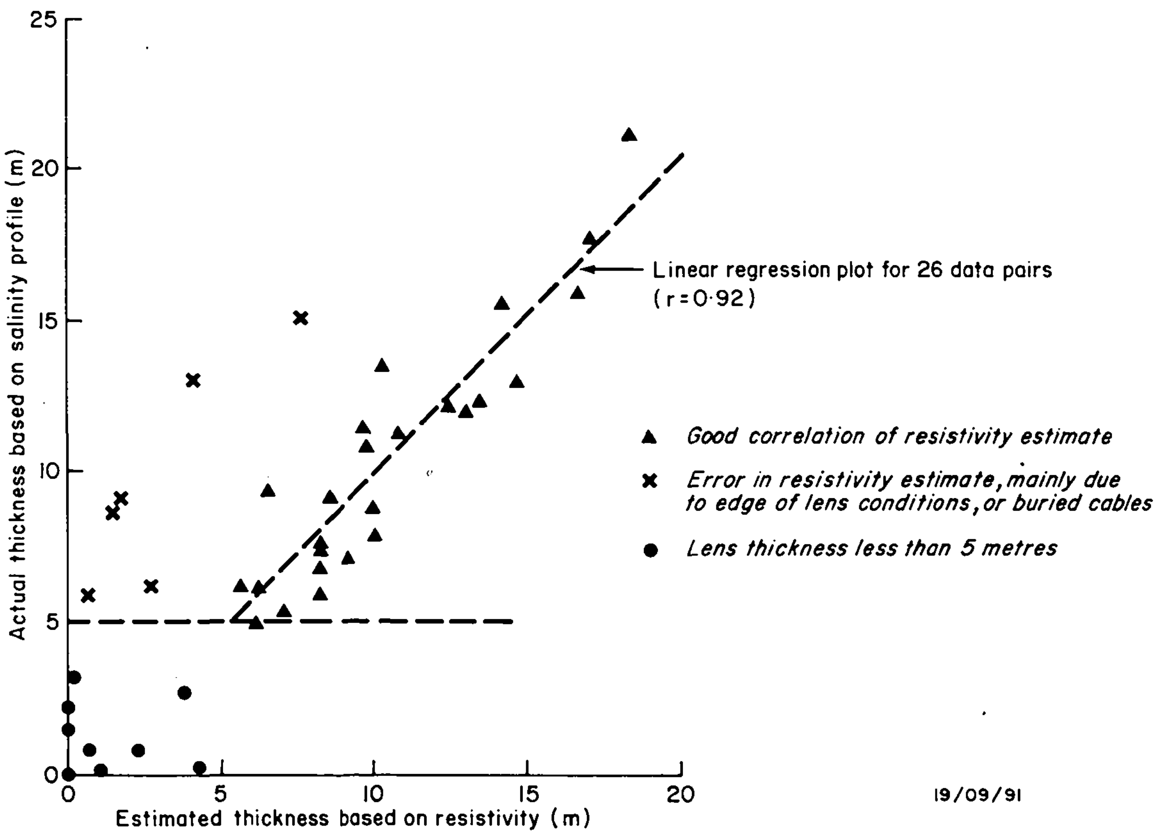
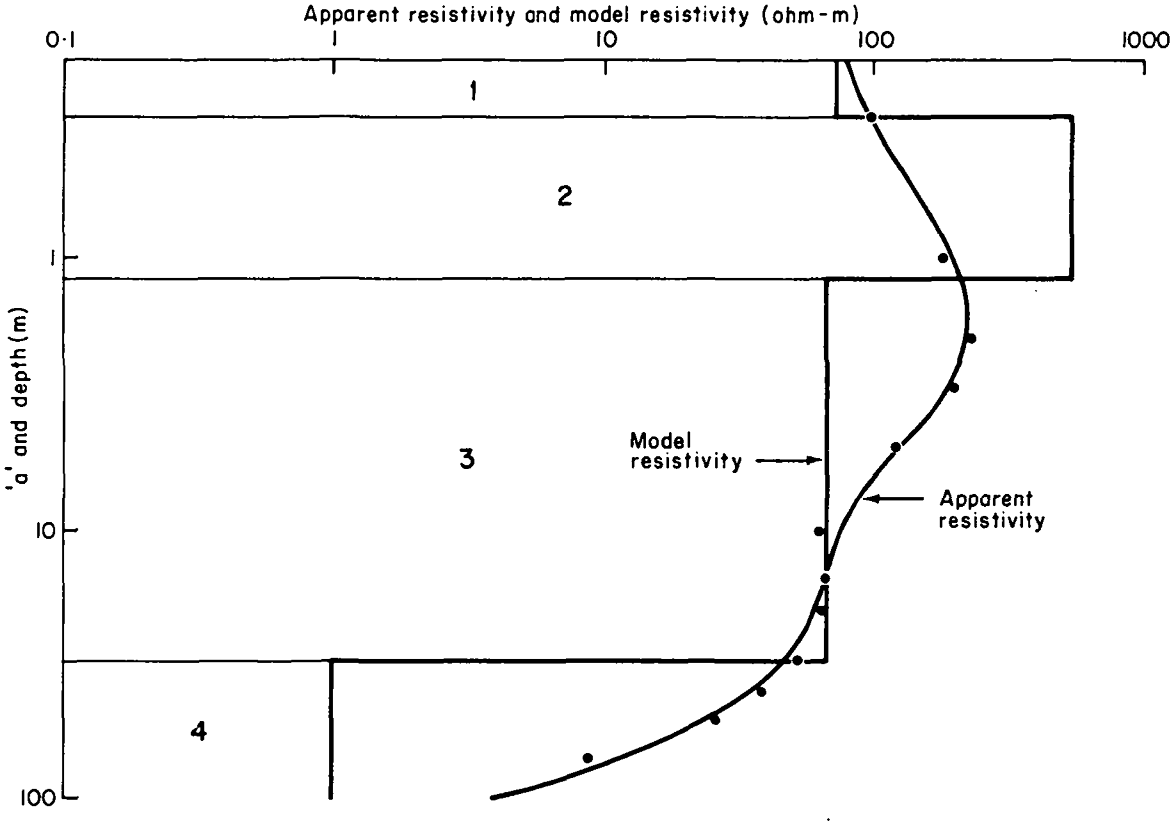


Figure 8

Comparison of freshwater lens thickness estimates based on resistivity survey with actual thickness measured in boreholes, Christmas Island Kiribati (after Falkland, 1983).

Other surface geophysical techniques, including gravity, magnetic, seismic, and other electrical techniques, may also provide useful hydrogeological information. A recent suggestion that an electromagnetic method may be useful for mapping the freshwater-saltwater interface (Stewart, 1982) requires further evaluation in the island situation. Downhole geophysical logging may be a useful method for correlating between boreholes in volcanic terrain.



Layer	Resistivity (ohm-m)	Thickness (m)	Interpretation
1	73	0·3	Soil moisture
2	542	0·9	Dry soil zone
3	67	30	Freshwater layer
4	1	—	Saltwater

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Figure 9

The resistivity field curve and layered resistivity model for a small island freshwater lens, Tarawa.

Drilling is used to delineate changes in lithology and structure at depth (Fig.10), and to provide information on the geological factors affecting groundwater occurrence (Marshall & Jacobson, in press). In atolls and limestone islands the solution of deeper strata during periods of emergence above sea level influences aquifer permeability and consequently the depth of the freshwater-saltwater interface. Aquifer testing to determine permeability and other hydraulic parameters can be done by pumping boreholes (Fig.11), and the results can be analysed by standard methods using logarithmic plots of drawdown against time or distance (Fig. 12). Permeability testing in sections of boreholes, or on drill core samples, may provide results of a different order of magnitude (Table 2).

Table 2. Permeability testing by different techniques, Tarawa

Technique	k (m/d)
Laboratory testing, core samples, a few centimetres long	1-10
Field testing, borehole sections about one metre long	5-20
Pump test, whole borehole (30 m)	180

Determination of the freshwater layer

Determination of the geometry of the freshwater layer is often the main objective of groundwater exploration in a small island. In the first instance the geometry of a lens can be defined by the Ghyben-Herzberg relationship, which indicates that the depth of the freshwater/saltwater interface below mean sea level is about 40 times the height of the water-table above mean sea level. However this relationship is simplistic and is affected by several factors including the geological heterogeneity of the island. Thus the layering of strata on Tarawa atoll (Fig. 10) has resulted in a thicker freshwater lens where the sand section is thickest; the sand

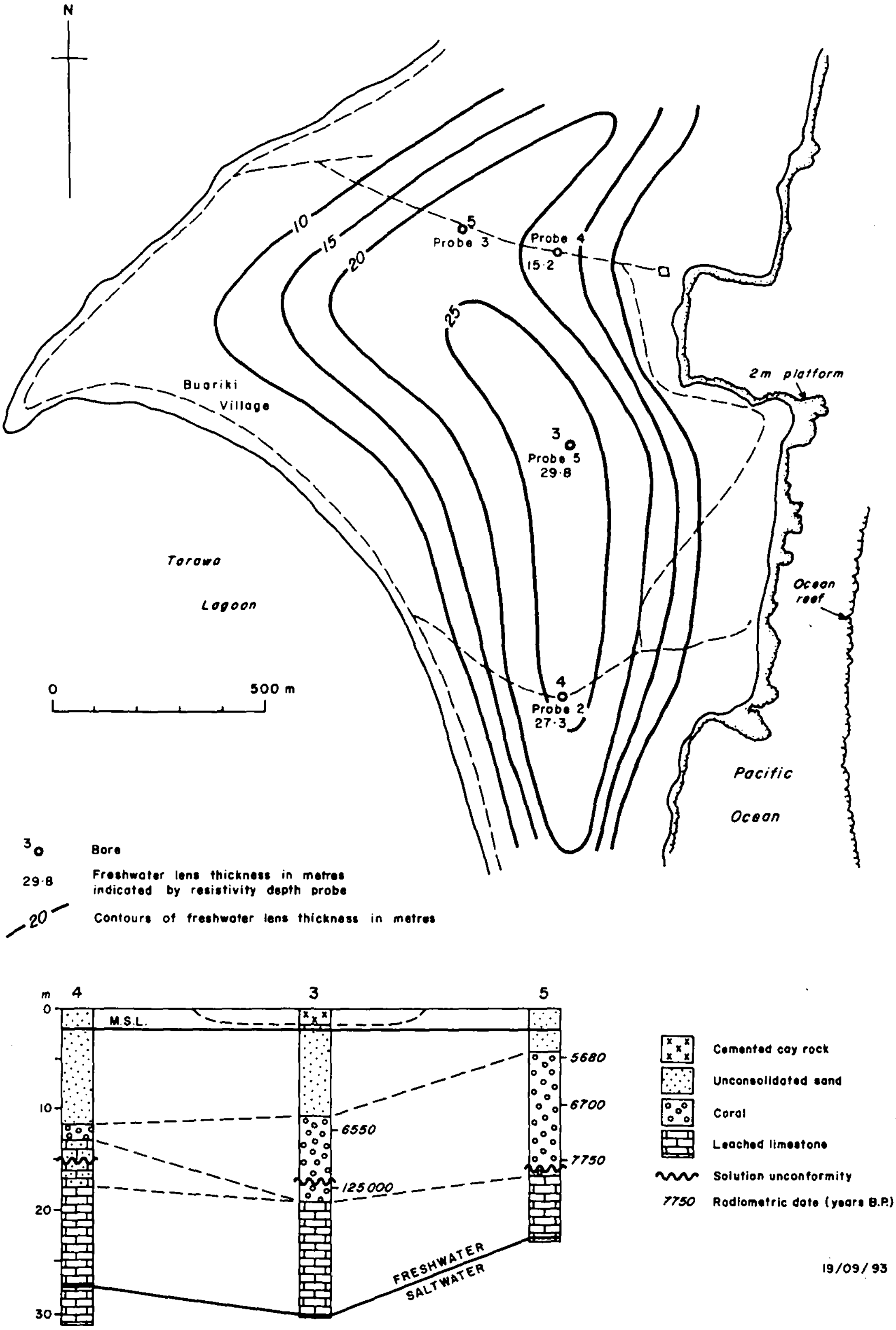

Figure 10

The Buariki freshwater lens, Tarawa, showing contours of freshwater thickness. The cross-section shows changes in lithology at depth in this case being less permeable than the underlying limestone. Changes in mean sea level (Fig. 6) also affect the freshwater lens, and a large tidal range will increase the thickness of the mixing zone at the base of the lens. For instance on the island of Bonriki, Tarawa, the mixing zone is about half the thickness of the lens itself (Fig. 7).

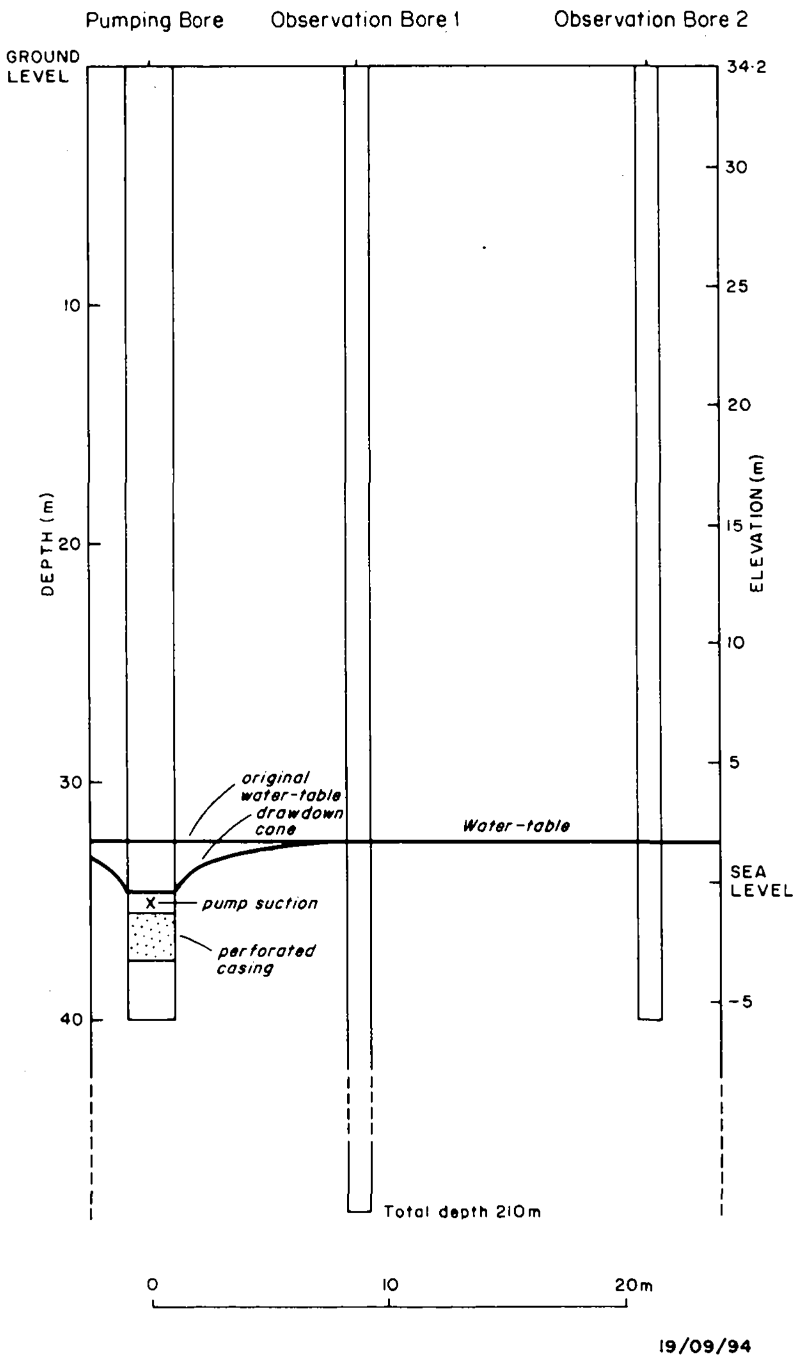

Figure 11

Arrangement of bores for a pumping test, Niue Island

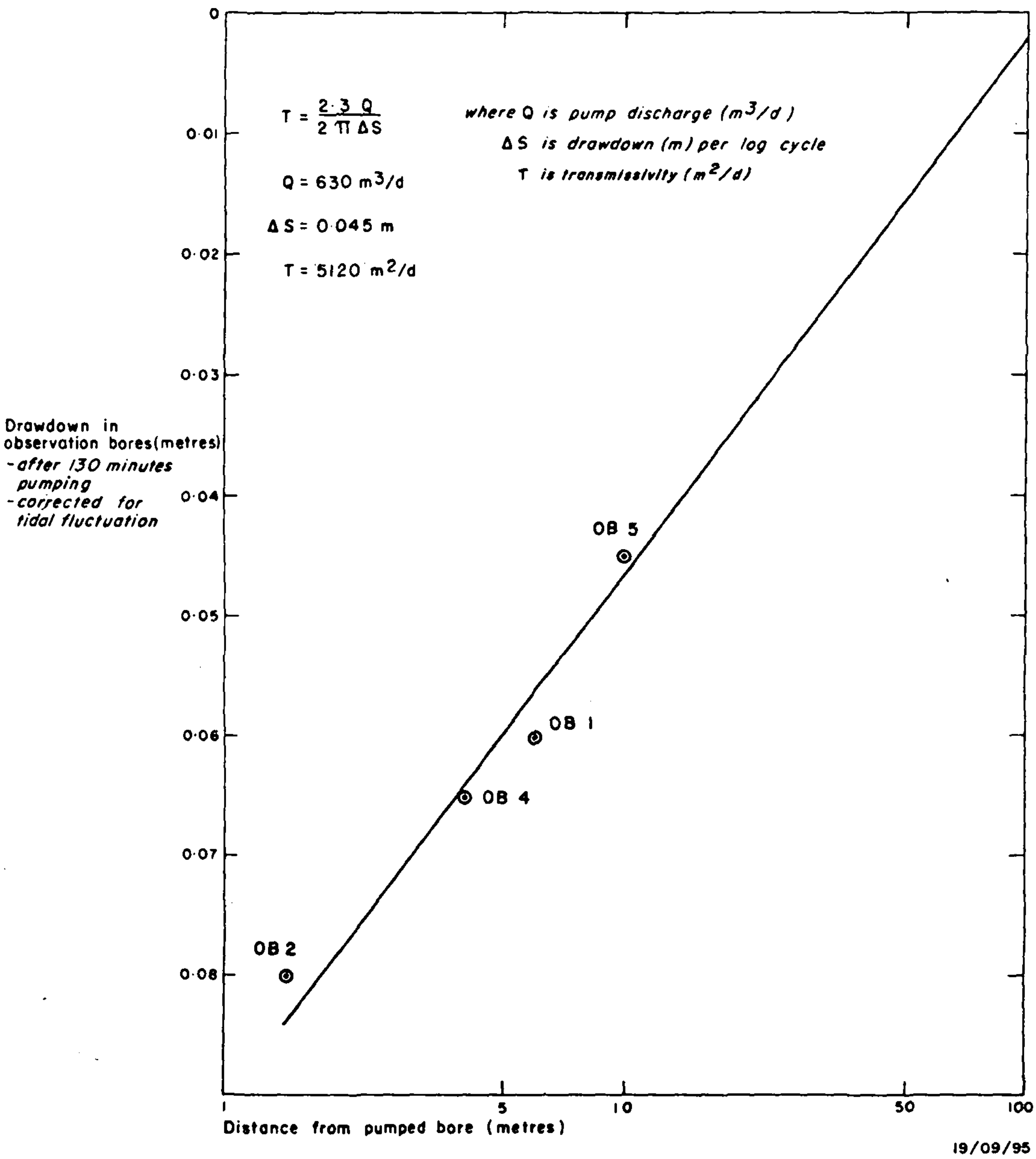

Figure 12

Results of an aquifer test, Tarawa. The plot shows drawdown in observation bores versus the distance from the pumped bore.

The water balance

Evaluation of the water balance is simplified on a coral atoll or limestone island where there is no surface runoff. The calculation of groundwater recharge is often the most difficult aspect, and this may be approached in several ways including the excess of rainfall over evapotranspiration (Fig. 13), and the chloride balance (Vacher and Ayers, 1980). Evapotranspiration may be estimated from pan evaporation or solar radiation measurements.

On volcanic and more complex tectonised islands, the surface water component must also be taken into account (Abell, 1976). On these islands the groundwater systems are also more complex (Fig. 14), and calculation of the water balance is correspondingly more difficult (Fig. 15). In recent studies on Norfolk Island the groundwater recharge rate was calculated as 25 percent using a water balance method (Falkland & Daniell, 1983) and as 18 percent using the chloride balance (Abell & Taylor, 1981). Different water balance conditions and different groundwater recharge rates pertain to areas with different types of vegetation.

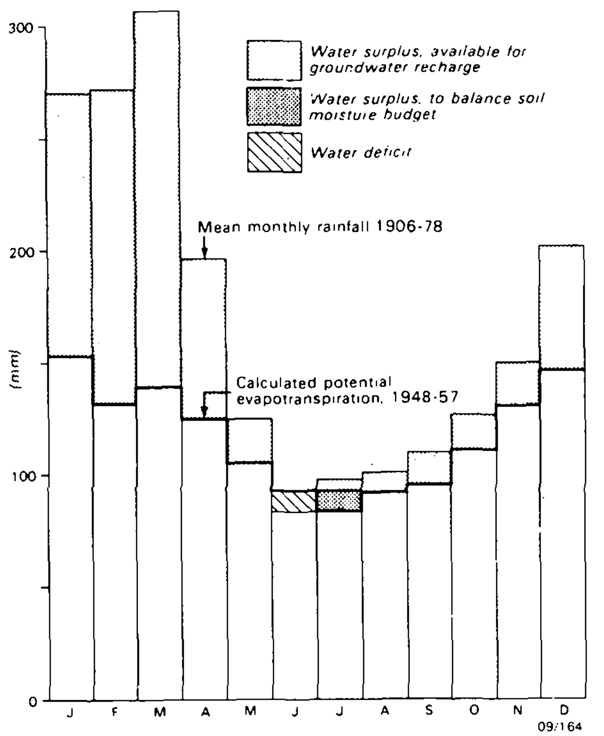

Figure 13

The water balance on a limestone island (Niue Island) calculated from monthly rainfall and evapotranspiration data

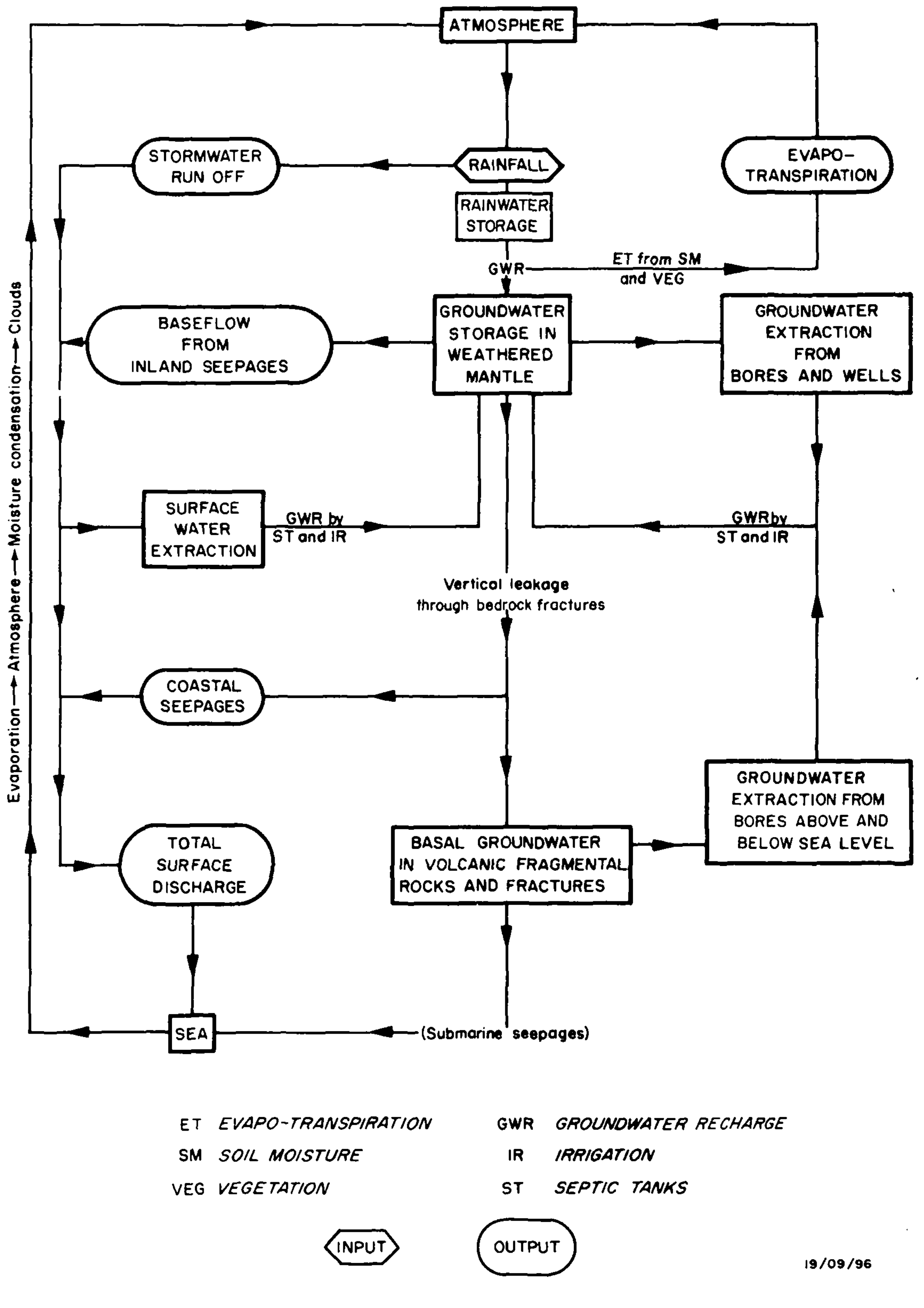

Figure 14

The hydrological cycle on Norfolk Island

(after Abell, 1976; Abell & Taylor, 1981).

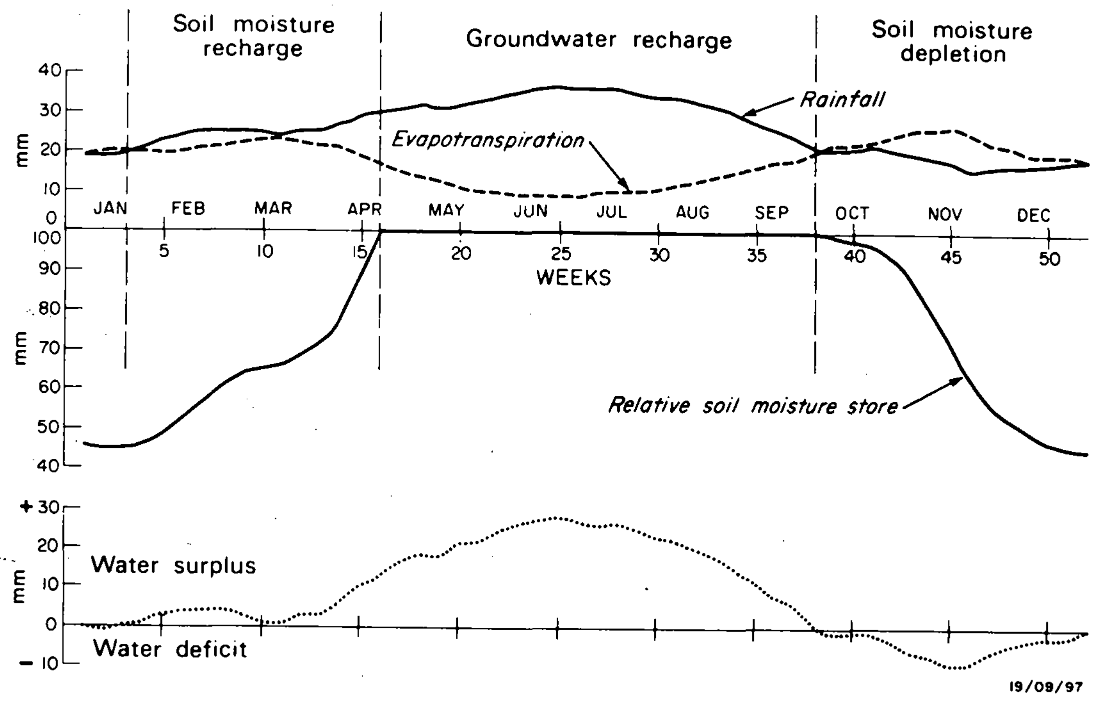

Figure 15

Annual water balance for grassland on Norfolk Island (after Abell, 1976)

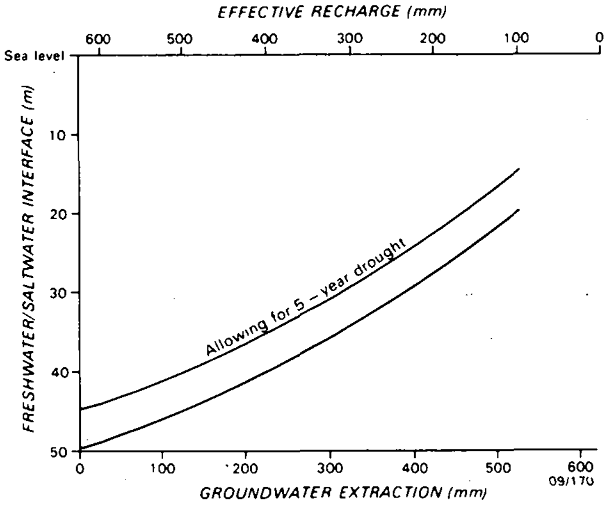

Figure 16

Effect of groundwater extraction on depth to freshwater/saltwater interface, assuming that the freshwater layer is initially 50 m thick. Calculated for Niue Island using Mather's (1975) method.

Safe yield

The safe yield or sustainable pumpage of an island aquifer depends on how much of the natural recharge and groundwater storage can be utilised without upconing of the freshwater/saltwater interface and contamination of the supply by saltwater.

A simple way of calculating safe yield on a small limestone island has been described by Mather (1975), and applied in several island studies as a first order approximation for the evaluation of groundwater resources (Jacobson, 1976). The method assumes that abstracting groundwater from a freshwater lens is equivalent to reducing vertical recharge. By simple formula, the effect of groundwater **extraction** on depth to the freshwater/saltwater interface can be estimated, the optimum extraction rate can be calculated, and allowance can be made for the effects of drought (Fig. 16). Further assessment of safe yield requires monitoring of the groundwater system especially if heavy pumping is involved. Modelling to simulate the effects of changing recharge conditions, and of groundwater abstraction, has been done in some island studies (Lloyd and others, 1980; Ayers and Vacher,1983; Daniell, 1983).

Water quality factors

Groundwater quality can be rapidly assessed by field measurements of electrical conductivity, which can be related to total dissolved solids content and chloride ion concentration for a particular groundwater system (Fig. 17). Values of electrical conductivity can be contoured (Fig. 18) to show more saline areas. The field measurements should be supplemented by fuller chemical analyses and by bacteriological analysis. The chemical analyses should include nitrate which is an indicator of groundwater pollution in the island situation. Island aquifers are highly susceptible to pollution, and the groundwater flow regime must be carefully considered in relation to the position of sewage and other waste disposal facilities, fuel storage tanks and industrial concerns.

Conclusion

Groundwater resources assessment on a small island can be considered as a sequence of activities, the basis for which is a hydrogeological appraisal and a data census of bores and wells. For a preliminary assessment some groundwater exploration and quantification of a water balance are necessary. The resistivity depth probe technique provides a rapid method of estimating the depth to the freshwater/saltwater interface.

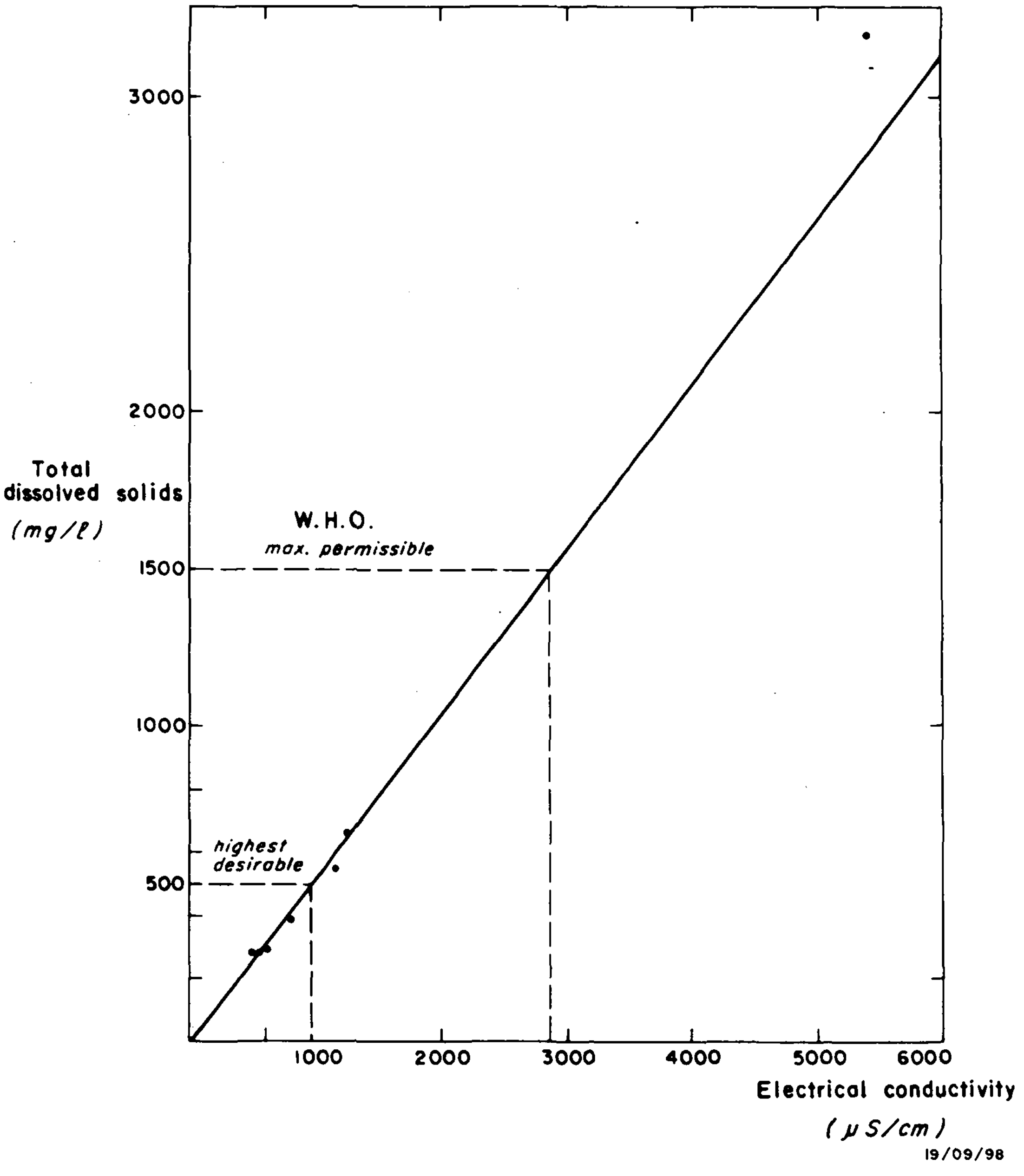

Figure 17

Relationship of total dissolved solids to electrical conductivity for the Tarawa freshwater lenses.

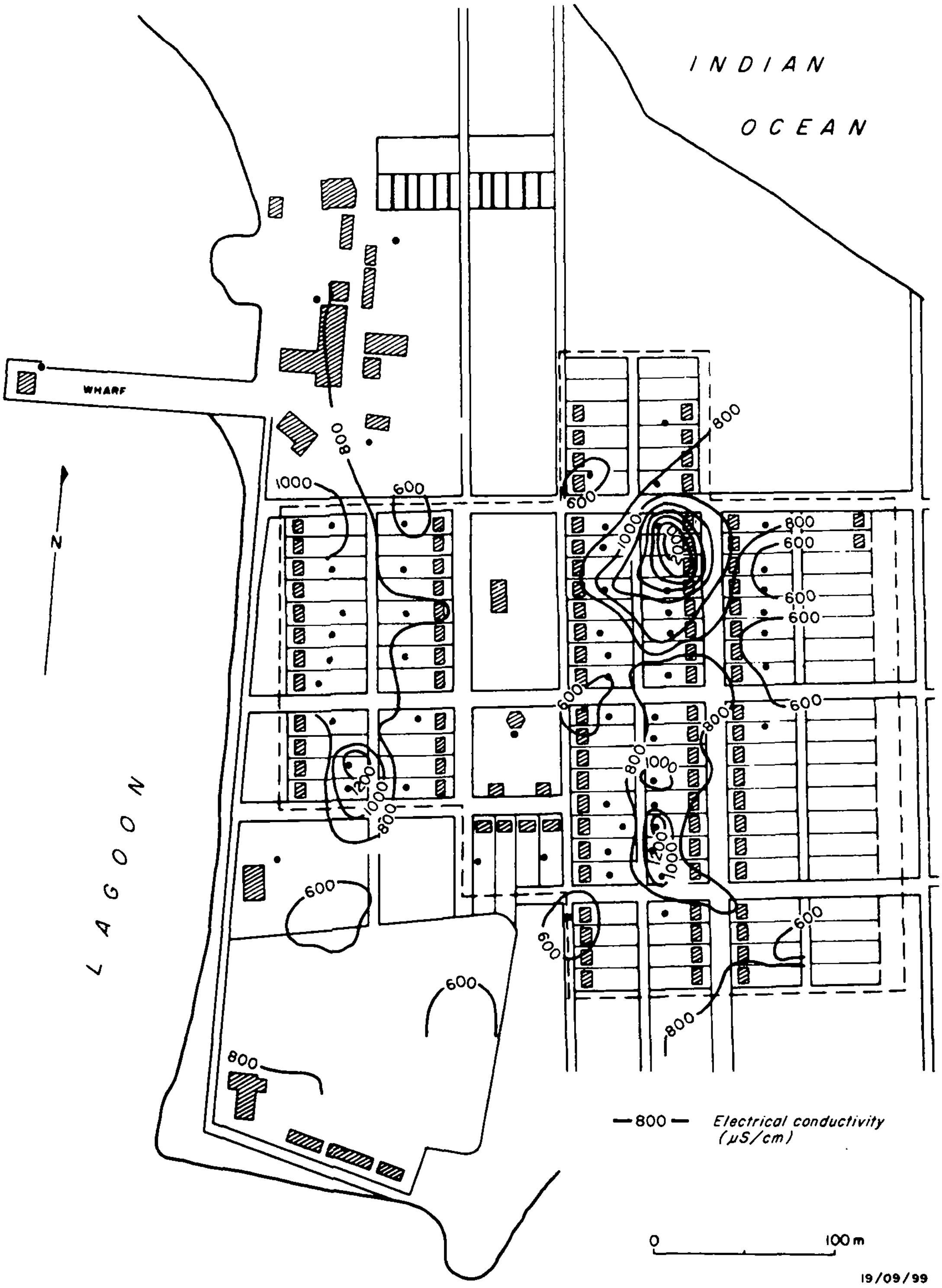

Figure 18

Results of a water quality survey in terms of electrical conductivity, Home Island, Cocos (Keeling) Islands.

Acknowledgements

I have enjoyed collaborating with several colleagues in these island investigations, including Alf Schuett, Peter Hill, Jock Taylor, Tony Falkland, Ken Campbell and John Marshall. I thank Bob Abell for comments on the manuscript. The paper is published by permission of the Director of the Bureau of Mineral Resources.

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ESTIMATE OF GROUNDWATER RECHARGE--THE CHLORIDE BALANCE APPROACH

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INTRODUCTION

Obtaining rates of recharge to groundwater-flow systems is one of the most difficult tasks in hydrogeologic investigations. Unlike many hydrologic parameters such as rainfall, wind speed, or humidity, recharge is not easily measured in the field. Estimates of recharge rates are usually acquired through, often, laborious computations using water balance equations in which recharge is the last parameter to be calculated, and thus is a "catch all" term. There exists, however, a relatively simple and straightforward method of estimating annual recharge to a fresh ground-water system. This method, described below, utilizes the chloride balance approach and requires only chloride-ion data from collected rainfall and ground-water samples.

RATIONALE

In the process of evaluating ground-water recharge of fresh-water lenses, it has been found that an estimate of recharge could be made by considering the chloride ion as a tracer which is concentrated by the processes of evapotranspiration (Vacher and Ayers, 1980; Ayers, 1981). Rainfall in coastal or island environments normally has a significant chloride-ion concentration due to aerosols (Garrels and Mackenzie, 1971, p. 137). Evapotranspiration, which involves fluxes back to the atmosphere with essentially zero chloride, concentrates the rain-derived chloride in the remaining soil-water excess or recharge. On most carbonate islands, where nearly all rainfall probably infiltrates the soil surface, the ratio Cl(R)/Cl(r) (where Cl(R) is the chloride concentration in rainwater and Cl(r) is the chloride concentration in recharge water) would measure the ratio of recharge to rainfall; i.e., r/R where r is recharge and R is rainfall. As an example, if 2/3 of the infiltrating rainwater is transmitted back to the atmosphere as a flux with Cl=0, then the chloride concentration of the remainder would be 3 times that of the initial concentration. The rationale is the same as that used to calulate the degradation of shallow groundwater resulting from recycling it as irrigation (e.g., Helwig, 1977).

AN EXAMPLE--METHOD AND RESULTS

In northern Guam, the evapotranspiration-related concentrative process can be utilized to determine recharge because the chloride concentration of rainfall is easily measured; the chloride concentration of recharge is approximated by the lowest concentration found in the fresh-water lens; and, the hydrologic circulation is not complicated by surface drainage.

Two rainwater-collecting stations were established (Figure 1), one at the Water and Energy Research Institute (WERI), University of Guam, and the other at Ypao Point near the Guam Memorial Hospital. Samples were collected using a prewashed glass bottle with an attached funnel. The collecting apparatus was placed in the open and left on site for approximately 24 hours (during expected rain days). A minimum of 250 ml of rainwater was obtained for each of the six collection dates.

Ground-water samples were collected from observation wells (Figure 1) penetrating the fresh-water lens. Six wells were selected on the basis of location and accessibility and sampled using a Kemmerer-type water sampler. All samples were taken at a depth of 6 meters below the water table.

Immediately after collection, chloride-ion concentrations were determined in accordance with Standard Methods for Examination of Water and Waste Water (American Public Health Association, 1975).

Results of chloride analyses on rain-water and ground-water samples are listed in Tables 1 and 2 respectively. Chloride-ion concentrations are given in milligrams per liter (mg/l). Sample collection dates are also listed.

From the data of Table 1, the chloride-ion concentration of rainwater is relatively low. The range of values is from 2.0 to 7.2 mg/l with a mean concentration of 4.5 mg/l. Although the time interval of collection is fairly short, it is assumed that this mean chloride-ion concentration is representative of rain water. No other chloride data for Guam's rainwater have been found in the literature; however, supplemental data from analyses conducted on storm runoff samples (WERI personnel) add validity to the assumption. These data are shown in Table 3. Chloride-ion concentrations found in storm runoff agree very well with those found in rainwater. These data represent an additional set of rain-water samples. The high value for Site No. 1 is probably the result of some local contamination and probably does not represent the norm.

Inspection of Table 2 indicates that chloride-ion concentrations of groundwater fall within two groups, one with a range of values between 72 and 151 mg/l and the other with a range between 9 and 15 mg/l. The data suggest that concentrations within the

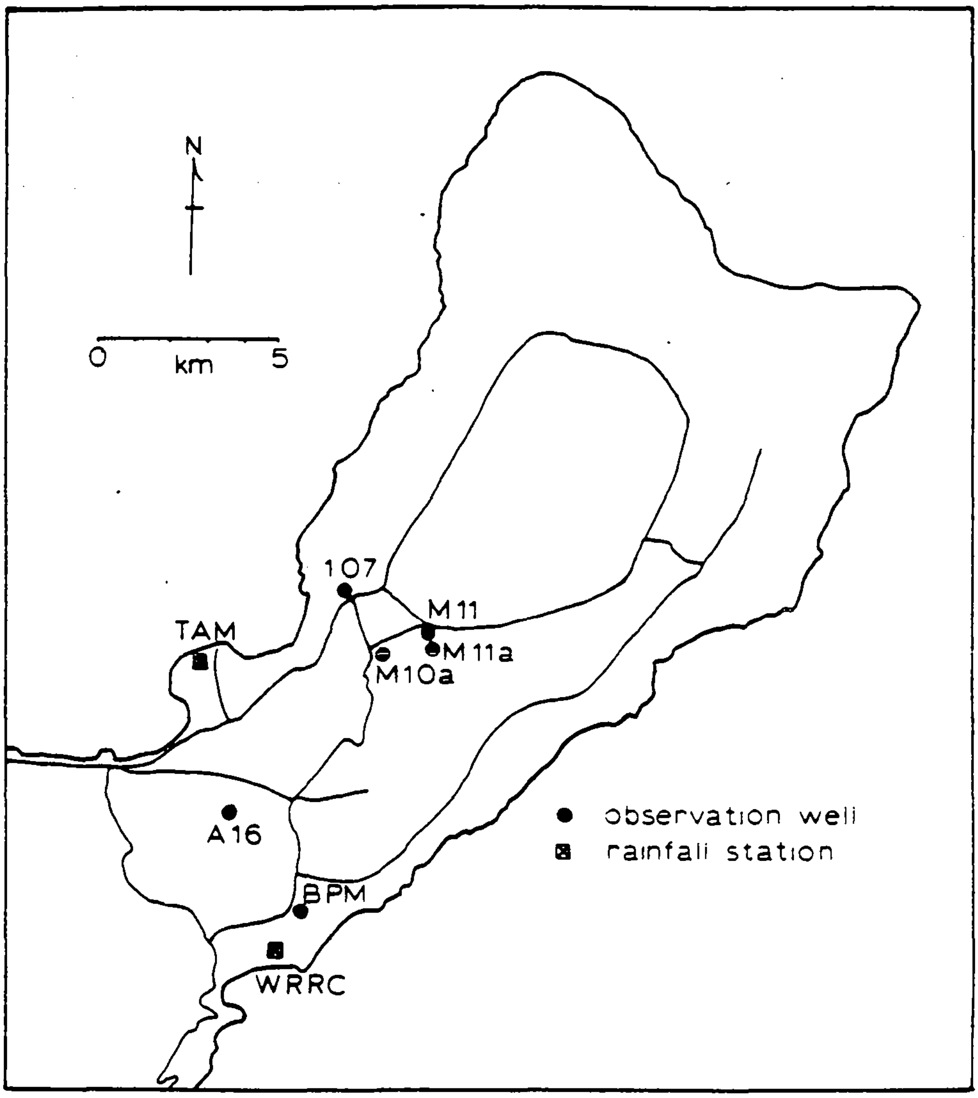

Figure 1. Map of northern Guam showing the locations of rain-water and ground-water sampling sites. Note that the designation WRRC is the location of the Water and Energy Research Institute, University of Guam.

Table 1. Results of chloride analyses on rain-water samples.

Sample No.	Date of Collection	Cl (mg/l)
*WRRC-1	6-18-80	6.0
WRRC-2	8-19-80	2.0
WRRC-3	9- 9-80	6.0
TAM-1	6-18-80	4.0
TAM-2	9-22-80	2.9
TAM-3	9-30-80	7.2
	Ave =	4.5

*WRRC designation indicates samples collected at the Water and Energy Research Institute (formally known as the Water Resources Research Center).

Table 2. Results of chloride analyses on ground-water samples.

Sample No.	Date of Collection	Cl (mg/l)
BPM	3-25-80	87.6
	6-18-80	91.2
A-16	3-25-80	125.0
	6-18-80	177.0
M-10A	3-27-80	9.7
	6-18-80	9.9
M-11	3-27-80	72.2
	6-18-80	72.7
M-11A	3-25-80	10.5
	6-18-80	11.7
107	3-27-80	13.7
	6-19-80	15.0

Table 3. Results of chloride analyses on rainfall-runoff samples.

Location	Date of Collection	Cl (mg/l)
Camp Watkins Road	10-27-80	27.0
Airport Parking Lot	10-27-80	6.7
Perez Acres	10-27-80	5.3
Latte Heights	10-27-80	5.6
Barrigada Heights	10-27-80	3.8

range of 9 to 15 mg/l represent the lowest chloride-ion concentrations found in the fresh-water lens. Concentration values with the high range probably represent sea- water intrusion on a small scale due to pumping within nearby well fields or local hydrogeologic anomallies.

The interpretation of these results is summarized in Figure 2. With the premise that the mean of the low range of chloride values for samples from the fresh-water lens represents the Chloride ion of recharge, then Cl(r) = 11.8 mg/l. From the rain-water analysis, Cl(R) = 4.5 mg/l. Thus Cl(R)/Cl(r) = R/r = 0.38. With R = 218 cm/yr (Mink, 1976), recharge is r = 83 cm/yr, and actual evapotranspiration is 135 cm/yr. The result agrees very well with previous estimates, as discussed below.

PREVIOUS ESTIMATES OF RECHARGE

One of the earliest attempts to estimate the magnitude of recharge in northern Guam was made by Peterman et al. (1945) as part of a ground-water study sponsored by the military. Study results indicated that the northern half of Guam (limestone plateau) received a recharge rate of 100 million gallons per day (mgpd) for the approximate 259 square-kilometer area or about 0.39 mgpd per square kilometer.

In a later study of water resources beneath the Marbo-Dededo area (north-central Guam), Davis (1964) estimated that from 0.73 to 0.89 mgpd of rainfall per square kilometer reached the fresh-water lens. This range of values was determined by two methods. The low end of the range was estimated by assuming that any month with less than 10.2 cm of rainfall is a drought month and therefore no water is available for recharge. Rainfall during the dry-season months of January through June is usually less than the 10.2 cm criteria and thus would not contribute to recharge. Rainfall during the remaining months, less the 10.2 cm/mo value, contributes approximately 101 cm of water to recharge. This latter volume, when multiplied by the area, yields the 0.73 mgpd per square kilometer estimate. Davis obtained data from Blumenstock (1957) for calculating the budget.

The high end of the range of recharge rates was obtained by assuming that runoff in southern Guam (volcanic upland) is equivalent to recharge in northern Guam (there is no surface drainage on the northern plateau). That is, if northern Guam was completely drained by streams, then the amount of water leaving the area would be equivalent to the amount of water that infiltrates as recharge. Davis found from past records that the average of the total flow for six drainage basins in southern Guam was approximately 0.89 mgpd per square kilometer and the range was 0.73 to 1.00 mgpd per square kilometer.

In an administrative report prepared for the U.S. Air Force, Davis and Huxel (1968) estimated the recharge rate over northern

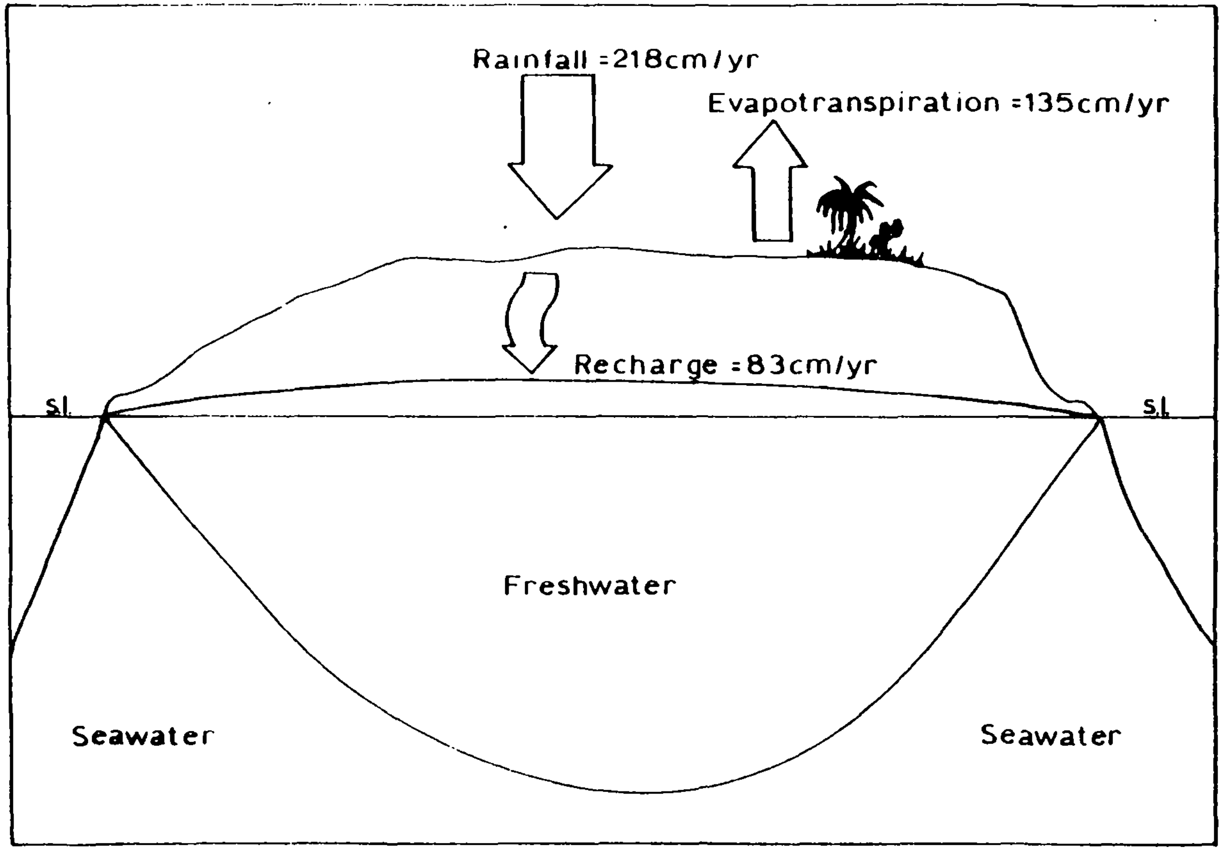

Figure 2. Cartoon depicting the interpretation of data results for the northern Guam recharge-estimate study.

Guam to be about 0.97 mgpd per square kilometer. Runoff records for the Pago and Ylig Rivers in southern Guam were used in the determination. Both streams drain basins that receive approximately the same magnitude of rainfall per square kilometer as northern Guam.

In a report of ground-water availability and current water well development, Sheahan (1968) estimated that 50 percent of the rainfall infiltrates the soil as recharge. His estimate is apparently based on a budget calculation using evaporation data; however, no data was presented in the report and no computational procedures were described.

Austin, Smith and Associates, Inc. (1970), in a report to the Public Utility Agency of Guam, presented a set of rainfall-runoff percentages for the wet and dry season months. Rainfall and runoff data were from 1959 through 1966 and included stage records from six streams in southern Guam. For the 8-year period of record, the mean dry season rainfall-runoff percentage was 38 and the mean wet season value was 63. It was assumed, as in previous studies, that runoff from the six watersheds was a measure of the recharge to the lens of northern Guam; no allowance was made for base flow from groundwater. These percentages convert to a recharge rate of about 1.04 mgpd per square kilometer.

As part of a study on the ground-water resources of Guam, Mink (1976), presented estimates of recharge based on hydrologic budget calculations and rainfall-runoff relationships. Using rainfall and evaporation data he estimated that from 0.52 mgpd to 0.95 mgpd per square kilometer reaches the fresh-water lens if no runoff from the northern plateau is assumed and that from 0.44 mgpd to 0.86 mgpd per square kilometer is available for recharge is 5% runoff is assumed.

In general, the results of previous studies on ground-water resources of northern Guam have presented a range of recharge rates that center on 0.77 mgpd per square kilometer with a deviation of about 0.20 mgpd. This converts to a rate from 79 cm/yr to 135 cm/yr or, expressed as a percentage of the mean annual rainfall, from 37 to 62 percent (assuming that 218 cm/yr is representative of the mean annual rainfall). The estimate, based on the chloride balance approach, falls within this range established by other investigators.

CONCLUSION

A relatively simple and straightforward method to obtain annual (and long term) recharge rates to fresh-water lenses has been dicussed and an application example has been presented. The technique requires chloride-ion concentration data from rainwater and ground-water samples. Assuming that the chloride ion is concentrated by evapotranspiration-related processes and that the freshest part of the lens can be identified, a rainfall-recharge ratio can be calculated. Results from the application of this method to the estimation of recharge in northern Guam (and elsewhere) agree very well with previous work which used other independent methods to obtain recharge estimates.

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WATER QUALITY MONITORING IN SMALL TROPICAL ISLANDS

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ABSTRACT

Water quality can be monitored by testing samples either on site or in the laboratory. In the latter case the samples need to be pretreated (according to the analysis required) in order to prevent changes during storage and transportation. There are advantages and disadvantages associated with both on site and laboratory monitoring and this paper presents a discussion of such aspects.

In small tropical island situations water for human use is usually obtained from either roof catchments or from wells dug down to the groundwater. Many of these wells are dug close to the coasts and are close to the centres of human habitation. There is therefore a high risk of contamination of the water by salt (from seawater intrusion) and by bacteria and viruses (from human and animal wastes deposited nearby). Thus the monitoring of the quality of water is important, particularly if the water is intended for human consumption. This monitoring can be achieved by the analysis of samples either on site or in a laboratory. Each analytical mode has certain advantages and disadvantages and this paper attempts to compare the on site and laboratory studies.

LABORATORY ANALYSIS

Two major advantages of the use of laboratory analyses are:

1. This mode is usually fairly cheap because labour is cheap and the cost of shipping samples relatively small; methods are usually well established and a wide range of analyses may be available.

2. In an established laboratory, trained personnel are always available This ensures that accuracy and reproducibility are maintained (this is extremely important) in long term monitoring studies.

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* Presenter of the paper

The disadvantages of such a procedure are:

1. Although labour is cheap, most of the people who are involved in collecting water samples are inhabitants of the sampling area and normally they do not appreciate the importance attached to such a job (usually only very basic training in water collection or sampling is given). Therefore the sample of water collected may not be truly representative of the area from whence the sample has been collected.

2. In most cases only one or two samples are collected from a location at a particular time to minimize costs e.g. freight, payment for analyses. Here again, if the water has been contaminated there is no way the laboratory can recheck the sample. The time it takes for the water to travel from the collection point to the laboratory can be fairly long. There is often a need for the analyses to be completed relatively quickly because if contamination is suspected (and later confirmed by the laboratory work) prompt action may be necessary.

Pre-treatment of Samples

The majority of the parameters normally determined on water samples change over a period of time. In many instances, it is recommended that certain parameters be determined on site e.g. pH, carbon dioxide content, dissolved oxygen, temperature, etc., while for the determination of other parameters, samples can be preserved and analysed within 24 hours or after several days or months depending on the analate.

Nowadays, it is recommended that three bottles are used for sample collection from each site if a wide range of analyses are required. They are treated as follows:

a) Water left untreated - for determination of nitrate, alkalinity, acidity, coliform counts, etc. This sample should be stored at $4^{o}C$ and analysed within 24 hours because, for example, if bacteria are present, microbial activity in water can change the chemical form of some elements in solution e.g.

$NO_2^- \longrightarrow NO_3^-$ by Nitrobacter sp.

$NH_4^+ \longrightarrow NO_2^-$ by Nitrosomonas sp.

$SO_4^{2-} \longrightarrow H_2S$ by Proteus sp. or Clostridium sp.

For microbiological parameters, water should be analysed preferably within 6 hours but not later than 24 hours. Freezing water usually retards bacterial growth but some bacteria die at such low temperatures.

b) Addition of $HgCl_2$ - for the stabilization and determination of certain nutrients in water e.g. PO_4^{3-}, NO_3^-

c) Addition of HCl/HNO_3 to pH < 2 - mainly for the determination of heavy metals. The acid minimizes precipitation and absorption of the ions onto the walls of the containers

d) Other treatments can be used depending on the analyses required e.g.
Hg - preserve water with 20% (w/v) $K_2Cr_2O_7$ (prepared in 1 + 1 HNO_3) at 4°C
CN - preserve water with NaOH to pH > 12, refrigerate, store in the dark

ON SITE ANALYSES

The major obstacle with this practice is the expense. On site analyses prove expensive because of the following:

1. A qualified person is usually required to do the analyses and has to travel to the sampling site.

2. There is also a need to transport all portable equipment to the testing site.

3. A wide range of equipment is required (usually fairly expensive) e.g.

   a) The Orion ion selective electrode meter enables an analyst to carry out a number of determinations depending on the number of probes available (e.g. nitrate, chloride, fluoride, ammonia, copper, sulphide, pH, etc.). Each probe costs between US$160-400 depending on the parameter to be determined and because it is an ion selective electrode system, a different probe is required each time a different determination is carried out. There are other brands similar to the Orion on the market.

   b) Millipore bacterial testing field kit.
   This kit comes with a portable MF-millipore petri dish incubator which is operated using a 12 volt battery or a 240V power supply. Total coliform, faecal coliform and fecal streptococcus are determined using this kit.

   c) Hach kit.
   This kit consists of a colorimeter plus chemicals, burettes, pipettes and cylinders. It has an advantage over the Orion selective ion electrode meter because a wider range of analyses (either by titrimetric or colorimetric methods) can be completed e.g.

alkalinity, acidity, bromide, carbon dioxide, chloride, chlorine, chromium, color, copper, flouride, hardness, iodide, iron, manganese, nitrate-nitrogen, nitrite-nitrogen, dissolved oxygen, pH, phosphate, silica, sulphate and turbidity.

As well as the three field kits discussed above other field equipment is commercially available but is usually of restricted application e.g. pH meter - pH

Dissolved oxygen meter - dissolved oxygen
Conductivity meter - conductivity, temperature and possibly salinity
Turbidity meter - turbidity

Other difficulties of working in isolated areas are:

1. Damage to fragile instrumentation from sea or road transport. Field equipment needs to be very robust

2. Only limited quantity of reagents can be taken and if these are lost, spilled or damaged no replacement can be made

3. If only one selective ion meter is taken it has to be standardized for each parameter at each sampling site - a lengthy procedure. The use of a temporary base field 'laboratory' within a few hours collection time of a number of sampling sites is often easier

The advantages of on site testing are:

1. A large number of analyses can be completed for little additional expense.

2. A much more representative sampling programme can be carried out.

3. In cases of doubt, it is easy to check the data by analysing another sample.

4. If some unusual problems occur, samples can be sent to a laboratory for further analyses.

5. Results are available much more quickly.

CONCLUSION

On site and laboratory analyses both give valuable data for the monitoring of water quality. For small island countries the relative merits of each type of analysis programme can only be assessed after a consideration of the situation of the collection site relative to the nearest suitable laboratory.

In the past problems have arisen because of poor sampling or long time lapses between sampling and analysis. It is probable that for many small island situations a combination of both on site and laboratory analyses will be required. A monitoring programme to obtain baseline data for water quality in many small tropical islands is an urgent need.

Discussion - Theme IV

(Keynote Speaker: Jacobson)

Q. (Dale) Which resistivity technique was most useful in identifying the lens.

Wenner configuration.

(Grimmelman) : Initial Assessments

Q. (Seychelles) Query on practicality of local data collection such as by villagers.

Stressed basic need for simple data.

Q. Use of electrical conductivity kit.

For quality assessment.

(Hall) : Hydrometric networks.

Q. (Solomon Islands) What are WMO's training activities in the Pacific region.

Little in Pacific, some roving seminars.

(Falkland) : Surface Water Resource Assessments

Q. Was terrain slope factor considered in the analysis.

In the high slope (volcanic) areas, runoff was not increased as expected due to better recharge.

Q. (Solomon Islands) Why did evapotranspiration, surface runoff and groundwater recharge not add up to 100% of precipitation.

Due to soil moisture changes over short period.

Q. (Dale) What factors were used in Penman analysis.

Pan and Penman figures were comparable. Therefore assumed OK.

Q. (Hall) How were peak flows established.

Not too relevant due to small proportion in the analysis.

(Scott) : New Technology.

Q. (Dale) Comment on suitability of equipment, costs and power supply.

Rechargeable dry cell or other optional power; possible costs £500 each system.

Q. Are field data loggers returned to base and repaired.

Yes.

Q. Time for technology transfer to Solomon Islands.

In due course, c. 6 years.

Q. (Mauritius) Can the loggers record intensity.

Yes, depends on no of tips for the selected time interval.

Comment (Malaysia): problem of redundancy of equipment due to rapid technology changes.

(Peterson) : Groundwater Recharge

Q. (Chairman) Did the lens change with season.

Not significantly.

Q. (Solomon Islands) What caused aerial variability in recharge.

Due to aircraft runways.

Q. Can percentage error be estimated.

Borehole data matches model estimates, possibly 10-15% error.

Q. Have other recharge estimate methods been compared.

Refer to Ayers talk (Chloride Ion).

Q. (Chairman) What variability in soil characteristics were tested.

The initial range was appropriate.

(Ayers) : Groundwater Recharge

Q. (Falkland) Where were rainwater samples collected.

In open areas across the island.

Q. (Vanuatu) Was long time for percolation to the water table allowed in sampling.

Not necessary, based on overall model period.

Q. (Solomon Islands) Were irregular Cl concentrations allowed for.

Freshest zone was tested.

Q. (Chairman) Were samples taken at water table level.

Not right at the top.

Q. Were Cl^- concentrations in soil moisture accounted for.

No.

Q. (Indonesia) Can this method be applied to larger recharge areas.

Within limits.

(Falkland) : Groundwater Assessment

Q. (Phillipines) Is there a rapid recharge calculation method.

Cl^- method is the most rapid, must come from the freshest part of the lens. Not applicable in developed areas.

Q. Does surface runoff have an effect on the Cl method.

It is an overall recharge model; must subtract runoff from precipitation if leaves area of concern.

Q. (Jacobson) What are some possible percentages typical of recharge in the water budget models.

			Rainfall
4-6%	Babelthuap	Volcanic	3759 mm
22%	Norfolk	Volcanic	1340
48-59%	Kwajalein	Small atoll	2500
38%	Guam	High limestone	2100
20-30%	Christmas	Large atoll	760

(Barker) : Modelling

Q. (Jacobson) What is the difference between an analytical and numerical model.

Numerical model gives a discrete value solution whereas an analytical model gives a solution in terms of a function.

Q. What variables are considered in E. European stochastic models.

All variables, rainfall, transmissivity, etc.

Q. (Jacobson) How successful have existing freshwater lens models been.

(Ayers) Numerical models in Guam and Bermuda. From Bermuda models, recommendations on brackish water zone use were made.

(Peterson) : Lens Storage/Monitoring

Q. (Seychelles) How often are storage measurements made.

At least monthly.

Q. (Jacobson) Which is better - several observation wells or multi-layered observation well.

Depends on local geology.

(Prasad) : Water Quality Monitoring

Q. (Solomon Islands) Where field samples cannot be return to the lab within 24 hours, is there any method to preserve bacteriological samples.

Analysis should be done on site.

THEME V WATER RESOURCES ASSESSMENT

...continued

COMMONWEALTH SCIENCE COUNCIL WORKSHOP ON
"WATER RESOURCES OF SMALL ISLANDS"

Keynote Speech: Water Resources Development and Management on Small Islands

By: Frank C. Go
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Suva, Fiji

The subject of our theme is Water Resources Development and Management on Small Islands. The largest concentration of these islands in the World are in the South Western Pacific bounded between longitude $150^{o}E$ to $130^{o}W$ and between latitute $10^{o}N$ to $25^{o}S$. Hundreds or more of these islands are inhabited and the total population numbers about 1.5 million. Large numbers of small islands are also found in Southeast Asia, the Indian Ocean, and the Caribbean. However, because I am more familiar with water resources problems in the South Western Pacific, I shall base my observations on conditions and problems found on these islands.

My discussion will be based on the perspective of a planner and engineer rather than that of a specialist in either groundwater development or hydrology. Groundwater development and management occupies the central position in our theme because groundwater constitutes the most important single water resource on most small islands and is the only fresh water resource of significance on coral atolls.

I shall also limit most of my discussion mainly to problems related to the development and management of water supply since the water resources found on small islands are primarily limited to this use. On the large high profile volcanic islands such as Fiji where perenial surface streams exist, water resources can be harnessed for the generation of electricity and the irrigation of crops.

Relevance of the Theme and Status of Water Supply Development in the South Western Pacific

As you all no doubt know, the 1980 to 1990 period has been designated by the United Nations as the International Drinking Water Supply and Sanitation Development Decade. The main target of the Water Decade is to provide water and sanitation for all people by 1990. A very crude estimate of the expenditure needed to meet the Decade's water supply goal is about US$60 billion. In this respect, the situation in the South Western Pacific is relatively good and the targets of the Water Decade are likely to be achieved. Furthermore, in countries such as Palau, Fiji, Cooks, Western Samoa, Tonga, Niue and Tuvalu, the targets are likely to be reached sooner, at least in a gross quantitative sense. With some exceptions, quality of service is however generally in need of upgrading.

The South Western Pacific covers a vast geographic area and although the problems are diverse, the constraints to development are common to most. These are: lack of funds, shortage of technical staff, difficult logistics and supply problems, weak institutional infrastructure, and lack of appropriate pricing policy and water legislation.

Population is mostly rural with a small number of urban centers. Urban population ranges from a low of 10% of total population in the Solomon Islands to over 90% in the Northern Marianas. Population growth and job opportunities bring about a rapid growth of these urban centers.

Quantitatively, most countries are well along in the provision of water service to residents in the urban centers. There are however deficiencies of a qualitative nature such as low pressure, service interruptions and lack of quality control. However, there are few outbreaks of water borne disease which can be ascribed to piped urban water systems in the recent past.

Information and statistics available to WHO indicate also a relatively high level of availability of rural water facilities, ranging from almost 100% to perhaps 40%. Most of the countries have on-going programmes to further develop and construct rural water facilities. The main constraint to a faster pace of development appears to be the availability of funds.

An inherent problem with the water supplies of the islands in the South Pacific is that yields are highly dependent on shifting climatic conditions. Surface streams are highly variable in quantity and quality and groundwater resources are generally small and subject to salt water intrusion during periods of drought and overpumpage. There is thus a natural geographical constraint which limit supplies. Water use habits of the island populations contribute to this water shortage problem since water is traditionally treated as a free good and there has been few actions to develop and implement policy to curb uneconomic water use or to promote conservation.

Two previous meetings related to water resources development in islands of the South West Pacific region had been convened within the last five years. One was a seminar on water resources for human and agricultural needs convened by the New Zealand Department of Scientific and Industrial Research, at Wellington, New Zealand, in 1979. The second was the meeting on Water Resources Development in the South Pacific convened by ESCAP, at Suva, in 1983. The proceedings of the first meeting contains a good collection of papers which reviewed the climatology and hydrogeology of the islands of the South Pacific. The report of the ESCAP meeting shows that the discussions span a wide range of subjects and included techniques for the assessment of water resources, and management problems and other issues. This last meeting identified the following as broad and long term perspective issues which are relevant to our theme.

(1) - need for data for water resources assessment

(2) - need for broad national water policy

(3) - need for appropriate institutional arrangments for water resources development

(4) - need for comprehensive legislation

(5) - need for the development of appropriate technology

I shall touch on these issues as appropriate when I discuss the various topics related to our theme. I believe that we should keep this list in view even though our theme will be focused primarily on operational level technical problems, constraints, and solutions. This is because good plans and management of resources are either impossible to develop or operationlize in the vacuum of accountability and public policy.

Small Island Hydrology

The development and management of water resources must begin with an understanding of the hydrological constraints.

Perhaps the most significant feature of note is that the hydrological cycle of small islands as compared to large continental land masses fluctuates and responds more rapidly to climatic factors. Further, as the location of most small islands is in the tropics, there is a high rate of evapotranspiration.

C. G. Revell stated that widespread rain production in the tropics results only from convergence and air lifting generated in synoptic scale disturbance - normally cyclonic wind circulations with horizontal dimensions of about 1000 km.

A starting point in planning for water resources development or for characterizing the hydrology of island groups is to understand the weather systems. Revell characterized the following South Pacific Island groups as follows:

- Tuvalu, Rotuma, Samoa, and Tokelau islands being in the South Pacific convengence zone tend to have more rain than groups further north or south.
- Vanuatu, Fiji, Tonga, Niue, and Southern Cooks, all lie in the region towards the fringes of the tropics in the trade wind zone and thus has more pronounced seasons. The islands tend to have long dry winter periods and wet monsoon summers. There is considerable inter-annual variations in rainfall.

- Nauru, Banaba, Kiribati and Phoenix are all in the equatorial dry zone and experience long period anomalies in rainfall unrelated to seasons, although in the main summer and autumn months are wetter than others.

The other three main factors affecting island hydrology are geology, topography, and ground cover. The three are interrelated. High profile and mountainous topography are generally characteristic of volcanic islands while flat topography are characteristics of corraline islands. Ground cover is generally more varied and dense on volcanic islands where there is surface runoff and high soils moisture.

Volcanics or uplifted islands generally exhibit more complex geological formations and have varying permeability and groundwater potential. Coral atolls on the other hand are characterized by relatively uniform formation of limstone and cemented or loose sand, and are highly permeable. Most small islands are coraline.

Water Resources Development

Significant and reliable surface water resources on the small islands are generally non-existent. And except for the largest high profile islands, their potential for economic development is generally low. And even when surface streams exist, they are generally unreliable and the water quality is highly variable and frequently subject to pollution. Since this Workshop's focus is on the small islands, our theme's subject will primarily be concerned with groundwater supply development.

Various speakers have already addressed various topics on island groundwater hydrology. I wish only to present what I consider to be the technological considerations a planner needs to know. Groundwater resources of small islands can be classified as either parabasal or basal. The larger high profile volcanic islands also have perched aquifers. The freshwater in a parabasal zone rests directly on impermeable volcanic basement rock. A basal groundwater zone floats on sea water and is commonly referred to as a Ghyben-Herzberg lens. I will limit my discussion to the Ghyben-Herzberg lens since it is the most important in the context of the small coral atolls. The principle, based on consideration of hydrostatic, states that the depth of fresh water is equal to 40 feet times the head of freshwater above sea level. Field studies show that the zone of diffusion between fresh and salt water is about 60 feet , and the 1000 ppm isochlor lies at the middle of the zone. When enough rainfall occurs to give uniform recharge to the fresh water aquifer, a Ghyben-Herzberg lens developed. If static condition of no recharge persists over time, the water table becomes flat and ultimately the fresh and salt water become mixed by diffusion and the Ghyben-Herzberg lens is destroyed.

Unlike parabasal on perched groundwater aquifer, the Ghyben-Herzberg lens does not have a stationary bottom configuration. In fact, the geometry of the lens changes with hydraulic head, salinity, and flow condition. Further, overpumpage or improper well design and siting can lead to upwelling of saline water into the freshwater lens.

Development and management of this groundwater supply thus require a critical understanding of the geological profile and hydrodynamic behaviour of the lens. Some of the key considerations are the following:

- lowering the water table will lead to an amplified rising of the saline - freshwater bottom;

- the Ghyben-Herzberg lens bow-out shape can only be maintained over time when there is freshwater recharge.

These considerations tell us that it is critical to maintain the water table condition, particularly during periods of drought when there is no freshwater recharge. (It has been observed that under condition of zero recharge and withdrawal, the lens is relatively stable.)

These considerations also explain why under certain condition,even seemingly small drop of the water table can lead to a disproportionate increase in salinity. It can also be seen that there will be an increase in salinity in the lens resulting from salt water diffusion and tidal action, during extended periods of drought.

When a freshwater lens has been completely destroyed by mixing with saline water, it may be irrevocable, at least in terms of man's planning horizon.

Israel, a country which probably leads the World in groundwater management, controls salt-water intrusion by deliberately allowing freshwater to flow towards the edge of its coastal plain, where it is captured in coastal collectors, a system of shallow wells along the sea-shore. This approach was intended to preserve the qualitative integrity of the freshwater lens.

I shall now briefly refer to the incrustation of wells, which is an ever present problem on coral islands. The basic problem is due to the procipitation of calcium carbonate resulting from the release of CO_2, which in turn is affected by the hydraulic drawdown. The sharper the hydraulic gradient, the more CO_2 is released. Thus, a partial mitigation of the problem is to design well systems composed of smaller wells and better well screen design.

Although it is generally agreed that wastes must be contained to avoid the spread of disease, the absolute natural constraint imposed on these islands by a limited and fragile water supply resource cries out for a re-examination of policy in respect of the carrying capacity of the more congested main islands. It is of course possible to envisage waterborne sewerage systems discharging to the sea or treated before using it to recharge the groundwater lens, but this also requires a generous supply of water. The alternative of using a conservancy system and night soil treatment and disposal clashes with the culture of the Pacific islanders. Saline water conversion is a possibility, but present cost levels are uneconomic.

Concern about groundwater pollution relates primarily to unconfined aquifers. Where goundwater supplies are drawn from deep and confined aquifers, unsewered sanitation is generally not a threat to the water supply provided the wells are properly grouted.

Although the relationship between groundwater quality and on-site sanitation is complex, various studies have shown that the unsaturated zone is the most important line of defence against faecal pollution of the aquifer. Maximisation of effluent residence time in the unsaturated zone is, therefore, the key factor affecting the removal and elimination of bacteria and viruses.

It has also been shown that the removal of bacterial and virus by physical filtration and absorption is to a great extent due to clogging around the latrine pit. Heavy rainfall may cause desorption resulting in a sudden increase in numbers of micro-organisms entering the groundwater. The chemical nature of the groundwater also affects the survival rates of bacteria. Acidic and saline groundwaters reduce the survivability of enteric bacteria.

When pit latrines penetrate the saturated groundwater zone, the clogging process is also found to be effective in limiting the extent of bacterial penetration. The maximum extent of the travel of bacteria and viruses is principally governed by the groundwater flow velocity, and data from the literature indicate that this is about the distance the groundwater flows in a period of about 10 days to 2 weeks. The decrease of bacteria in this zone is largely due to die-away. Due to the various factors affecting flow velocity, establishing a safe minimum lateral spacing between a water supply and an on-site sanitation unit is difficult. However, a widely accepted rule is to provide a 50 feet separation between a pit latrine and a well.

Recharging of the groundwater can mitigate drought induced problems, particularly in respect of controlling the increase in the chloride level in the fresh water lens. But this is also marginal or impossible on the small islands since the recharge water can only come from the capture of surface runoff which is generally non-existent.

One inescapable conclusion from all that I have said about the nature of the groundwater supply on small coral atolls is that the central consideration in water resources management is to preserve the integrity of the Ghyben-Herzberg lens in both qualitative and quantitative sense.

On the small islands without reliable surface streams, the only reasonably economic alternative to groundwater is the capture of rainwater. An important advantage of this system is that it does not conflict with the sanitation imperative, and it needs only minimal or no treatment. Rainwater capture systems are most economic when they are large and when sited in areas with a well distributed rainfall pattern. These areas are in the South Pacific convergence zone and the area straddling the 10° north latitude. Because of economies of scale, large systems can be constructed more economically to provide long term storage to bridge periods of extended drought. The pattern in many areas however is to construct small individual household rainwater tanks, generally 500 to 1000 gallons in capacity or smaller. Water tanks are either built of metal or reinforced concrete.

However, the individual household water tank approach generally is not a solution in the face of extended periods of drought lasting several months. For example, on islands in the equatorial dry zone which are subject to long period anomalies in rainfall such as Nauru and Kiribati. Provision for water supplies on these islands must give priority consideration to long term storage requirement which can not be met by individual household tanks economically. Even at subsistence level of usage, the storage capacity provided generally will not last over 1 to 2 months, for the average family.

To provide long term storage volume, a large reservoir will obviously cost less than many small tanks. The large schemes however generally require a distribution system which adds to cost and needs a means for capturing the rainwater. Large rain water catchment schemes are also more difficult to undertake because they require more coordinated planning and a conscious attempt to integrate funding sources. They also require a longer planning horizon than exists in many small islands.

Models are methematical descriptions of physical systems. The equation of a straight line is a model. However, groundwater models can be very complex because the subsurface geology is complex. You need good field information and judgement to develop a good model. Otherwise, you only have a mathematical expression. I have heard it said that if you already have all the information you need to develop a good model, you don't need one. I believe however that modeling can be a useful management tool and that it can be used to guide development because the model allows you to explore a range of possibilities. We have to clearly understand however that all hydrological models are subject to probabilistic events and there is a great margin for error.

For the larger high profile islands, surface supplies and springs exist and can be exploited. If the distance to a surface water supply source is not excessive, it is generally more economic than groundwater. However, considerations which can add substantial cost to surface water supplies are requirement for treatment, storage reservoirs, and pumpimg. These considerations can in fact change the relative cost advantage of a surface water supply over a groundwater supply alternative.

Surface water supplies are more effectively exploited on the islands located in the Pacific Convergence Zone such as Western Samoa where rainfall is more evenly distributed throughout the year. On islands subject to pronounced seasons and dry winter periods, surface supplies as I have noted are frequently unrealiable in quality and quantity.

A very important advantage of surface water supplies over groundwater supplies, particularly in the rural areas, is that it is frequently possible to eliminate the need for mechanical pumping. Aside from the saving of recurrent cost, avoids maintenance and repair problems associated with pumping equipment. This is usually an over-riding consideration for rural water supplies.

The construction of a reservoir to increase the yield of a stream is generally only economic for a large scheme because it is subject to substantial economies of scale. The same applies to surface water sources that require treatment. The latter will in addition require a strong commitment to the operation and maintenance of the treatment facilities. This requires institutional development and training of personnel, both are difficult tasks in the context of small island countries.

Conservation, Economics, and Cost

It is not uncommon in the South Pacific to encounter both complaints of a water shortage and water wastage at the same time. The problem arose because water shortages were either greatly aggravated by uneconomic water use and outright waste or substantially created by the absence of conservation ethics and appropriate financial pricing policy to restrain uneconomic water uses. In places, water is provided free of charge to all consumers, including those of profit making enterprises. When water is provided at zero price, it is not likely that even under the best of condition that the supply-demand relationship can be maintained in balance for long. On the small islands where this resource is limited, it invites recurrent crises. There are of course real water supply resource constraints, but many of the problems are due to bad or misguided policy and an absence of financial accountability in the provision of water supply service. In too many cases, what otherwise would have been manageable physical and supply constraints were made into a crippling problem.

Even when there is a charge for water service, it is invariably heavily subsidized and more importantly it does not provide any incentive for prevention of waste. It is not uncommon to encounter water rates that do not even provide revenues sufficient to pay for recurrent costs of operation and maintenance. Operating deficits of water departments are usually covered by direct government appropriations. This kind of situation usually places the water authority at the center of politics and creates institutional myopia since realistic longer range planning and operating policy is not possible when the operational budget is decided annually. It is also characteristic in this situation that preventive maintenance work is ignored and the system quickly goes into disrepair, since politicians do not generally give funding priority to longer range objectives. The seeds for the next crisis are planted.

A realistic assessment of most water supply systems invariably reveals water wastage and leakages as a major causes of water shortages. The absence of appropriate water charges is the most serious policy deficiency. How else can one rationalize claims of water use rates exceeding in some cases over 250 gallons per day per capita under the conditions found on the islands of the Pacific? And then proceed to instigate for the addition of facilities to alleviate what is claimed to be inadquate system's capacity? Reasonable per capita consumption in the urban areas of these islands can not reasonably exceed 50 to 60 gallons and water use rate in the rural areas is unlikely to exceed 15 to 20 gallons.

One reason claimed for the reluctant attitude to either charge for water service or charging the full cost of water production is that the islanders by tradition have looked on water as a free public good. Another explanation is that almost all major water systems and projects were historically developed and financed by the administering powers and grants from bilateral aid agencies. The latter factor to a major extent made it possible for the local authorities to ignore financial discipline either in the development or operation of island water systems. Investment decisions generally are opportunistic and based only on criteria of the funding agencies. Investment criteria are rarely if ever used as tests of project feasibility.

Water loss due to leakages in excess of 50% has been cited in several places. This massive loss combined with water waste create conditions of water shortage leading to frequent service interruptions and the imposition of water hours. And although a system may be producing the equivalent of 250 to 300 gallons per capita the situation is perceived as one of water shortage. The ususal response of the authorities is to increase supply by drilling more wells. This approach provides some immediate relief but frequently aggravates the long term management problem by diverting attention from the leakage problem. Further, the approach does not solve any of the long term problems nor can reliance on the strategy provide a system which insures good water service standards.

Average cost figures for the construction of water supply facilities are necessarily difficult to pin down since they depend on service levels, treatment requirements, quality of service, design criteria selected, geographical imperatives, hydrological dictates, etc.etc. It appears that global average figures (which are necessarily very crude estimates) are about US$150 per caput for urban type piped water systems and about $50 - $60 per caput for rural standpipe and individual systems. Cost levels in the South Pacific appear much higher and there is a wide diversity. I have encountered one instance indicating that reticulation system's repair and replacement to eliminate leaks alone would cost upward of $400 to $500 on a per caput basis.

Saline water conversion is a natural alternative to groundwater or rainwater on small islands, the challenge however is to achieve conversion at a reasonable cost.

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POLLUTION OF SMALL ISLAND WATER RESOURCES

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ABSTRACT

In this paper the possible sources of pollution of water from the point when it leaves the clouds as rain and moves through various parts of the hydrological cycle are considered. Only those pollution sources likely to be significant in small island situations are examined in any detail. Examples used to illustrate the points made are taken from small islands. The following topics are included:

- contamination of rain
- contamination of roof catchments
- industrial discharges
- agricultural discharges
- domestic waste
- important water contaminants
- public health implications
- mining discharges

Water is a major natural resource of all small islands particularly the amount of natural water that can be used for human consumption. The development of many small islands may be limited by the quantity of potable water present. It is essential, therefore, that every effort is made to efficiently utilize the limited fresh water resources and that the pollution of such resources is kept to a minimum. In this paper the likely sources of pollution are discussed and possible methods of limiting pollution are indicated.

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*Presenter of the paper

Two forms of contamination of rainwater before it reaches the ground have received widespread attention in recent years. These are radioactivity from atmospheric nuclear weapon testing and acidity from the discharge of acidic oxides into the atmosphere by industry particularly from the burning of fossil fuels. 'Acid-rain' has caused widespread destruction of forests and freshwater biota in North America and Europe. Levels of radioactivity in air and rainwater since the termination of atmospheric testing in the South Pacific have been falling and island populations in general have a lower exposure to radioactivity than continental populations (BACON et al., 1983). Similarly the rainwater falling on most oceanic islands is believed to have low acidity as these islands are generally far removed from the major sources of gaseous oxide discharges. Prospero (pers. comm.) has shown that nitrate levels in South Pacific island aerosols are one half to one third those of the Northern Hemisphere and sulphate levels are also lower.

There is some evidence available to indicate that elevated levels of certain metals, particularly zinc, cadmium and lead in rainwater samples may result from galvanized iron roofs or those painted with lead containing paints being used as catchment areas for drinking water. Analytical data on such water is scarce but the levels of zinc found by Downes (1981) in the Tokelaus and Niue are significant. Paint containing 0.6% lead is still sold as 'lead free paint' in Tonga and is painted on roofs used for water catchment (INR, unpublished data, 1984). Downes also found elevated levels of organic matter in water collected from roofs made from traditional materials but no investigations of the long term effects of drinking such water have been made. Tastes and odours may result from such matter.

There is little industry on most small islands but on those with intensive industry such as Guam and Oahu high technology solutions and extensive environmental monitoring are required to prevent pollution of groundwater. A number of problems have emerged on other islands. On atolls with major airfields the leakage of underground fuel and oil tanks and pipelines into the groundwater lens has occurred (F. PETERSON, pers. comm.). On those islands which were the centre of extensive military activity (particularly Micronesia) the leakage of polychlorinated biphenyls (PCBs) from discarded electrical transformers has been detected. PCBs are quite resistant to environmental degradation. On islands with timber industries the treatment of timber with fungicides (e.g. copper/chrome arsenates and chlorophenols) is of concern. Spillage of chrome arsenate into a small river in the

Solomon Islands led to fish and invertebrate kills for a considerable distance downstream (MOWBRAY, 1984). Fish canneries are found on a number of small islands and frequently cannery waste is dumped in landfill sites and the leachate reaching a groundwater lens is a source of concern. Such a problem is suspected to have arisen in American Samoa.

The use of fertilizers on small islands is very limited and at present this probably is not a problem. Pesticides, however, are of more immediate and serious concern. Many of those still in use are banned in developed countries but are still manufactured there and exported to less developed countries. Some pesticides are extremely long lived in the environment and with the fragile, limited nature of many small island groundwater resources, small streams and lagoons these pesticides and their residues may cause irrepairable damage if released in quantity. Mowbray (1984) has documented 585 compounds and over 1000 formulations in use or registered for use in the Pacific island region. There is a widespread lack of legislation in the small island states and an almost complete lack of residue monitoring and operator training. There is also little control over the disposal of unwanted pesticides and the reuse of pesticide containers for the storage of food and water. Most evidence for pesticide spills and their effects is anecdotal and even where literature references are cited the original information was generally anecdotal and not derived from formal scientific investigations. Mowbray (1984) cites some typical incidents.

1. 'Accidental' spillage of lindane and DDT into the lagoon on one of the Tokelau islands led to fish kills

2. Endrin contamination in the Truk lagoon

3. Endrin and sodium arsenate leakage from storage containers into a stream and hence into the lagoon on Yap led to fish kills and later sickness in seabirds, chickens and rats

4. Considerable quantities of DDT given to the Kingdom of Tonga under aid programmes present a difficult disposal problem as DDT is now banned from use in Tonga

The direct spraying of insecticides into 'babai' (Cyrtosperma sp. - swamp taro) pits on Micronesian atolls is also of interest as this precludes any chance of the organic rich topsoil layer absorbing and immobilising the chemicals as babai are planted directly into the upper layers of the groundwater.

There is no small island data on problems due to the leaching of toxic chemicals from domestic garbage disposal sites into water supplies. This is likely to be of more concern as populations and technological status increase. The most important pollutant of small island water resources both in terms of quantities and extent is sewage. On many islands with shallow unconfined aquifers and limited land area, toilets and wells, bores and small streams are close together and almost inevitably contamination occurs. Although bacteriological monitoring of such water systems is minimal a number of results from various Pacific islands are shown in Table 1. The WHO standards (1971) for drinking water are total coliforms less than 10 per 100 ml and faecal coliforms zero. Many diseases can be related to the water system and these can be broken into a number of categories (FEACHEM et al., 1977).

1. Infections spread through water supplies - water-borne infections
2. Diseases due to the lack of water for personal hygiene - water-washed diseases
3. Infections transmitted through an aquatic invertebrate animal - water-based diseases
4. Infections spread by insects that depend on water - water-related insect vectors
5. Infections primarily of defective sanitation

Table 2 (adapted from FEACHEM (1977)) shows a list of the water-related diseases, their frequency, severity, chronicity and possible improvements with better water supply systems. Many of the diseases are common on small Pacific islands. Truk and Tarawa have had recent cholera epidemics and typhoid outbreaks on a small scale have been common on many islands. Infective hepatitis, dysentery, gastroenteritis, scabies and diarrhoeal diseases are also common.

Water protection practices are often poor. On Savo Island (Solomon Islands) many open wells are uncovered and through long usage have developed depressed areas around their sides (BRODIE et al., 1983). These wells become drainage areas and since they are often situated within the village, faecal matter from pigs and children are readily washed into the well by rain. Most wells showed total coliform levels greater than 200 per 100 ml and in many wells values were considerably higher. In contrast the wells on Nikunau (Kiribati) are covered, situated 500 - 1000 m from the villages, windmill pumped and the water piped to the village (BRODIE, 1983). Total coliform levels in all wells were less than 100 per 100 ml. On Truk and Ponape (Federated States of Micronesia) the water and sewage systems partially date from the 1930s and were heavily damaged during World War II. They have not been adequately maintained since then and it is believed that contamination of the water supply is a result of broken water pipes being in close proximity to broken sewage pipes.

One further problem of sewage contaminated waters occurs due to the dependence of many islanders on lagoonal shellfish and other invertebrates as a food source. Shellfish and other filter feeding animals are well known for their ability to accumulate bacteria, viruses, metals and organic chemicals (PHILLIPS, 1980). Faecal pollution of bivalves may well be at a high level on many islands and the few studies carried out confirm this. Recent work in Fiji (BRODIE & NAQASIMA, unpublished data) shows levels in commonly eaten freshwater and marine bivalves of > 35,000 faecal coliforms per 100g. Similarly in Tarawa levels of up to 100,000 per 100g were common (JOHANNES et al., 1979). Standards for shellfish meat in the US are less than 230 faecal coliforms per 100g (USEPA, 1976) and in Canada less than 140 faecal coliforms per 100g (MARR, B.L., 1975). Similarly, although the US standard for shellfish harvesting waters is less than 14 faecal coliforms per 100 ml studies in Palau showed many shellfish growing waters to have levels in excess of 200 per 100 ml and in Ponape in excess of 5000 per 100 ml (COWAN, 1982). Shellfish can transmit the organisms which cause many of the diseases listed in Table 2.

The parameters often measured in a water quality survey are listed together with the WHO Standards (1971) in Table 3. Each of these parameters is monitored for a specific reason. Coliform counts are a good indicator of faecal pollution of water and hence the possible presence of pathogenic bacteria or viruses. Nitrate, nitrite, ammonia and phosphate may also indicate sewage contamination. Nitrate and nitrite also have associated health problems on their own account. Mineral oils contain aromatic compounds, many of which are carcinogenic. High sodium chloride levels in water are linked to increased risk of heart disease while copper, cadmium, lead, mercury, arsenic and many other metals are toxic. Cyanide and other organic chemicals such as phenols and trihalomethanes are also harmful. Calcium, magnesium, iron, manganese and sulphate have minor health effects if present in large amounts but are often monitored since they also may have deleterious effects on the water pumping and reticulation system e.g. corrosion and scale formation.

As mining activities are not common on the small islands as covered in this paper the effects will not be discussed in detail. In the few cases where mining has occurred such as the phosphate mines on Nauru and Banaba (Ocean Island) and the copper mine on Bouganville the effect on local water systems has been so catastrophic that essentially they no longer exist in their original form. However, the economic value of the mine has normally been considered sufficient to outweigh any such environmental damage.

In conclusion the most clearly perceivable pollution threats to small island resources are the inappropriate use and handling of pesticides and inadequate sewage disposal. Monitoring of water supplies for such pollutants is an obvious priority. The training of operators in the correct handling of pesticides is of equal importance. These are low cost operations compared to the continuing job of providing adequate and safe water and sewage schemes on small islands.

TABLE 1

COLIFORM LEVELS IN ISLAND DRINKING WATER

Island	Number of Bores/Wells Tested	Total Coliforms per 100 ml	Faecal Coliforms per 100 ml
Vaitupu (Tuvalu)	15	200 - > 5000	0 - 300
Niue	18	0 - 500	< 10
Tongatapu (Tonga)	12		Mostly 0
Savo (Solomons)	55	10 - > 6000	
Nikunau (Kiribati)	6	< 100	
Christmas Island (Kiribati)	3	3800 - 4400	50 - 1000

TABLE 2

MAIN INFECTIVE DISEASES IN RELATION TO WATER SUPPLIES

Category	Disease	Frequency	Severity	Chronicity	Percentage suggested reduction by water improvements
1a	Cholera	+	+++		90
1a	Typhoid	++	+++		80
1a	Leptospirosis	+	++		80
1a	Tularaemia	+	++		40?
1b	Paratyphoid	+	++		40
1b	Infective hepatitis	++	+++	+	10?
1b	Some enteroviruses	++	+		10?
1a.IIb	Bacillary dysentery	++	+++		50
1a.IIb	Amoebic dysentery	+	++	++	50
1b.IIb	Gastroenteritis	+++	+++		50
IIa	Skin sepsis and ulcers	+++	+	+	50
IIa	Trachoma	+++	++	++	60
IIa	Conjunctivitis	++	+	+	70
IIa	Scabies	++	+	+	80
IIa	Yaws	+	++	+	70
IIa	Leprosy	++	++	++	50
IIa	Tinea	+	+		50
IIa	Louse-borne fevers		+++		40
IIb	Diarrhoeal diseases	+++	+++		50
IIb	Ascariasis	+++	+	+	40
IIIa	Schistosomiasis	++	++	++	60
IIIb	Guinea worm	++	++	+	100
IVa	Gambian sleeping sickness	+	++	+	80
IVb	Onchocerciasis	++	++	++	20?
IVb	Yellow fever	+	+++		10?

TABLE 3

WHO STANDARDS (1971)

Parameter	Highest Desirable Level	Maximum Permissible Level
Total coliform	<10/100 ml	
Faecal coliform	0/100 ml	
Total solids	500 mg/l	1500 mg/l
Mineral oil	0.01 mg/l	0.30 mg/l
Calcium	75 mg/l	200 mg/l
Chloride	200 mg/l	600 mg/l
Iron	0.1 mg/l	1.0 mg/l
Magnesium		150 mg/l
Manganese	0.05 mg/l	0.5 mg/l
Sulphate	200 mg/l	400 mg/l
Zinc	5 mg/l	15 mg/l
Arsenic	0.05 mg/l	
Cadmium	0.01 mg/l	
Lead	0.1 mg/l	
Mercury	0.001 mg/l	
Cyanide	0.05 mg/l	

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RAINFALL DATA PROCESSING

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1. Abstract

Acquisition, quality control, archiving and summarising of rainfall data are normally the responsibility of a National Meteorological Service (NMS). Procedures and output are generally similar in most countries, as described for example in international agency guides (WMO 1981, 1983 a, b, etc.).

Computer processing is now in wide use. It makes data more readily available, permits better quality control, and potentially, gives better user-orientated output, but in many countries the systems are not yet fully implemented. Low cost micro-computers now make it possible to improve data processing in small developing countries and they are useful for special small-scale investigations.

Lack of rainfall data from specific locations is a common problem in water resources assessment especially in small islands.

Some examples of the data and analyses used in Fiji to assess small island water resources are summarized.

2. Introduction

2.1 Routine rainfall data summaries published by a N.M.S. usually include maps of average rainfall (annual, seasonal,monthly), station tables giving the long period monthly averages etc., monthly or annual data summaries for each year. Frequently other statistics (distribution parameters, deciles etc.) may be available for monthly and annual totals, and sometimes for other intervals (2 to 24 months). For short period studies frequency tables of n-day (n = 1 to 100) totals may be available.

Similar information may be published for measured tank evaporation along with calculated estimates of evaporation from open water or evapotranspiration from pasture etc.

These standard products should meet most user needs for preliminary planning information.

Other agencies may undertake rainfall measurements, but ideally, all data will be archived and summarized by the NMS which should be the lead agency in setting observation standards and developing applications to meet routine user needs. Developing countries especially can ill afford to have fragmented data resources.

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Use of computers is making current and historical data resources more accessible and enables more detailed and complex analyses to be carried out. Large central computers are generally needed to archive historic data records, and to produce the routine annual summary reports, etc. Micro-computers used in-house, and exploitation of current data exchanged through the World Weather Watch system, primarily for weather forecasting, make it possible to produce and disseminate up to date selective summaries. The volume of data which can be held in micro-computers is increasing rapidly: they provide previously unimagined capability for rapid data capture and for complex data analysis at low cost and minimum delay.

2.2 List of Data files and Applications

Typical data files of rainfall and other observations required for water planning such as would be maintained by a NMS, and typical applications are listed below.

2.2.1 Data Files

Daily rainfall data
Hourly rainfall data
High intensity rainfall data (extreme values for selected short durations)
Daily tank evaporation data
Summary data (monthly and annual values of rainfall, number of raindays, evaporation)
Climatological data (temperture, humidity, wind, cloud, sunshine duration, solar radiation, occurrences of rain, snow, hail, frost, dew, thunderstorms, etc.): data and summary files.

Applications

(Usually carried out in computer)

Prepare and publish routine summaries, long term averages, maps of isohyets etc.
Calculate potential evapotranspiration/open water evaporation for individual months or shorter intervals as well as long term averages.
Calculate n-day frequencies
Calculate consecutive months' totals and distribution statistics
Calculate depth-duration-frequency relations
Calculate water balance, preferably daily, between rainfall and a measure or estimate of evaporation or evapotranspiration.
Examine interstation correlations (monthly, seasonal etc.).

When a new water supply scheme for a small island is proposed, the engineer may find that reliable rainfall readings have been made for many years in the area concerned, that data have been checked and summarized, that detailed data (daily or perhaps hourly) are available, and that high intensity frequency/duration statistics and other data summaries are also readily accessible. However, more often there are no measurements from near the catchment, and then estimates are required, and rainfall measurements must be started.

3. Fiji Examples

3.1 Networks

In Fiji, rainfall and climatological stations were set up where needed and as opportunity arose. The aim is now to have raingauges at about 10km minimum distance apart in the larger islands and at least one gauge on all the permanently inhabited remote islands, as well as those installed for specific projects . This has not been achieved. Storage gauges and chart recorders are used in some remote places. Partly because of the lack of computer or other facilities for data translation, there has been no development of electronic data logging or telemetry.

3.2 Data Processing

Computer processing of current and historic rainfall and climatological data has commenced using the Fiji Government central computer and micro-computers in the Meteorological Office and in Public Works Department Hydrology Unit, which controls about half the rainfall network. All data are being fed into unified archives. The system is not yet completely developed and assistance in the computer processing is still being received from New Zealand Meteorological Service, using data transferred on tape. Data are captured by keying from manuscript sheets.

3.3 Routine Summaries

Conventional summaries include maps of mean rainfall (Krishna 1980), mean rainfall tabulations, annual and monthly summaries (N.Z.Met.S. : suspended since 1971, but to be resumed soon) and a preliminary monthly summary (Fiji Met.S.---) which includes rainfall and water balance indices, issued promptly after the end of the month. This is based on daily weather reports from 25 stations which represent most areas of the group (Coulter 1984a). Other publications include more details for specific stations: rainfall; extremes, quintiles, high intensity/duration statistics; evaporation, evapotranspiration etc (Fiji Met.S. Inf. Sheets.).

3.4 Special Summaries

3.4.1 Quantiles

For water resource assessment, the question most commonly asked is for quantile figures: the rainfall totals expected in a particular interval (e.g. April to August) with a probability of once in say 2,5,10,20,50 years. Computer tabulation of successive K-month (consecutive) totals commencing with each calender month make it easy to pick out extreme cases and construct a cumulative frequency graph from which quantile thresholds can be selected. A further computer analysis gives deciles and other statistics-mean, S.D., gamma parameter etc. At least 30 and preferably 50 years of data are needed to obtain reasonably precise decile thresholds from the ranked values. If fewer data are available it becomes desirable to estimate the quantiles from the parameters of a theoretical distribution fitted to the values. This also allows interpolation between stations.

These analyses have been done in New Zealand for a selection of Fiji stations. They could easily be done manually, or using a programmable calculator or hand computer. This would be satisfactory for a special investigation but for general survey the lack of memory is a limitation and the need to re-key data for each job is a constraint. For systematic work the large data base held in the main frame or a disc-based micro-computer system would be needed.

Use of the consecutive months' tabulations and the gamma distribution is described by Coulter, Kishore and Kumar (1983) and Coulter (1984b) in which station details are also presented. E.g., the average six month (May to October) rainfall total in the small Mamanuca Islands (located some 15km west of the large island of Viti Levu) is estimated to be about 450mm. This estimation is from stations on Viti Levu and on the more distant Yasawas (60km to the north) and from rainfall maps. Similarly, the gamma shape parameter is estimated to be about 7.5. From a graph or table of the gamma function the amount not likely to be exceeded once in ten years (first decile) is 0.58 of the mean or about 260mm. The estimates of mean rainfall and that of gamma may both have large errors, thus the final decile estimate is only a rough approximation. No data are available from the group. (Coulter 1984b).

Graphs and tables of the direct and inverse gamma distribution function, and also a BASIC program to calculate the gamma distribution values (complete, incomplete and inverse) are given in that paper. The program is suitable for a hand computer or a small micro.

3.4.2 Water Balance

A simple daily water balance budget using daily rainfall as income with a daily potential evapotranspiration value as water need, can provide indices of soil moisture status, of "dry" periods, and of available surplus for recharge or runoff.

We have used average monthly Penman PE where available, (and estimates for other places), and in order to provide climatologically comparable indices, assign an arbitarary soil moisture storage capacity (usually 75mm), believed to represent a soil moisture deficit at which water stress will have affected pastures and some crops. Indices are computed currently for some 25 stations, and for about six stations long period statistics up to 40 years have been evaluated. (Coulter 1984b).

The results are useful in identifying and comparing periods of soil moisture deficit (agricultural drought) and from the resources point of view, give a better index of the amount of water available for run-off or storage than is obtained from the raw rainfall figures.

3.5 Estimation of Potential Evapotranspiration

3.5.1 Tank Estimates

These are commonly used to estimate open water evaporation (from a lake or dam) and for crop water requirements.

Different factors apply to different kinds of pans and different crops e.g.;

E (open water) = 0.7E (pan), for a U.S. "Class A" pan, for annual average open water evaporation. Disadvantages: leaking tanks, birds and animals, non-standard tanks and exposure, missing data on account of heavy rain, difficulty in determining appropriate pan and crop factors for new areas.

3.5.2 Estimation Methods using climate data

(a) "Thornthwaite" method needs only average temperature data (monthly means) but gives only average estimates reflecting the broad climatic regime and the time of year. Results are not good for a specific month/year.

(b) "Combination" methods, combining energy balance and aerodynamic considerations, the best known being "Penman". These make use of solar radiation data (measured or estimated from sunshine duration), wind, temperature and humidity. They have a physical basis.

The estimate is derived as the sum of an energy term and an aerodynamic term, dependent on net radiation and on saturation deficit and wind speed respectively. The former is usually the greater, especially in the tropics. The "Priestley-Taylor" modification uses only the energy term multiplied by 1.26, this factor having been found to apply widely in humid regions.

Originally "Penman" gave open water evaporation but it was extended to give evaporation from a well watered, short continuous vegetation cover, i.e. "potential evaporation" or "potential evapotranspiration" (PE).

More elaborate formulations give actual evapotranspiration taking account of stomatal resistance etc., and drying soil.

There is still uncertainty regarding estimating PE from forest canopies, hilly terrain or intercepted water.

For the simple Penman estimation one needs the following data:

(a) Net radiation, air temperature and humidity, wind speed,(ground heat flux, normally neglected).

OR (b) Global radiation, sunshine duration, temperature, humidity and wind speed

OR (c) Sunshine duration, temperature, humidity, wind speed.

OR (d) For Priestley-Taylor estimates: radiation or sunshine duration, temperature, humidity.

The Penman method has been found to give reasonably good results in a wide variety of climates. While Penman himself put it forward as an estimator for monthly totals, it appears to give useful results on a daily basis. Estimates of monthly totals may be in error by about 10-20 percent, daily values by 20 to 40 percent,or more,but should be better if based on measured radiation.

To Summarise

Penman (or Priestley-Taylor) is probably the most generally useful method.

Tank based estimates are often used, especially in irrigation applications.

Thornthwaite is not recommended when better estimates are available as is usually the case. May not give useful values for individual months.

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ROOF CATCHMENT TANKS - FIJI

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The collection of rainwater as a source of individual or community water supply, unless in a very wet climate where average annual rainfall is close to 4000mm, tends to satisfy rudimentary water needs at best. Nevertheless, in some areas such as the South Pacific atols and drier islands of Fiji, rainwater catchment serves as a viable water supply. These areas tend to have unreliable surface water supplies and ground water investigations have proven, initially, too costly.

DESIGN

The design and calculation of storage volume for rainwater catchment tanks is a controversial subject and many methods can be used. In the case of Fiji, where a distinct dry and wet season occurs, a design method has been chosen which was created by H.M.C. Satyn (and revised by C.L.P.M. Pompe of the West Java Rural Water Supply Project) for Indonesia where the climate is similar. Please refer to Pompe's reprinted article at the end of this paper for design details. This method is based on the importance of calculating storage to provide enough water for the period when there is no rainfall or when it is insufficient to meet water needs. A water balance equation is used to analyze potential rainwater storage throughout the year. Inflow to water storage is :

Inflow = Roof Area x Rainfall x Runoff Factor

Outflow to storage is :

Outflow = Consumption x leakage x evaporation

Monthly rainfall data over a period of 20 years can be analyzed by characterizing each month's rainfall as being wet, insufficient for storage, or dry. A cut off figure called the 'critical rainfall factor' is calculated which represents when inflow to storage equals outflow for a certain roof area and population. Months with rainfall greater than this factor are considered wet; lower than this factor the month's rainfall is insufficient; and if the rainfall is 0 then the month is considered dry. Each year is thus given a numerical representation of how dry it was; the dryer years receiving a higher numerical value and thus requiring greater storage volume. The highest value is then chosen to be used when calculating the volume of storage needed. This method has been applied to various locations in Fiji by utilizing the rainfall data supplied by Fiji Meteorological Service.

Minimum monthly rainfall figures were used over a period of 30 years data instead of analyzing each year's monthly rainfall data to find the minimum rainfall as explained in Satyn's method.

Rainfall data was used from 40 stations throughout Fiji and a map drawn showing minimum storage volume needed for individual family roof catchment tanks in various parts of Fiji (see Fig 1). Basic design criteria used here were :

Water consumption per person per day = 11.3 litres or or 2.5 gallons

Average family = 6 persons

Average Roof Area = $54m^2$

These design criteria can be changed resulting in a different storage volume calculation.

From this initial map, charts were drawn up which show minimum storage volume needed for varying roof areas and number of consumers for different parts of Fiji (see Figs 2,3).

For example, a village in the eastern Lau Group of 200 people could have 4 options for a roof catchment water supply.

1. Individual family tanks : 33-2000 gallon tanks collecting from $54m^2$ roof area.

2. Community roof catchment tanks : 8-8000 gallon tanks collecting from 4 roofs ($250m^2$) and serving 24 people each.

3. Community tanks : 4-15000 gallon tanks collecting from 8-10 roofs each ($500m^2$) serving 50 consumers.

4. Community tanks : 2-30000 gallon tanks collecting from 15 roofs each ($1000m^2$) and serving 100 consumers each.

Economically, the community tanks would cost less for the village where more people use larger sized tanks. Practically, the individual family tanks would tend to be a better choice since these would encourage tighter family water conservation practices as well as a sense of responsibility for their own water supply.

CONSTRUCTION

Fiji uses several different types of roof catchment and water storage tanks introduced through different government ministries, organizations and individuals. The construction and design of these tanks ranges from the economical types; bamboo cement, ferrocement, curved cement block tanks, to the portable emergency relief types; plastic membrane, prefabricated swimming pools and corrugated steel tanks.

The Public Works Department, Fiji, presently widely uses and has used in the past the premade curved cement block tanks. The blocks for these tanks are made locally by Humes Industries and are cemented together and secured by outside steel rings. The storage capacity of these tanks range from 600 gallons to 30,000 gallons. Some of the benefits of this type of tanks are that the cement blocks are portable and can be put together by local PWD workmen. The disadvantages include broken blocks during shipment, rusting of the steel cables holding the tank together, and reliance upon an outside firm for tank supply.

Less widely used at present are the square tanks made of reinforced cement blocks and plastered inside and out. These tanks, through past experiences, tend to crack and leak at corners and various other stress concerntration points due to non-flexible construction. The galvanised corrugated iron tanks (800 gal) are used for individual house roof tanks by PWD. Their popularity is decreasing due to a short life span, due to corrosion, of about 5-10 years.

Larger sized tanks, 20,000 to 50,000 gallon capacity, are presently being contracted out to an outside ferrocement tank construction company, Ferro Tank Ltd, by PWD. These tanks are well made and are quaranteed for 25 years. Unfortunately, the cost of these tanks dictate their use in only major PWD Water Supply Schemes. Also all construction is done by Ferro Tank Ltd workmen and not PWD labor.

Recently, the Public Works Department has begun switching over to ferro cement water tanks in place of the Humes cement block tank for village water supplies where smaller tanks are needed. These tanks are used for both rainwater catchment and gravity feed storage of creek water. The ferrocement tanks have the advantages of being constructed on site by PWD workmen making use of local sands and labor, are less expensive than the Humes tanks and are less prone to corrosion as with the Humes tanks. At present, the ferrocement tanks have been constructed up to a capacity of 6,600 gallons; diameter 16ft; height - 8ft.

The first village-based training of ferrocement technology to PWD - Fiji began with the construction of one 2200 gallon roof catchment tank in the village of Namulomulo, Tailevu in July of 1983. The design of this tank was taken from "Ferrocement Water Tanks" by S.B. Watt. This tank was financed by the Public Works Department as a pilot project using one tank construction trainer, one PWD carpenter and the rest, village labor. The cost for tank materials was $250 while the reusable formwork was $150 (see Fig. 4). This tank was connected to one side of the village church roof and completed within one week. Following the success of this first tank, two additional tanks are planned of 5000 gallon capacity to be built by PWD. Several villagers expressed an interest in building their own tank formwork so that they can build individual 2200 gallon tanks for their own homes.

The construction of these tanks consists of laying a 6" cement floor, erecting a rolled corrugated iron formwork which is held together with timbers, angle irons and bolts, and wrapping this formwork with chicken wire mesh and binding wire. A sand cement plaster is then applied to the outside of the formwork followed by a second coat to create a 1½" thickness.

The formwork is then taken down and lifted out of the tank. Two plaster layers are applied inside the tank followed by a layer of chicken wire and plaster on the floor. The total wall thickness is about 3 inches. A roof framework is then erected and covered with chicken mesh and plaster. The thin wall construction and totally enclosing, tied in mesh wire gives the tank structure a greater ability to withstand stresses which occur in the walls from various natural forces, such as the continuous cooling and heating of the tank by the sun and water.

The continuation of tank construction skills within the PWD Rural Water Supply is being accomplished by training carpenters from each of the 3 PWD divisions in Fiji and supplying formwork for both the 2200 gallon and 6600 gallon tanks to each division. Set material lists have been developed which can be easily used by the PWD rural water supply designers. At this time one 2200 gallon and 10-6600 gallon ferrocement PWD-made tanks have been completed. Over 15 new tank construction jobs await funding and implementation.

The future plans for tank development in Fiji include the construction of a 20,000 gallon ferrocement tank in the outer Lau island of Moala and the encouragement of designing village water supply schemes using individual house roof catchment tanks instead of community tanks.

Individual roof tanks for each house would tend to supply more water and would teach water conservation for each family. One drawback would be the construction costs would be slightly higher than a community tank. A general observation in Fiji is that many village and settlement households, which complain of water shortage and require costly government shipments of water during the dry season, do not even have simple rain water collection systems from their own roofs. The development and continuation of simple roof catchment tank designs and construction in Fiji remains a pressing development strategy for the future.

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FIGURE 1.

FIG. 1

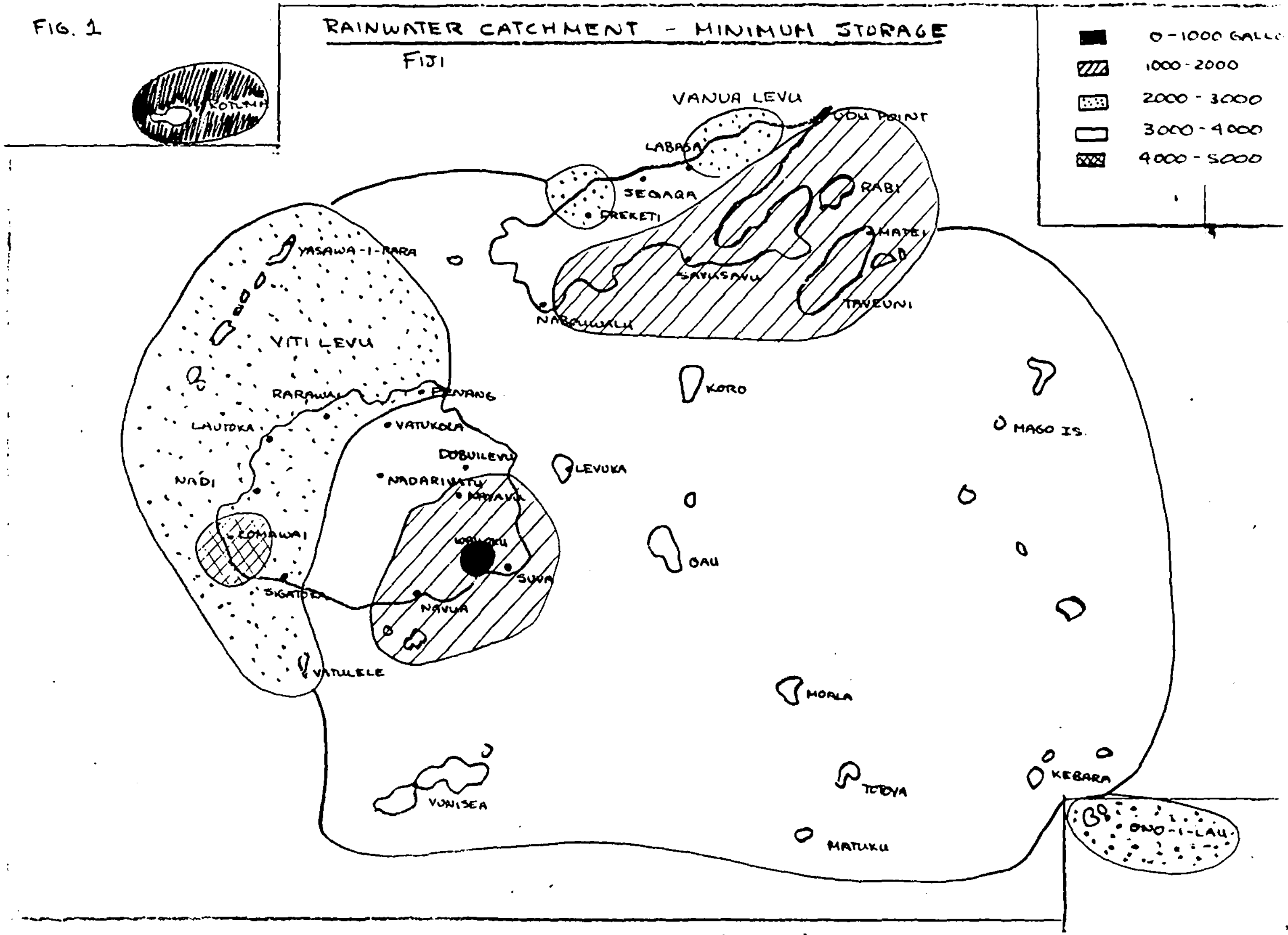

FIG. 2

MINIMUM TANK VOLUMES FOR VARYING ROOF AREA AND NUMBER OF CONSUMERS

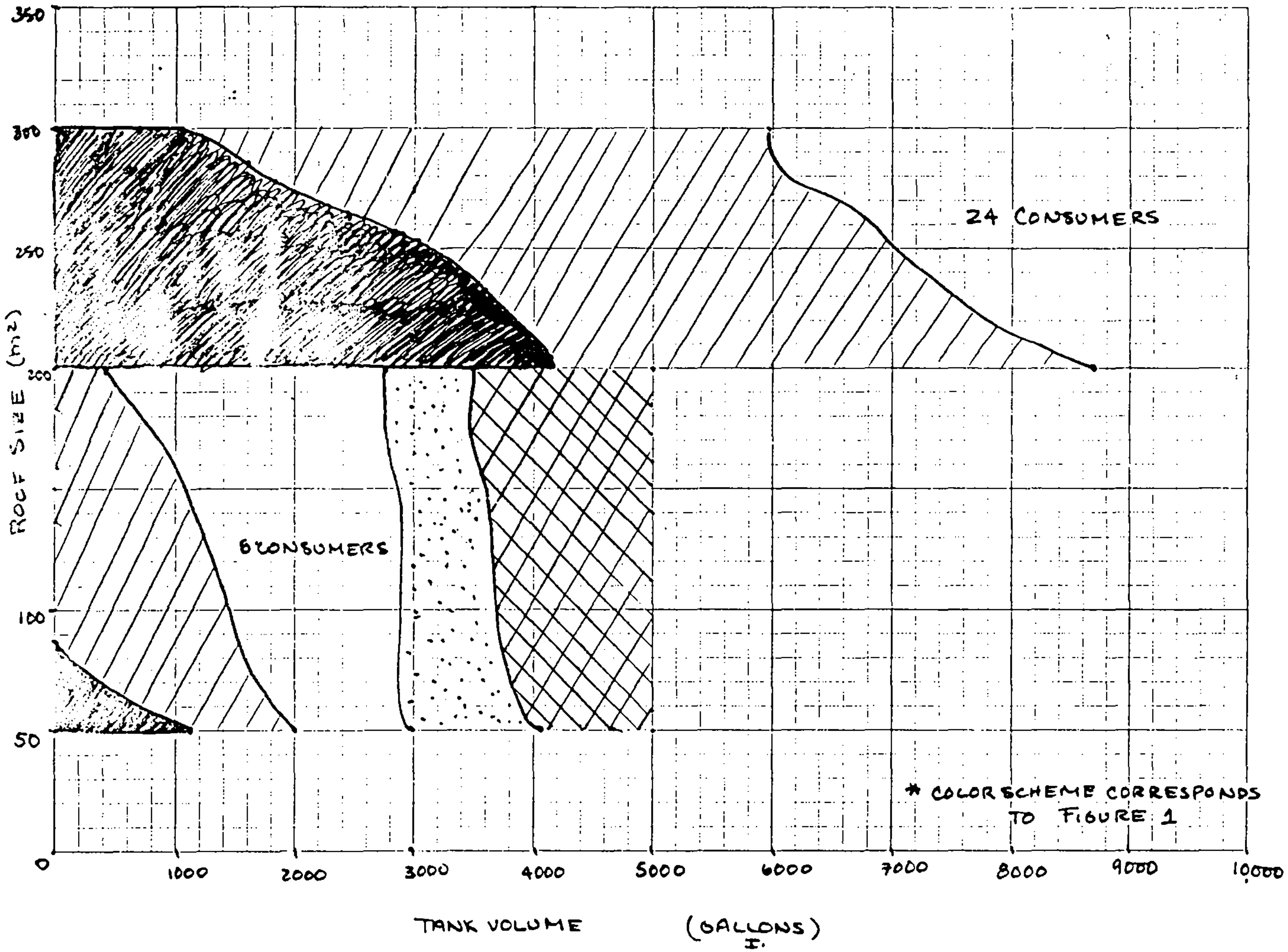

FIGURE 2

FIG 2 (CONT.)

MINIMUM TANK VOLUMES FOR VARYING ROOFAREA AND NUMBER OF CONSUMERS

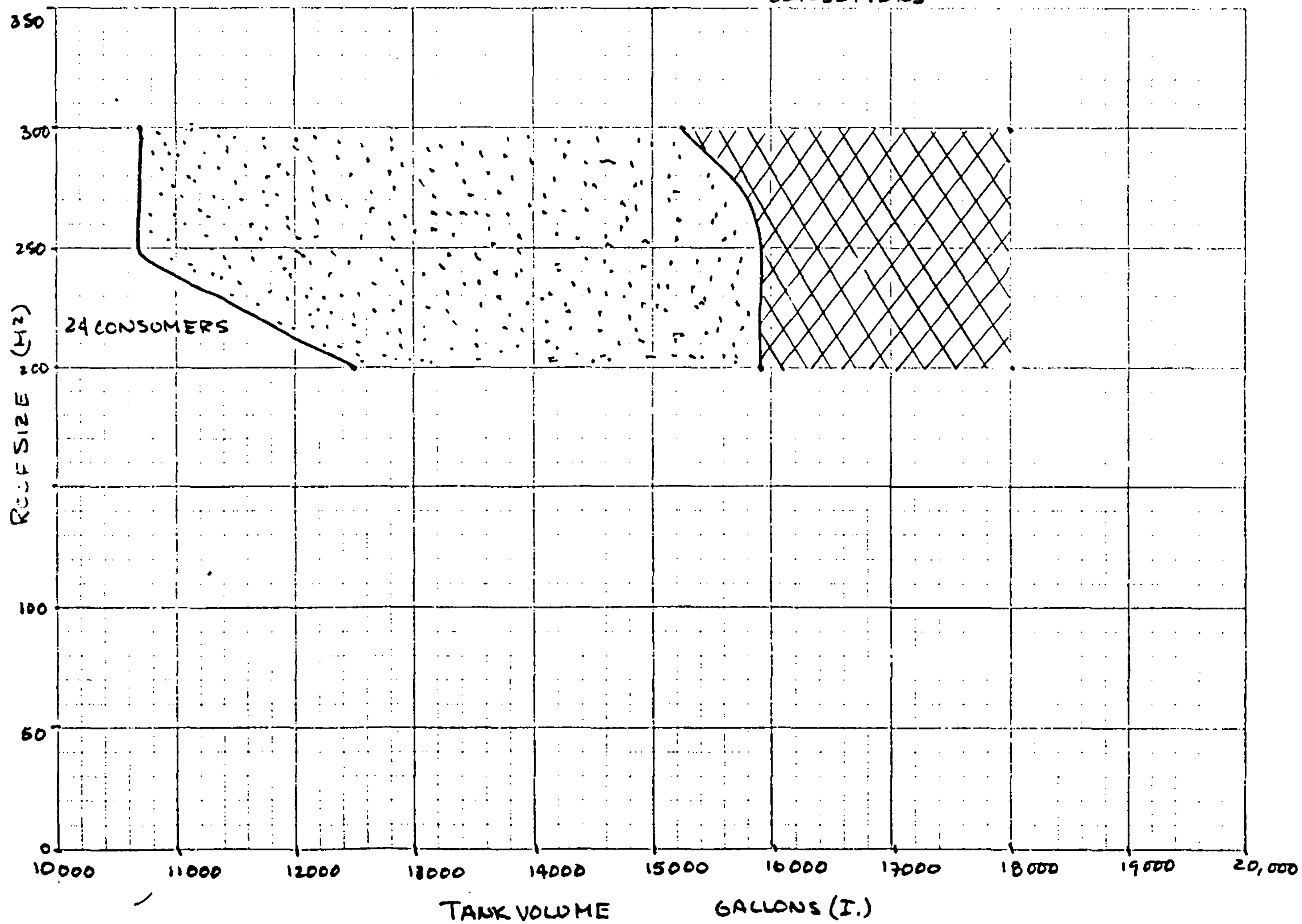

FIGURE 2 (CONT.)

FIG. 3

MINIMUM TANK VOLUMES FOR VARYING ROOF AREAS AND NUMBER OF CONSUMERS

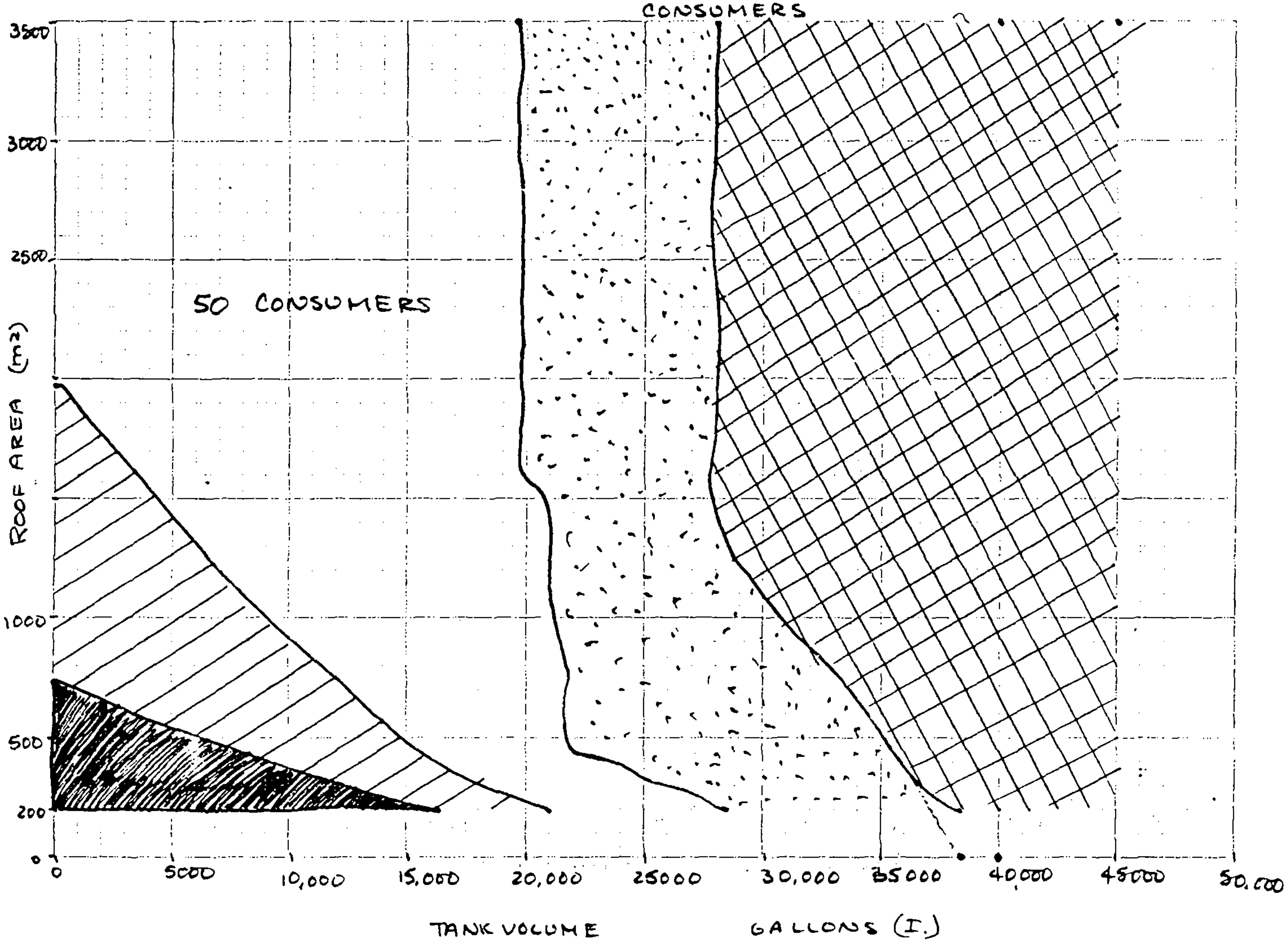

FIGURE 3

FIG. 4 COST COMPARISON OF SELECTED WATER TANK TYPES - 1984

TYPE	SIZE (GALS.I.)	MATERIAL COST	COST $FD/GAL (I)
PWD-FIJI FERROCEMENT	2500	250	0.10
	6600	530	0.08
	10000	850	0.09
FORMWORK (REUSABLE)	2500	150	
	6600	400	
	10000	800	
HUMES CEMENT BLOCK	2400	795	0.33
	6500	1340	0.21
	11700	2574	0.22
W.H.O. MODULAR FERRO-TANK	2700	430	0.16
	6600	745	0.11
	9900	1035	0.10
FERRO TANK INC. FIJI	5000	2000	0.40
	10000	4000	0.40

DESIGN AND CALCULATION OF RAINWATER COLLECTION SYSTEMS

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INTRODUCTION

Dry seasons occur even in monsoon areas. If there are no nearby wells or rivers, people will walk long distances to obtain water. A solution to this problem may be the catchment of rain water—an ancient custom still practiced in many countries in the world where rainfall is collected during the wet season to use in the dry season. The questions are (1) what should the volume be of such a rainwater collection system and (2) how should such a collector be designed?

This paper deals mainly with the first question: the calculation of the volume of the rainwater collector.

H.M.C. Satijn (1979), who was a former project participant, analyzed the problem and designed a computer simulation model of the rainwater collection system. Because computers are not widely available, I was asked to review Satijn's work and to develop a slide rule-calculation method that could be used by regional technicians. Thus, a step-by-step method was designed to enable technicians to calculate the volume of rainwater collectors by using available monthly rainfall data.

The results of the calculation are not sacrosanct because, first of all, the variables of themselves vary widely, such as consumption or the water demand. Thus, if 5 ℓ/person/day is the basis for calculating drinking water needs, there is no way of knowing the actual use and the variation in conservation and utilization. What must be borne in mind in the statistical calculation of rainwater catchment systems is that its accuracy will depend on correct input. It is also important to be realistic in using the statistical calculation method, rather than concentrating on complicated statistical computations.

The vital question is "Who pays?" If the farmer (user) pays, he will construct a 15-m^3 collector and in the dry season will be conservative in using his water while praying to Allah that rain will soon fall again. When the government or an international organization pays, the designer might think of future users and design a 20- or even 25-m^3 collector.

The basic principle of this method is the importance of calculating storage to provide enough water of the period of the year when there is no rainfall or when it is insufficient to meet water needs. In the following sections the step-by-step method and the theoretical background of the method are presented, and the last section includes some design criteria for the rainwater collection system.

CALCULATION OF RESERVOIR VOLUME

In this section, a step-by-step method is presented to calculate the volume of rainwater catchment reservoirs.

STEP 1. Daily consumption (liters/day × number of users)

a. Drinking and cooking = ... × ...... = ...
b. Washing and bathing = ... × ...... = ...
c. Livestock water = ... × ...... = ...
d. Irrigation = ... × ...... = ...

Total Daily Consumption = ...

STEP 2. Monthly consumption, MC (liters/month)
MC = total daily consumption × 30.5 days = ... × 30.5 = ...

STEP 3. Catchment area, A (m^2)
Determine available catchment area, A = ...

STEP 4. Runoff factor, ROF
Determine ROF: for vegetative cover ROF = 0.5;
for hard paved areas ROF = 0.9
Runoff factor, ROF = ...

STEP 5. Critical rainfall, CRF (mm/month)

$$\text{Calculate CRF} = \frac{MC}{ROF \times A} = \frac{.....}{..... \times .....} = ...$$

STEP 6. Go to Rainfall data
Circle rainfall having more than critical rainfall with green; circle rainfall figures having less than critical rainfall with red, and the dry months with black

Calculate the total supply, TS, values (the length of storage periods that supply water)

YEAR	MONTHLY RAINFALL DATA OF .... Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	TD	TI	TS = TD+s.TI
Critical Rainfall, CRF = ... mm/mo (Stop 5) Shortage factor, s = 0.6 (Indonesia)															

STEP 7. Determine Time Storage, TmS (mo)
Determine the TmS value from the following:

a. Number of rainfall data, 10: T10S (storage not sufficient once in 10 years) is equal to the highest value of TS; T20S is equal to 1.1 × highest value of TS
b. Number of rainfall data, 15: T10S = next to highest TS; T20S = 1.1 × next to highest TS
c. Number of rainfall data, 20: T10S = 0.9 × highest value of TS; T20S = highest value of TS

STEP 8. Determine leakage, L
L = 0.1 puddled clay-line reservoir
L = 0.05 concrete-lined reservoir
L = 0.01 ferrocement or steel reservoir

STEP 9. Determine evaporation, E (m/mo)
E = 0.1 m/mo for open reservoir (Indonesian conditions)
E = 0.01 m/mo for ventilated, roofed reservoir
E = 0.0 m/mo for closed reservoir

STEP 10. Determine evaporation surface, S (m^2)
Calculate open water surface, S = ...

STEP 11. Calculate storage volume, SV (m^2)

$$SV = \frac{(MC \cdot 10^{-3} + S \cdot E) \cdot TmS}{(1 - 0.5 \cdot L \cdot TmS)} = \frac{\ldots\ldots}{\ldots\ldots} = \ldots\ldots$$

MC = STEP 2 (ℓ/mo); S = STEP 10 (m^2); E = STEP 9 (m/mo); L = STEP 8; and TmS = STEP 7 (mo).

THEORETICAL BACKGROUND OF THE METHOD

The roof or any surface area on which rainfall is collected is called the catchment area. From this catchment area, the water is conveyed into the collector (Fig. 1). A filter is mostly used to treat the incoming water before it enters the collector to prevent pollution, and its capacity should be large enough that the inflow is not obstructed. The disadvantage of an open collector is evaporation; and in closed collectors, a certain amount of leakage outflow. Thus, outflow can consist of leakage and withdrawal for consumption.

During the wet season, there is both inflow and outflow; in the ~~wet~~ dry season, there is only outflow. In Indonesia, a certain part of the wet season is characterized by less inflow than outflow. Therefore, it is for this particular period that rainwater collectors would provide storage for surplus rain water.

This period of insufficient rainfall is determined by the rain, R; the constant runoff factor, ROF; and the catchment area, A, for the flow of water into the storage which can be expressed as

$$IN = ROF \times R \times A \,.$$

If the inflow exceeds the outflow (consumption, leakage and evaporation), then

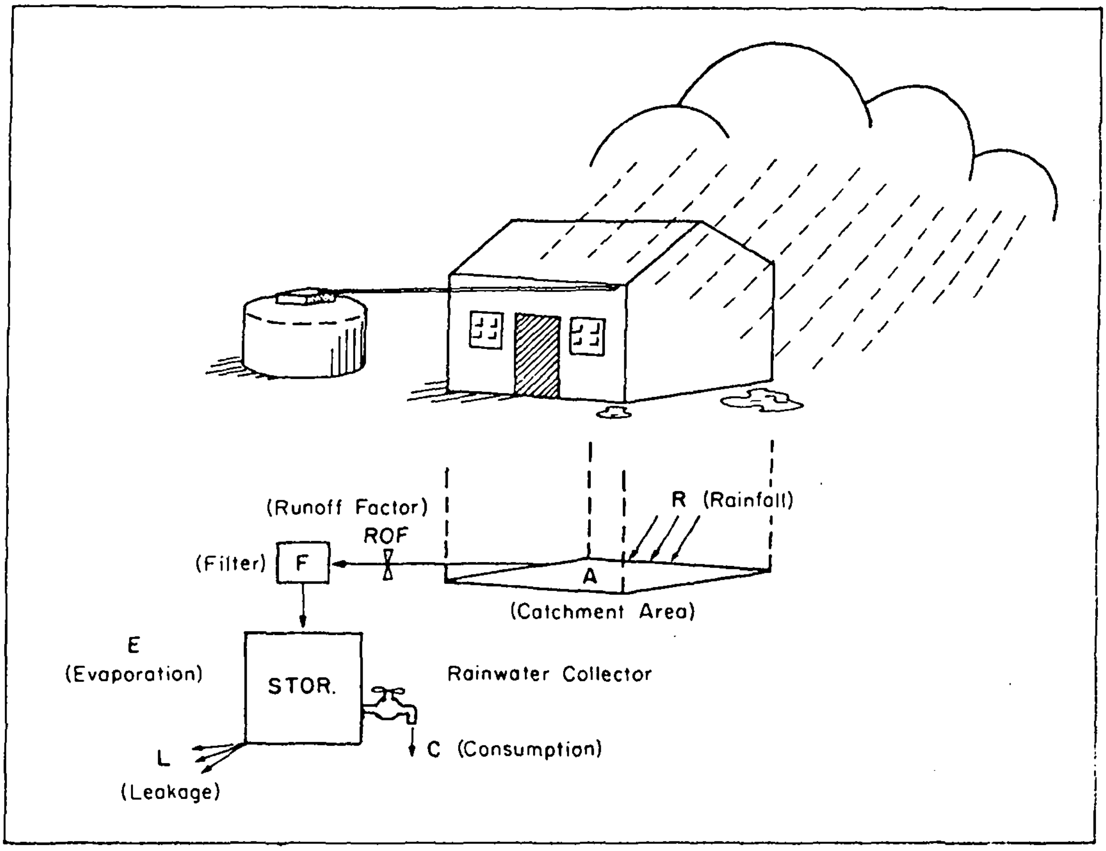

Figure 1. Rainwater collection system

the storage is charged or overflowing. When rainfall is insufficient, the inflow is less than the outflow. In the situation where the inflow equals the outflow, the critical rainfall, CRF, can be derived from

$$IN = ROF \cdot R \cdot A = ROF \cdot CRF \cdot A = OUT$$

which results in

$$CRF = \frac{OUT}{ROF \cdot A}$$

Thus, the year can be divided into periods with sufficient rainfall; the wet period, TW, ~~and periods with insufficient rainfall; and~~ the dry period, TD, and the insufficient rain period, TI. This division is schematically shown in Figure 2. It must be noted that this calculation method is based on the importance of the adequacy of storage to provide water in periods of insufficient and no rainfall.

THEORETICAL BACKGROUND. The length of the period in which the storage has to supply the outflow is determined by the rainfall data. These TS periods seem to follow cumulatively an exponential curve in the form, $a.e^{-bx}$ for the northern coastal plain of West Java, which is approximately $1.2 \cdot e^{-0.38 \times TS}$. However, to calculate the different parameters by local technicians will prove to be too difficult. Furthermore, it must be borne in mind that this calculation only results in an "estimation" of the needed storage capacity. Therefore, TS is exceeded once in 10 years, and T10S is directly derived from rain-

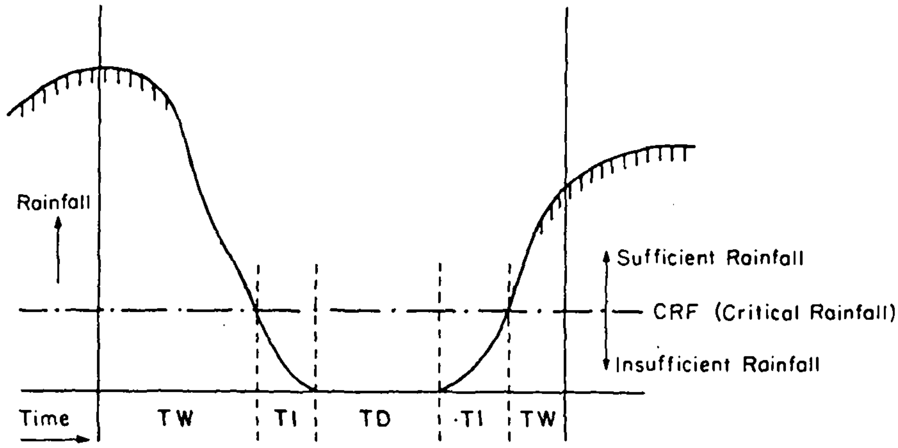

Figure 2. Annual rainfall in relation to water supply by rainwater catchment

fall data and not calculated with statistical parameters. Thus, if about ten years of rainfall data are available, the highest value for T10S is selected; and if the storage is insufficient only once in 20 years, then T20S = 1.1 × T10S. Although this is a rough calculation, it seems to work well in our case as shown in Figure 3.

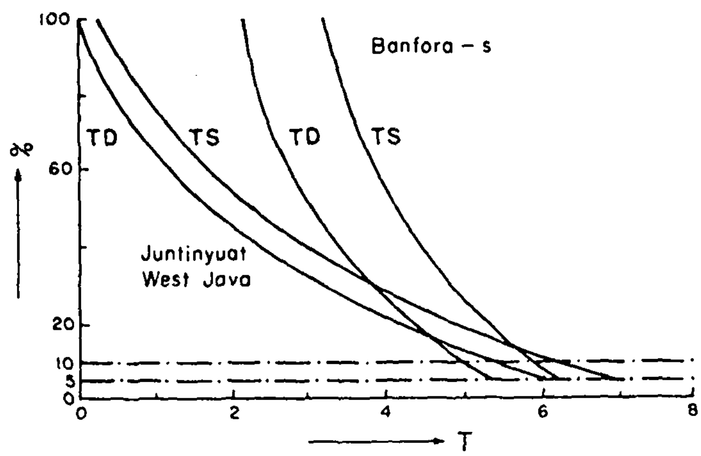

Figure 3. Cumulative frequency distribution length of dry TD periods and length of periods supplied by water tank

During TI, the period of insufficient rainfall, only part of the outflow is supplied by rain catchment; the rest should be provided from storage. To calculate this condition, the shortage factor, s, is used. Thus, in Figure 4, r = rain water supply and s = the storage addition. One should also take into consideration that during the first light shower, rainfall often evaporates

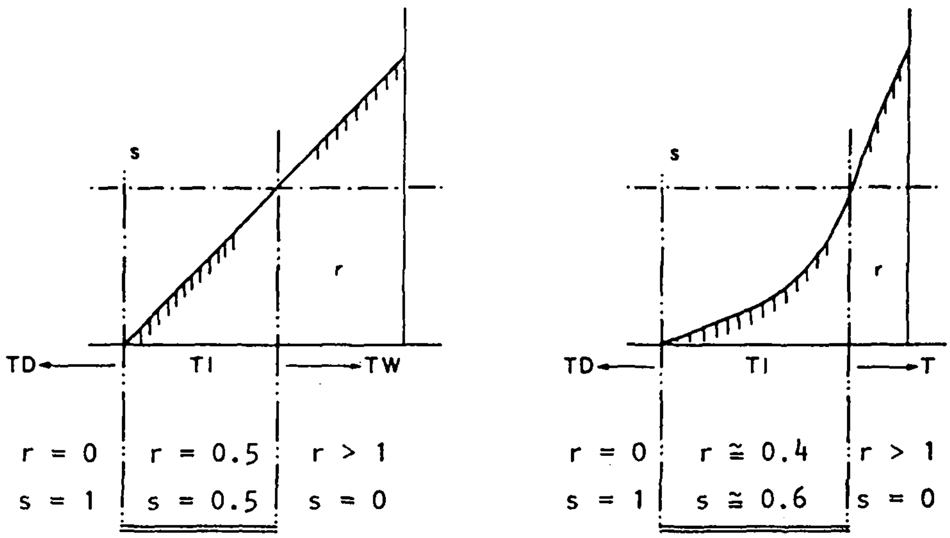

Figure 4. Section of graph showing period of insufficient rainfall

when it falls on hot surfaces, such as roofs. For example, when the s value is theoretically 0.5, use s = 0.55. Thus, TS = TD + s × TI. Because the value of s is difficult to determine for Indonesian conditions, the shortage factor, s, can be put at 0.6.

To obtain the TmS—such as the T10S, which is the storage-supply period, TS, that is exceeded once in ten years, the TD and TI is elaborated on the rainfall data sheet into TS by using the relation of TS = TD + s × TI. For the TS, the highest value for T10S is used if ten years of rainfall data are available. Then, if 20 years of rainfall data are available, we use T10S = 0.9 × the highest value or T10S = 0.0 × T20S.

Now that we know the TmS, we have to find an expression for the necessary volume of storage. To calculate this volume, VSTOR, the discharge, OUT, must be first determined. This discharge can be divided into consumption, leakage and evaporation. Consumption is difficult to determine exactly; and to do so, the following questions must be answered:

1. How (cooking, drinking, bathing, irrigation) will the water be used?
2. What quantities per month per use per family members per animals per hectares will be required?
3. How many family members, animals and hectares will require water?

Based on these consumption factors, the monthly consumption is expressed as MC. The leakage related to the volume of stored water which decreases over time is expressed as

$$OUT_{leakage} = \frac{1}{2} \cdot L \cdot VSTOR \cdot TmS.$$

Evaporation is proportional to the open water surface, temperature, wind conditions and time. To simplify this calculation, we used Penman's simple relation of

$$OUT_{evaporation} = A \cdot E \cdot Time.$$

Using Penman's constant, E, in this relation, E may amount to 0.1 m/mo for Indonesian conditions. To obtain the total outflow times the length of the period that the storage has to meet demand in the needed volume, let

$$VSTOR = \frac{(MC \cdot 10^{-3} + A \cdot E) \cdot TmS}{1 - 0.5 \cdot L \cdot TmS}$$

in which MC is expressed in ℓ, A in m^2, E in m/mo and TmS in mo.

Following the step-by-step method, the local technician should be able to easily calculate the VSTOR relation on his sliderule.

DESIGN CONSIDERATIONS. In closing, I would like to suggest the following design considerations:

1. Use as impervious as possible lining, such as plastic sheets or a thin lining of bamboo cement or ferrocement laid on the natural slope of the ground
2. Minimize evaporation by installing a roof or covering the cisterns with soil or concrete; wood should not be used
3. Filter the inflow at the entrace point of storage to eliminate dust and foreign matter
4. Guard against mosquitos or their larvae especially the species that are carriers of diseases.

In addition, users should be taught to boil water used for drinking purposes if the water quality is questionable. I do not pretend to have given a complete listing of all design considerations for rainwater cisterns. The viewpoints presented in this paper are the results of lessons experienced in our West Java Rural Watersupply Project.

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SURFACE WATER RESOURCES DEVELOPMENT ON SMALL ISLANDS

- A CONSULTANT'S VIEWPOINT

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SYNOPSIS

A recent study of two of the Southern Group of the Cook Islands provides examples of resources assessment techniques where hydrological data exists in a limited form. Such studies are little different from those on large land masses except that source options are often more limited, higher risk are incurred and practical water supply constraints exist where populations are small. This paper concentrates on tropical islands with community water supply requirements.

INTRODUCTION

Surface water source options are

(i) stream intakes (gravity or pumped)

(ii) impounding dams

or, more rarely,

(ii) 'artificial' catchments

Roof rainwater tanks are not included here as they only serve individual properties and can rarely be made large enough to give satisfactory supply security. Ideally, island public supply systems should provide water at tolerable pressure even through the worst drought in 30 years; however it may be appropriate to restrict this supply quantity to basic domestic and public health demands not exceeding 200 l/h/day. Larger supplies for agricultural use, including vegetable and orchard watering, may be made available only nine years out of ten.

Stream intakes may be direct, often from a reach ponded by a weir, or indirect using a porous pipe collector in streambank alluvium. The latter are included here as surface water sources because experience shows that they rarely tap groundwater but simply filter the local streamflow. (The galleries on Rarotonga are of this form.)

Island catchments are often small with incised streams requiring care about defining the catchment area available to a gravity intake. Many are not perennial, especially where dry seasons are strongly marked (eg Pulau Banggi and Pulau Jambongan, Sabah) or where the underlying geology is porous (Aitutaki, Cook Islands). Where an intake can be placed at a major springhead (e.g. Honiara, Solomon) then an economic supply is more likely.

Impounding dams require much higher technology if serious leakage and flood overtopping problems are to be avoided. Their initial capital cost is high and their useful life may be curtailed by sedimentation from land development effects. They provide substantial supply security and become a necessity once demand outstrips stream intake capability. They also bring the need for operating restriction rules so that supply storage never quite empties in any circumstance. Occasionally off-channel storage may be constructed, sometimes with an artificial liner (as at Akoao, Rarotonga).

Artificial catchments may be created by bituminising a sand slope or depression (e.g. Rottnest Island, Western Australia). Or they may be concreted or, more rarely, be found as natural features where sheet rock runoff can be led to a storage pond. However this technique cannot normally serve more than a few hundred people.

Demand management is not strictly a resource option but it is increasingly favoured by government as a means of achieving a satisfactory supply without large new capital investment. This strategy usually embodies several of the following

- water conservation publicity
- plumbing bye-laws to limit new water fittings to economical ones e.g. dual flush toilets

- reduced distribution pressures
- active leakage control
- garden watering rosters to limit peak consumption
- charging policies that penalise excess water use above a metered threshold.

The usual difficulty when assessing small island resources is the lack of long flow records. There is rarely time or money to spend on collecting these so some plausible form of flow data generation or transposition must be adopted.

PRACTICAL CONSTRAINTS

It is only worth assessing resources for areas where it is practicable to harness the runoff. So it is unlikely that catchments of less than 1 sq km will be of value for water supply.

Other features that must be considered in finalising a system of sources include

- intake level to maximise catchment and minimise excess reticulation pressure (but with sufficient margin to permit later addition of filtration plant)
- intake weir height to maximise storage
- hydraulically efficient intake to minimise entry head loss while excluding debris
- access to source for maintenance even during wet spells
- trunk main route that avoids channel crossings with a flood washout risk
- generous intake pipe capacity to allow for later deterioration and for peak demands including conjunctive use
- island ring mains and network pressure analysis for designing augmentation
- service reservoir storage of one day's supply.

In addition records need to be kept of intake abstraction, periods of closure, spillweir overflow, weir scour releases and pipework changes. Without such details the long term task of yield review is greatly hampered.

RESOURCE ASSESSMENT

Rainfall records are important for establishing the normal climate pattern and the degree of variation about it. Long records, especially those in excess of 30 years at a single site, are vital. Those shorter than 10 years are useful for determining mean rainfall but can mislead on drought potential. Those shorter than 2 years in duration are of little use unless they are far removed from other longer term raingauges or are in a region of reliable and orographically controlled rainfall.

Fig. 1 shows the first comprehensive rainfall map of Rarotonga (Ref. 1) which has been constructed by averaging mean rainfalls estimated by ratios of recorded rainfall at adjacent sites. Greatest weight was given to the longest records. It was necessary to separate the primary long 'Rarotonga' record into its component parts as its site moved in successive steps westward into the drier zone at the airport.

Long records permit identification of rainfall sequences that caused known waterlogging and runoff events. They identify the relative importance of notable wet and dry sequences and, when expressed as percentages of mean rainfall, enable comparisons to be made with neighbouring stations. (Table 1 gives Rarotongan results and highlights the severity of the 1982/83 drought). They also provide the essential input to an appropriate soil water balance model from which a monthly 'flow record' may be generated; such data series are unlikely to be good enough even after calibration to give intake yield estimates but they can be invaluable for conservative reservoir sizing.

The local stream runoff process needs to be identified. Is it solely surface and soil drainage water? Or is there a strong springflow component? Is the stream gaining or losing water in successive reaches? (One Rarotongan hill stream on reaching the coastal sands and gravels was observed to lose roughly 1 l/s per 10 m length of bed.) Any rainfall/runoff modelling process should incorporate the major known natural processes and then allowance should be made for existing water rights that involve consumptive use.

Rainfall records in the tropics are rarely capable of good correlation with neighbouring stations because in any given convective storm the small variable rain cell sizes produce rapid rainfall gradients over two or three kilometres. However records should be analysed for coefficient of variation and as rainfall intensity - duration - frequency curves.

These, when compared with other stations, identify homogeneous meteorological regions. It is then possible to confidently transpose flow records between catchments of similar slope, land use and geology within each such region; this is normally done by expressing flows non-dimensionally as a percentage of mean annual flow. That mean flow can be predicted for any ungaged river site by reading rainfall from an isohyetal map, deducting typical evapo-transpiration losses and expressing the result in appropriate units.

One useful approach is to express water supply demand in terms of millimetres of runoff per month from a given catchment. Testing the local rainfall record with this figure will rapidly identify typical resource deficiency periods.

INTAKE YIELD CALCULATION

All flow records, however brief, should be collated and oral evidence should be gathered about 'no-flow' events or of periods of water supply restriction. Normal quality control of published figures is needed so that the flow rating adopted is not in question. Sometimes frequency of channel bed shifts makes the conventional flow record unacceptable but the current meter check gaugings remain as useful intermittent evidence of flow conditions.

Low flows should be analysed to give ranked annual minimum flows. Weekly flows are ideal where the source will supply a system with adequate service reservoir storage. The ranked flows should be plotted on appropriate probability distribution paper using an unbiased plotting position formula; normally annual series of this type follow extreme value theory and will form a straight line on Gumbel probability paper. Experience suggests that 13 years or more of data is necessary to provide a reliable indication of the underlying probability distribution of drought flows.

Interpretation of the plotted points by eye will permit a straight line to be drawn from which the T year flow can be read off (Ref. 2). The line should be set to give a realistic return period for the lowest event(s) whether outliers or not. 'Flats' and 'gaps' in the plotted sample may be recognised as features that will disappear with the acquisition of further data.

Where sufficient daily (or continuous) flow records exist a flow duration curve should be drawn up because this will given additional information about the degree of intake yield restriction that would recur in the event of repeated weather conditions.

It is helpful to express such curves in dimensionless form (Fig. 2) by dividing by the mean flow for the period analysed. If rainfall records suggest that the long term flow will be a certain percentage away from that which has been recorded the curve can be adjusted by that factor before use.

Where the climatic pattern gives repeated spates in a perennial river with little seasonal variation it is possible to draw up a convincing flow duration curve with only one year's data, accepting any random gaps that have occurred.

To the extent that the dimensionless curve is like others from streams with longer records elsewhere it gives some weight to transposing the latter (by the ratio of mean flows) to the ungauged site of interest.

RESERVOIR YIELD

By the usual techniques (Ref. 2) a reservoir yield/storage characteristic curve can be obtained for a site with a flow record or at which a flow record can be modelled.

In the simplest of cases the curve will refer to the worst historic drought but modern practice is to produce a family of curves by runoff probability analysis. This means that a curve of yield against return period of failure can be drawn up for any particular reservoir.

For island resource assessment it can be helpful to produce a dimensionless yield/storage curve of the type derived for Rarotonga (Fig. 3). The curve results from analysis of a generated flow record for a notional 1 sq km hill catchment with 3000 mm p.a. rainfall and 1036 mm p.a. actual evapo-transpiration. The 'record' was calibrated by reference to intermittent flow records in 1960 and 1961.

The curve can be applied at any watertight site on the island once its mean flow has been estimated by each water balance approach. Only a lake evaporation adjustment is required at a particular site, together with the addition of a dead (i.e. bottom water) storage allowance.

The nature of the yield/storage relationship shows the critical drawdown period from full to empty. Because

$$\text{Gross Yield} = \frac{\text{Inflow + Storage}}{\text{drawdown period}}$$

the relationship is an envelope of a series of straight lines.

Consequently if a catchwater is added to bring water into the reservoir from an adjacent catchment, the curve can rapidly be adjusted to allow for the increased yield on each straight line which relates to each separate critical drawdown period. (The critical drawdown period is the duration that gives minimum gross yield for a reservoir of given storage capacity.)

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2. Twort A.C., Crowley F.W. and Law F.M. Water Supply Third Edition. Edward Arnold 1985.

YEAR	%	YEAR	%	YEAR	%
1899	110	1927	100	1955	118
1900	74	28	76	56	122
01	104	29	99	57	103
02	87	1930	105	58	87
03	79	31	75	59	132
04	90	32	99	1960	110
05	78	33	124	61	86
06	83	34	140	62	113
07	104	35	106	63	87
08	140	36	109	64	101
09	112	37	92	65	73
1910	117	38	104	66	84
11	88	39	137	67	154
12	102	40	86	68	92
13	79	41	72	69	100
14	85	42	97	1970	134
15	55	43	100	71	98
16	148	44	81	72	73
17	125	45	115	73	111
18	124	46	115	74	101
19	82e	47	124	75	93
1920	116	48	70	76	126
21	132	49	91	77	94
22	106	50	73	78	114
23	92	51	97	79	87
24	104	52	79	1980	142
25	94	53	108	81	104
26	78	54	95	82	59
				83	68

Notes : Based on following averages 1899 - 1934 2110 mm/yr; 1935 - 1967 2017 mm/yr; 1968 - 1983 1887 mm/yr

e means estimate for part of year

Table 1 ANNUAL RAINFALL PERCENTILES AT RAROTONGA (1899-1983)

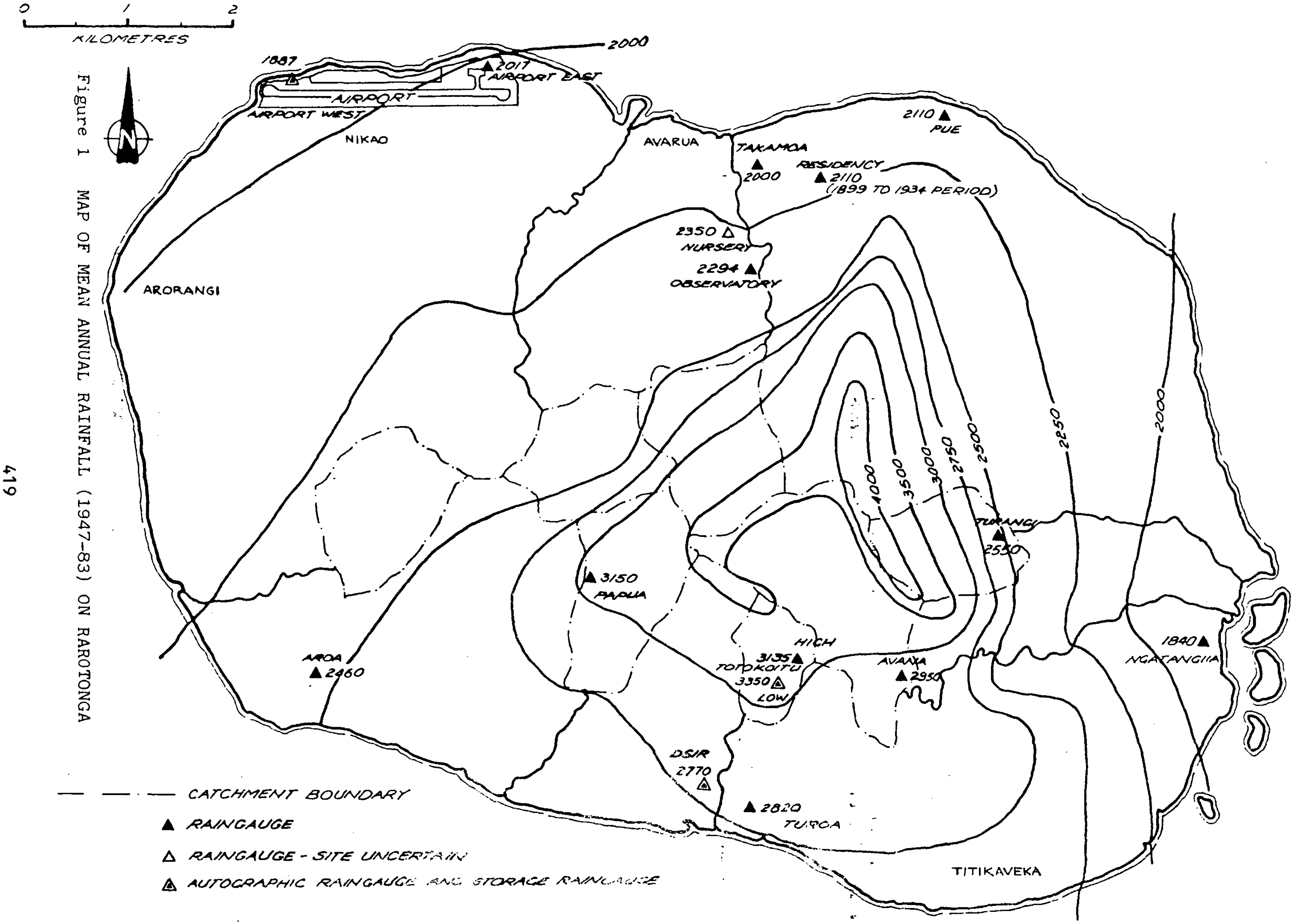
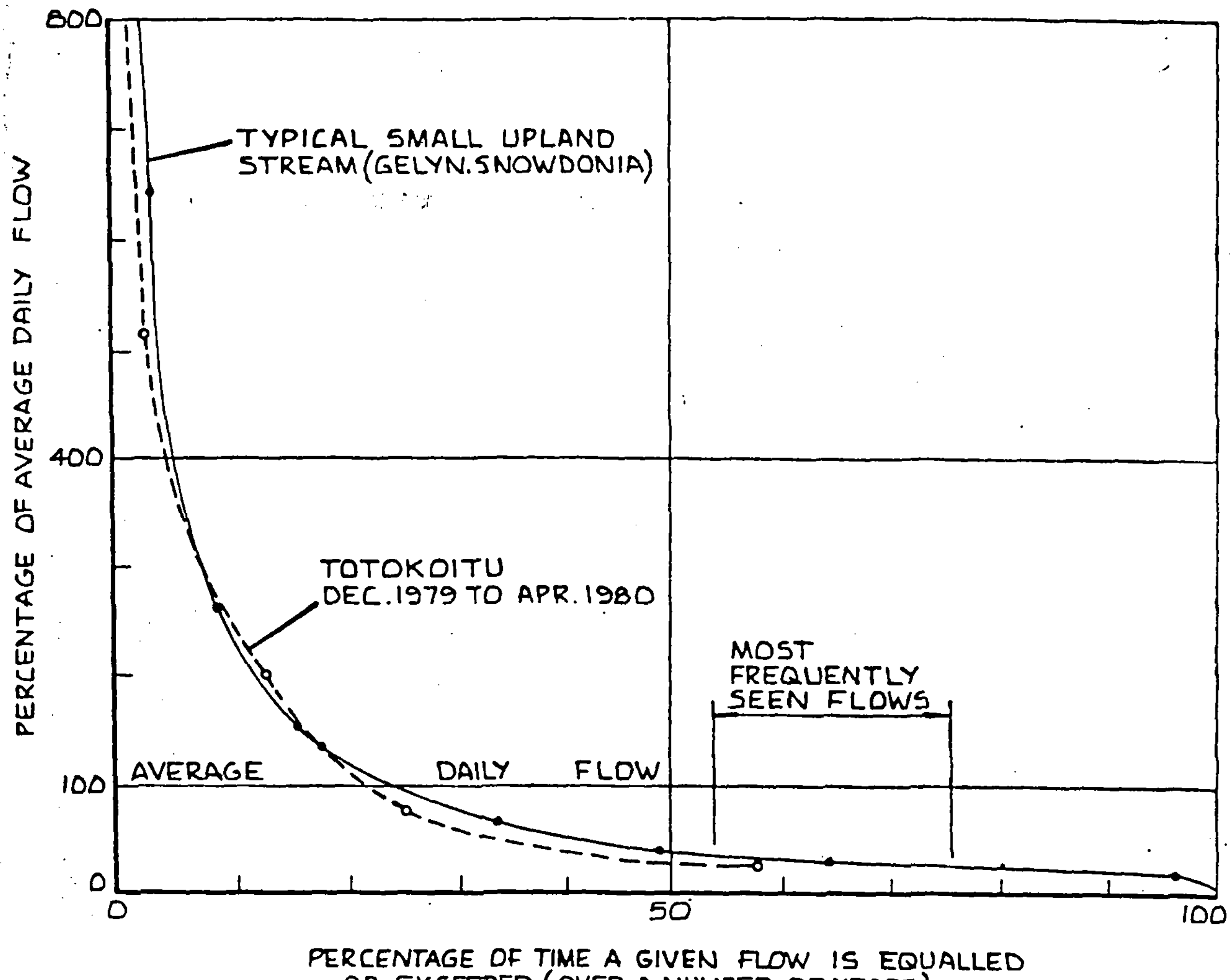


Figure 1 MAP OF MEAN ANNUAL RAINFALL (1947-83) ON RAROTONGA

NOTE: CURVE DERIVED BY MEASURING THE NUMBER OF HOURS THE STREAM HYDROGRAPHS EXCEED GIVEN STATED LEVELS OF FLOW.



(AFTER TWORT, HOATHER AND LAW, "WATER SUPPLY" 2ND EDITION. EDWARD ARNOLD)

Figure 2 FLOW DURATION CURVE FOR TOTOKOITU STREAM, RAROTONGA

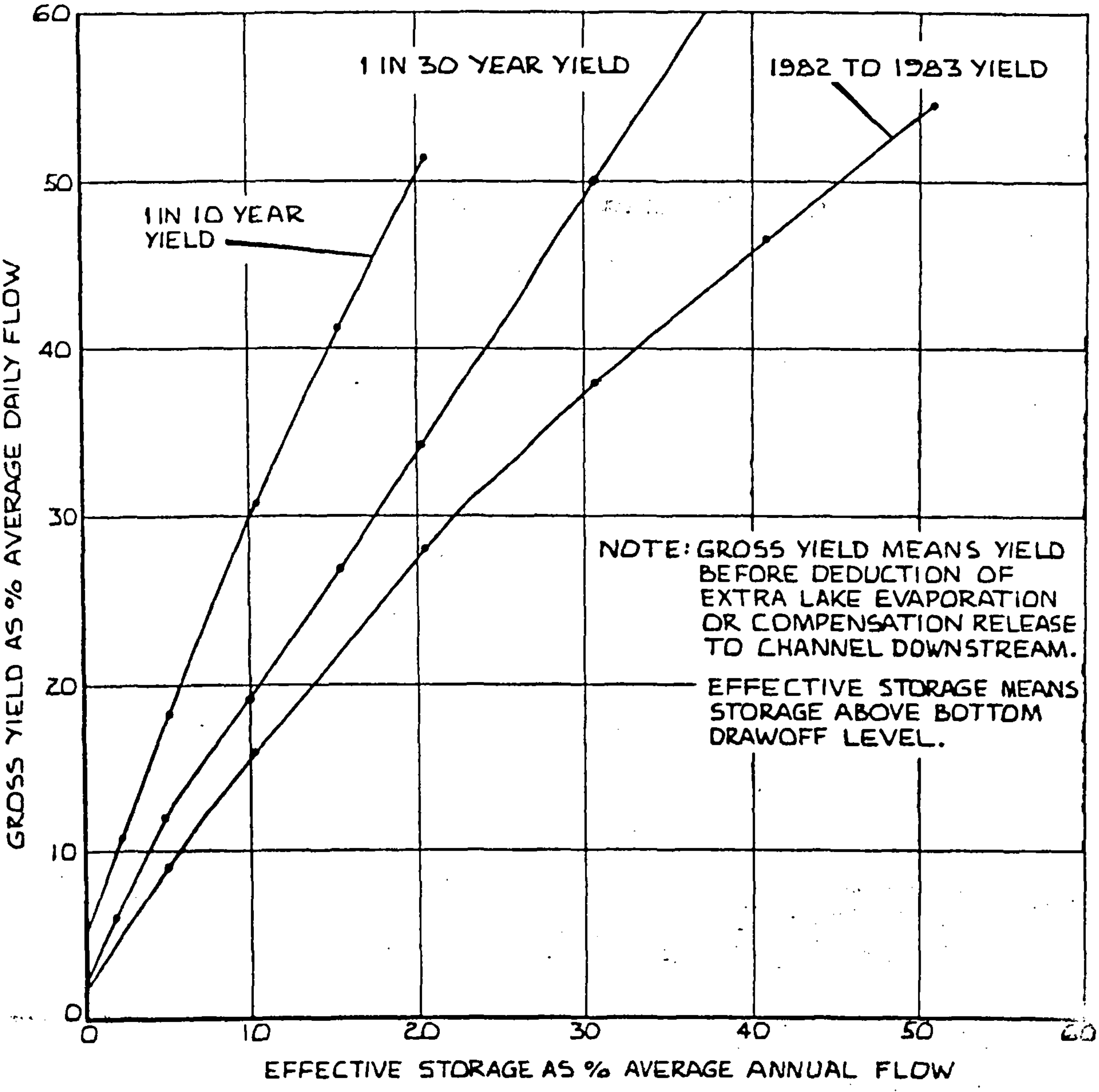


Figure 3 DIMENSIONLESS RESERVOIR YIELD STORAGE DIAGRAM FOR RAROTONGAN STREAMS

GROUNDWATER RECHARGE STORAGE AND DEVELOPMENT ON SMALL ATOLL ISLANDS

Frank L. Peterson[1]

INTRODUCTION

The sole source of groundwater recharge on atoll islands comes from direct rainfall. A portion of the rainfall is directly evaporated from the ground surface, an additional portion is evaporated and transpired from the soil zone, and the remaining rainfall component recharges the groundwater body. On most small atolls, the permeability of the surface materials is large enough so that surface runoff to the ocean is negligible and can be ignored in any water budget calculations. Fresh groundwater within atolls occurs as a lens-shaped body commonly called a Ghyben-Herzberg lens, which floats on and displaces seawater by virtue of the difference in densities of fresh water and seawater. Under conditions where the aquifer material is homogeneous and isotropic, the Ghyben-Herzberg lens has a lenticular shape with the upper and lower boundaries forming parabolas. This characteristic shape results from a flow of fresh groundwater through the aquifer toward the coast in response to the hydraulic gradient (Fig. 1).

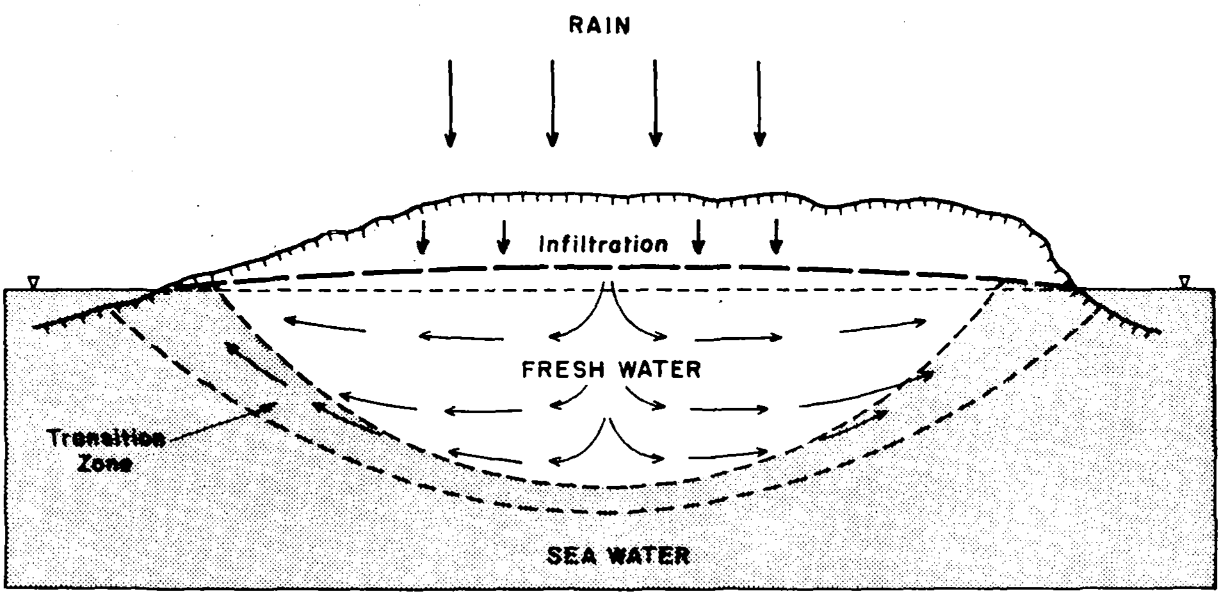


Figure 1. Groundwater lens on homogeneous island

As shown in Figure 1, the fresh groundwater and the underlying seawater are not separated by a sharp interface, but, instead, by a zone of mixed fresh and salt water commonly called a transition zone. The mixed zone is produced by natural disturbances, such as tidal fluctuations, wave activity, and seasonal variations in recharge, as well as by pumping activities by man. In the transition zone, the concentration of salt increases continuously from that in the uncontaminated upper fresh water to that in the underlying salt water. The thickness of the transition zone, and thus the thickness of the potable portion of the freshwater lens, is mainly a function of the extent of disturbance of the interface and the flow velocity in the fresh portion of the lens. If the

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fresh groundwater flux is high, the transition zone will be thin; if there is considerable disturbance of the interface, the transition zone will be thicker. On most small atoll islands relatively small groundwater fluxes and continuous tidal fluctuations result in a relatively thick transition zone and a thin freshwater lens. Extraction of fresh groundwater by pumping further stresses the system and induces even greater mixing.

To efficiently develop fresh groundwater from such a fragile atoll lens, great care must be taken not to exceed the sustainable yield of the system, where sustainable yield is the amount of water that may be extracted on a long-term basis without having deleterious effects on the groundwater resource. On small atoll islands the most critical factors controlling sustainable yield are recharge to the groundwater body, storage within the groundwater body and methods of development. This paper will address all of these parameters. Since I have done extensive groundwater work in the Marshall Islands, I will draw heavily on my experiences on one of these islands, Kwajalein, to illustrate the computation of groundwater recharge and storage and methods of groundwater extraction by skimming wells (Hunt and Peterson 1980).

GROUNDWATER RECHARGE

Recharge to the groundwater lens on small atoll islands can be determined by several alternative methods. One of the simplest and yet most powerful methods is the water budget approach.

A water budget or balance is simply an accounting technique in which additions to the defined watershed area by rainfall are equated to losses from the system through natural and artificial processes. The rationale behind a water balance computation is to use known or assumed components of the equation to solve unknown components of interest. A water balance equation applicable to small atoll islands would generally include the following addition and loss terms:

ADDITIONS	LOSSES
Rainfall	Surface runoff and catchment
	Evapotranspiration
	Groundwater flux and mixing
	Pumping
	Change in groundwater storage

The water balance for small islands can be expressed by two equations, one of which applies to the ground surface and the other within the groundwater body.

At the island's surface:

Recharge to groundwater lens = Rainfall - Evapotranspiration - Runoff (1)

Within the groundwater lens:

Recharge = Mixing and flux loss to the transition zone + Skimming well production + Change in storage (2)

Equation (1) is used to compute total recharge to the groundwater body and equation (2) shows the disposition of that recharge once it reaches the groundwater body. First, the determination of groundwater recharge as given by equation (1) will be explained, and later in the section on Groundwater Storage the components in equation (2) will be addressed.

As indicated earlier, some portion of rainfall will be lost to evapotranspiration (ET), some will be used to saturate the soil, and, if the amount of rain is great enough, some will exceed the holding capacity of the soil and percolate down to the water table as groundwater recharge. A first approximation of this process may be obtained simply by subtracting the monthly potential ET from monthly rainfall. Any excess rain is then counted as recharge. This approach is quite common and yields recharge estimates of about 40% of total annual rainfall for Kwajalein (Table 1). This approach relies on monthly averages and may be somewhat overconservative, however, as it assumes that water is constantly available for evapotranspiration, which is not always the case. A more precise approach, if data allows, is to use weekly or even daily soil water budgets, which more closely approximate the actual physical soil water movement processes.

TABLE 1. ALTERNATIVE RECHARGE ESTIMATES, JULY 1978-JUNE 1979, KWAJALEIN

		Groundwater Recharge (mil gal)	Groundwater Recharge (10^6 m^3)	Recharge as % Rainfall
1	Monthly rainfall in excess of ET	177	1.048	41
2	Daily soil water budget, 0.15 m soil	401	1.518	59
3	Daily soil water budget, 0.3 m soil	360	1.363	53
4	Daily soil water budget, 0.6 m soil	324	1.226	48
5*	Daily soil water budget, 0.15 m soil	360	1.363	53
6*	Daily soil water budget, 0.3 m soil	324	1.226	48

*Calculations 5 and 6 assume wilting point field capacity difference of 10%; calculations 2, 3, 4 assume 5%.

Figure 2 shows a schematic diagram for the soil water budget. When rain falls, it enters the surface soil horizon where moisture is stored. If the field capacity (storage threshold) of the soil is exceeded, water "overflows" the soil reservoir as recharge. Since the distance between the surface soil layer and the water table on atoll islands is usually only about 1 to 2 m and the material is generally composed of coarse sands and gravels which do not retain significant amounts of moisture under unsaturated conditions, it can be assumed that all water which overflows the surface soil reservoir directly recharges the groundwater body. Conversely, evapotranspiration from the reservoir depletes soil moisture at the daily ET rate until wilting point (evapotranspiration threshold) is reached, after which ET ceases. Thus, daily additions by rainfall and losses to ET determine the status of soil water storage and amount of recharge at any time. For the situation on Kwajalein it has been assumed that once the recharge reaches the groundwater body no additional ET occurs. On other islands with very shallow water tables and extensive vegetation this may not be the case, and ET may continue to extract water directly from the groundwater lens.

The greatest potential source of error in the recharge computation is associated with values assigned to the soil reservoir parameters, namely, the thickness of the surface soil layer and the storage and ET threshholds. Soil profiles on Kwajalein were generally observed to range from about 0.15 to 0.3 m. Consequently, recharge computations were made for 0.15, 0.3, and 0.6 m soil horizons. The difference between the wilting point and field capacity for Kwajalein soils is estimated to be about 5%, thus, recharge computations were made using both a 5% and a 10% difference. Table 1 shows alternative recharge determinations for Kwajalein, using the above parameter values.

In addition to total annual recharge, the water budget approach allows computation of the time and the areal distribution of recharge. For example, it is often very useful in managing groundwater extraction to know exactly

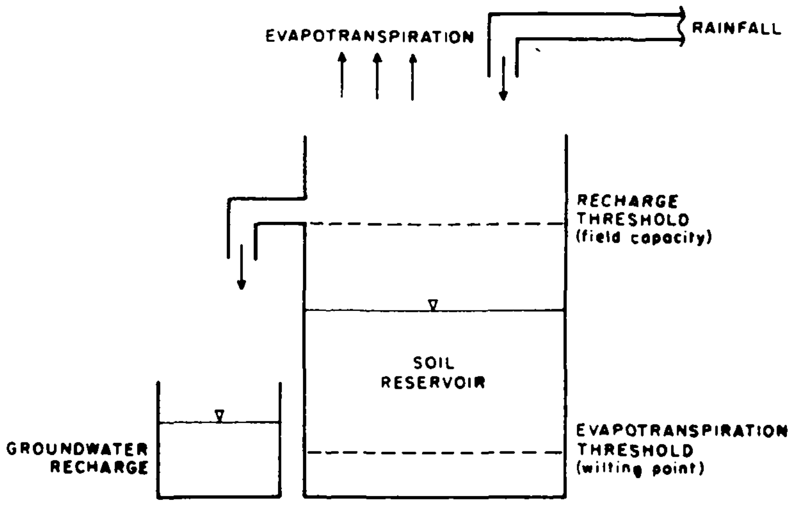

Figure 2. Schematic representation of groundwater recharge budget

when and where recharge is occurring. On larger islands both soil thickness and soil infiltration parameters may vary considerably, thus causing the areal distribution of groundwater recharge to vary. Even on small atoll islands where soil recharge parameters are generally quite uniform, other factors, such as the location of impermeable surfaces and airstrips, may cause significant variations in the areal distribution of groundwater recharge. On Kwajalein, for example, the use of the water budget illustrated conclusively that one recharge sub-area that contained less than 20% of the total recharge area actually accounted for almost 50% of the total groundwater recharge. This information was very useful in managing groundwater extraction.

GROUNDWATER STORAGE

As described previously, to efficiently develop groundwater resources in general and especially those of small atoll islands, both recharge to the groundwater body and the amount of groundwater in storage must be determined. There are several methods of estimating groundwater storage, most of which do not measure the groundwater directly but rather use indirect means. Some of these include various geophysical methods, water budgeting, Ghyben-Herzberg head relations, and various groundwater flow and quality models. The only method of direct determination of groundwater storage is by use of boreholes. In fact, the only sure method of checking the validity of indirect methods is with boreholes.

The greatest problem with the use of boreholes is usually their cost. This is especially true on larger and higher islands where the depth to water tables and the total groundwater thickness often are great. On small atoll islands, however, where the areal extent of the fresh groundwater body and its thickness are small, construction of boreholes may be relatively inexpensive. Furthermore, permanent boreholes make long-term monitoring possible. Recent work, especially in the Marshall Islands, indicates that the hydrogeology of atoll islands is more complex than once thought, and in many instances fresh groundwater occurrence may be strongly controlled by low permeability horizons. The existence of such layers and their effect on the fresh groundwater body can be determined with certainty by boreholes.

The two most common methods of borehole construction are by drilling and driving. Driving wellpoints has the advantage of being relatively inexpensive and does not require large equipment; however, driving may not be possible through some hard impermeable layers. Drilling has the advantage of being able to penetrate virtually any type of material and allows sample collection.

The areal distribution of borehole networks and individual well depths are important considerations. Ideally, the boreholes should cover as much of the areal extent of the groundwater body as possible, however, costs are often a limiting factor. Figure 3 shows the areal extent of the fresh groundwater aquifer on Kwajalein and the borehole network constructed to monitor it, and Figure 4 shows well depths at each borehole site. The principal criterion for borehole depth is simply to allow monitoring of the entire thickness of fresh water so that, at a minimum, boreholes would sample the top, bottom, and middle of the groundwater body. The two most common ways of achieving this are to either use a series of individual bores or to nest several piezometers within a single borehole. A single continuously perforated borehole is not recommended because tidal pumping effects rapidly mix the entire borehole water column, and in fact may allow contamination of the upper, freshest part of the aquifer by more saline waters from below.

Two borehole parameters are commonly used to determine fresh groundwater storage, head, and salinity. The head method utilizes the Ghyben-Herzberg relationship to delineate the total freshwater thickness. However, on small islands where the freshwater lens is thin and the tidal range is usually greater than the head above sea level, heads are often of little value in determining total groundwater thickness. Thus, head measurements are useful primarily when boreholes do not penetrate the entire freshwater thickness, and even then provide only rough estimates of the total fresh groundwater storage.

The most reliable method for determining fresh groundwater thickness, and thus total groundwater storage, is direct measurement of some form of groundwater salinity, either total salinity, total dissolved solids, chlorides or electrical conductivity. The following concept of relative salinity, described by Vacher (1974) provides a simple method of relating groundwater salinities to depth.

The range of salinities in the freshwater lens and upper transition zone may be thought of as various blends of the freshwater and seawater extremes. The salinity of any particular mixture may be described by the relative salinity, rs, expressed as a percentage of one of the end members of the blend. Relative salinity is defined as

$$rs = 100\ (c - c_f)/(c_s - c_f) \qquad (3)$$

where c is the concentration of any particular species in the blend, and c_s and c_f are the respective concentrations in the salty and fresh end members. In this case, blends are expressed in percent seawater with fresh water = 0% and seawater = 100%. Relative salinity may be used for any of the several parameters that describe salinity, such as chloride ion concentration, total dissolved solids concentration, or electrical conductivity.

The physical process of dispersion produces a salinity profile for which the vertical distribution of salt concentration can be described by a mathematical equation known as the error function. Although the error function curve is sigmoidal in shape, by plotting the salinity profile on probability graph paper, a straight line relating relative salinity to depth is obtained as shown in Figure 5. Using probability paper and known salinity data for a given location, a straight line may be fitted to these data and then extrapolated to other depths or salinities of interest, such as the 250-ppm isochlor or the mid-point of the transition zone. The following is an example of this method of calculating the salinity profile by using electrical conductivity data from one of the monitor boreholes on Kwajalein.

The calculations were made from the neap tide data of 6 June 1979 at moni-

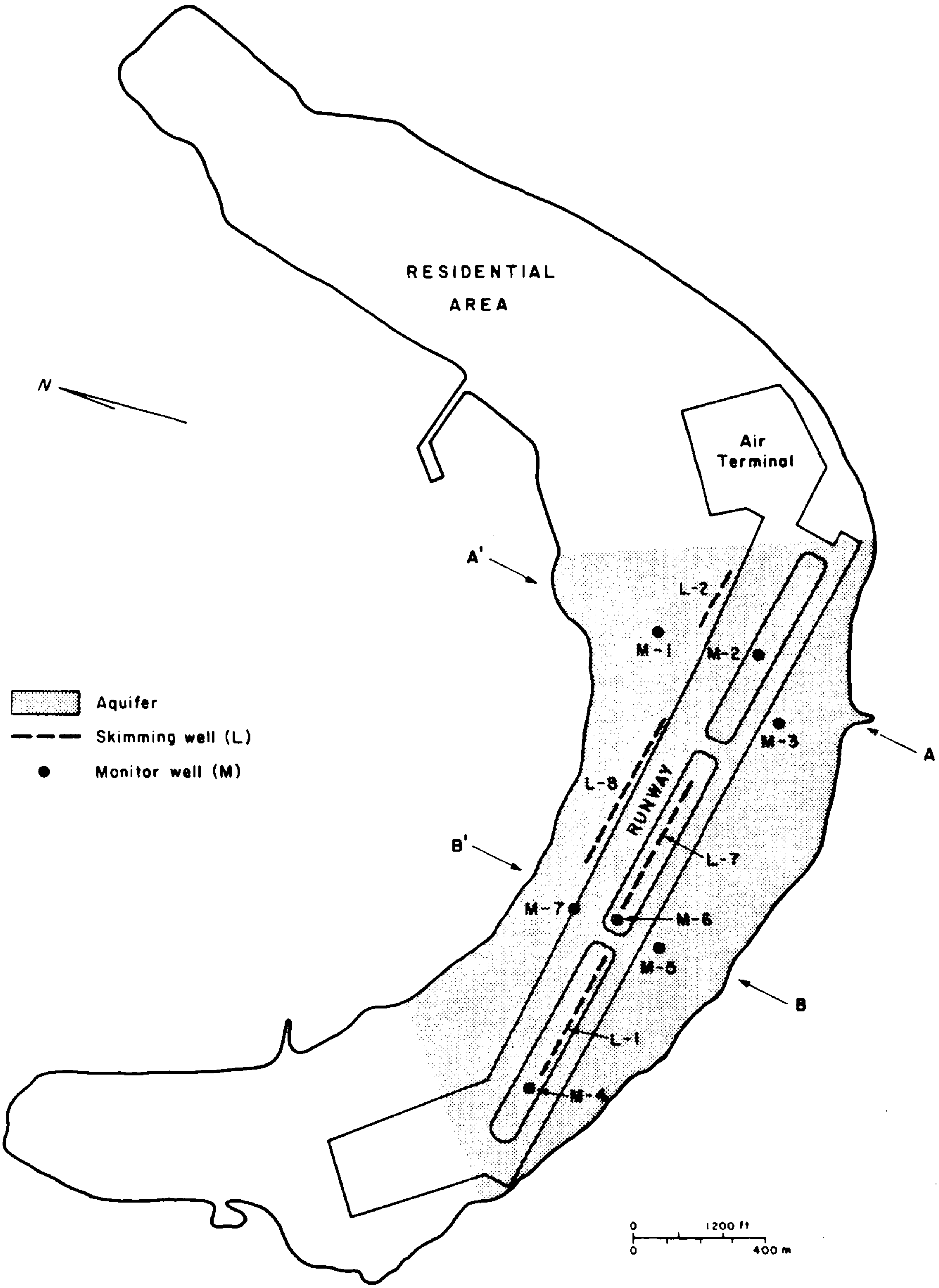

Figure 3. Location map of Kwajalein Island showing extent of groundwater aquifer, production skimming wells, and monitor wells

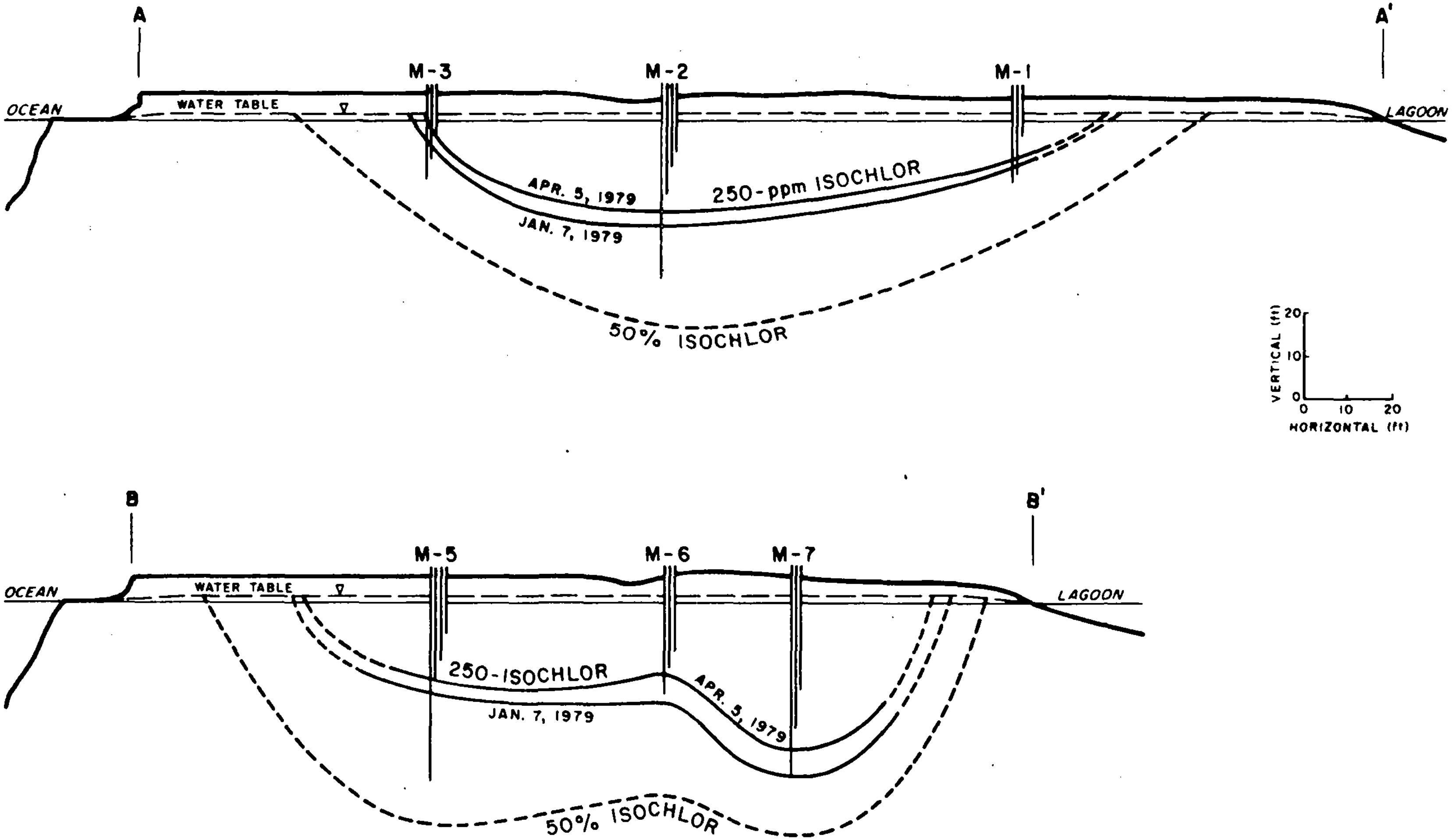

Figure 4. Cross sections through the Kwajalein Island groundwater lens

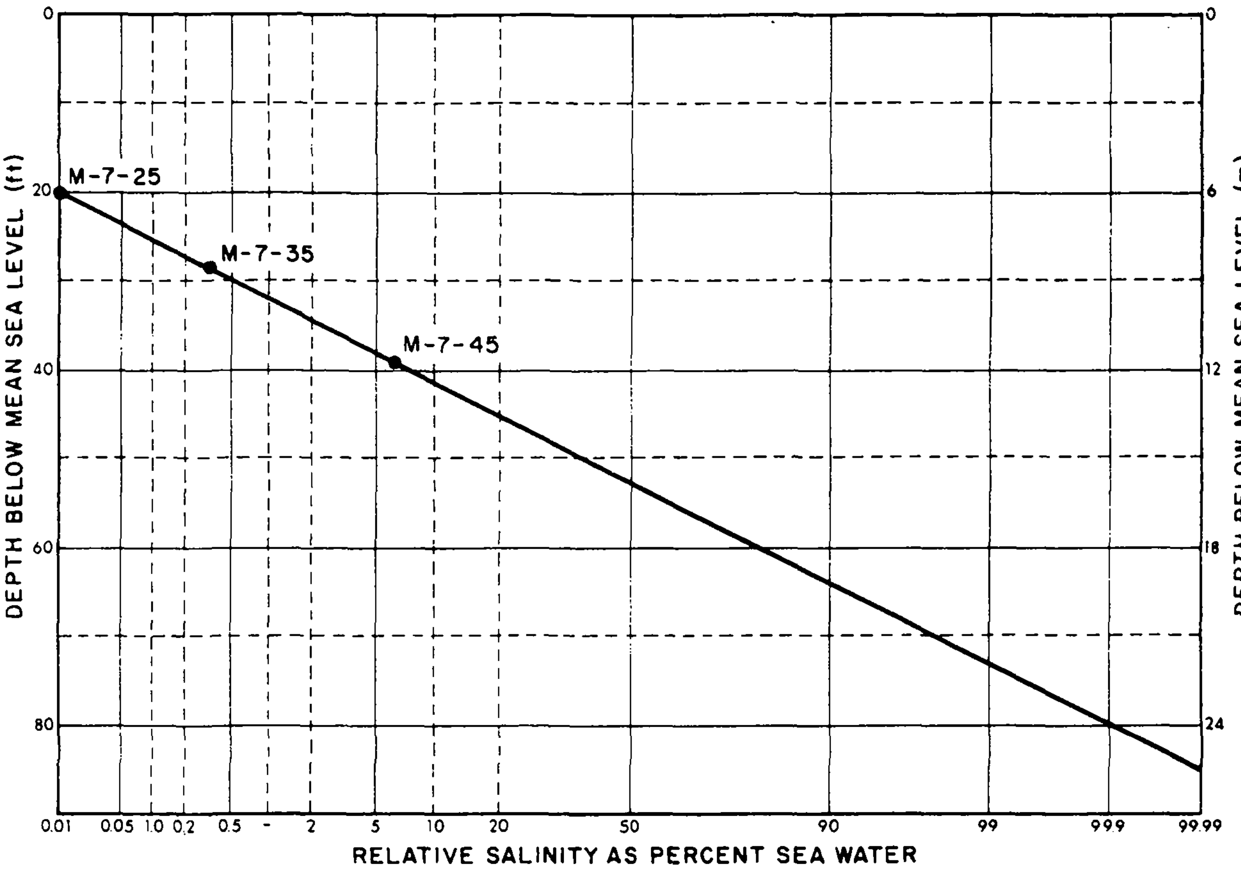

Figure 5. Probability plot of salinity vs. depth, monitor site M-7
6 June 1979, Kwajalein

tor site M-7. The representative conductivities, which are an average of high and low tide values on this date, are as follows:

Well No.	Well Bottom Elevation, MSL (ft)	(m)	Average Conductivity (μmhos)	Relative Salinity rs (%)
M-7-25	-19.8	-6.04	305	0.01
M-7-35	-28.4	-8.66	495	0.35
M-7-45	-38.9	-11.86	4000	6.58

Relative salinities are calculated using equation (3), and end member values of c_f = 300 μmhos for the conductivity of fresh water and c_s = 56,500 μmhos for the conductivity of seawater. For M-7-45,

$$c = 4,000$$
$$c_f = 300$$
$$c_s = 56,000$$

so that

$$rs = 100\ (4000 - 300)/(56,000 - 300) = 6.58\% \ .$$

Plotting relative salinities against well depths on probability paper yields the salinity depth profile of Figure 5. Consequently, the potable water zone (defined as having an upper limit of 250-ppm chlorides on Kwajalein) can be very accurately delineated at each of the monitor well sites. On Kwajalein, 250-ppm chloride water has an electrical conductivity of about 1.130 μmhos, and thus using equation (3), the relative salinity of the 250-ppm isochlor may be expressed as

$$rs_{250} = 100\ (1130 - 300)/(56,500 - 300) = 1.48\% \ .$$

Referring to Figure 5, the 1.5% relative salinity is seen to occur at about -10 m MSL at monitor site M-7.

Total groundwater lens storage can be determined by integrating the potable water thickness obtained at each monitoring site over the entire lens area. On Kwajalein where the groundwater lens recharge area is only approximately 1.3 km^2, over the past five years the total potable groundwater storage has averaged about 1.1×10^6 m^3 (300 mil gal), and has varied as much as 25% of total storage. Figure 4 shows typical lens cross sections constructed through the monitor wells along lines A-A' and B-B' (location given in Fig. 3). It is interesting to note that the freshwater lens in the vicinity of monitor well M-7 is considerably thicker than at other locations. This is primarily due to the very high groundwater recharge that occurs in this area as described previously.

On Kwajalein the recharge and the storage determinations have proved extremely useful in managing the time and areal distribution of groundwater extraction.

DEVELOPMENT

As has been stated previously, one of the most difficult tasks facing hydrogeologists today is developing fresh groundwater from small atoll islands. As we have seen, fresh groundwater bodies on these islands, if they exist at all, are typically only a few meters thick and are extremely sensitive to salt water intrusion. The Ghyben-Herzberg relationship governs the lens thickness, and thus any drawdown at the top of the lens causes a thickening of the underlying transition zone and a corresponding thinning of the fresh portion of the lens.

An optimum groundwater development system extracts water from the top of the lens over a large area at a low steady rate. This has the dual advantages of developing the uppermost, freshest portion of the lens and creating minimum drawdown effects. Conventional vertical wells, except for those that are very shallow and extract only small quantities of water, are not well suited for development of thin lens systems. Instead, shallow horizontal skimming wells or tunnels provide the most efficient means of groundwater development.

Numerous different types of horizontal skimming systems are in operation. On Kwajalein alone, at least five different designs have been used. Although somewhat different in detail, the three principal skimming wells on Kwajalein (see Fig. 3) have several features in common: (1) all consist of several hundred meters of small diameter perforated pipe placed at the bottom of trenches backfilled with gravel, (2) all lie just below the mean water table, (3) all are oriented roughly parallel to the long axis of the island, and (4) all are pumped fairly steadily at low rates that cause minimal drawdown. The amount of fresh water (with chlorides well less than 250 ppm) developed by this system on Kwajalein is remarkable. As shown in Table 1, recharge to the 1.3 km^2 groundwater body averages about 1.2×10^6 m^3/yr. From this, using the skimming wells described above, approximately 1.9×10^5 m^3 (50 mil gal) of fresh water can be developed annually.

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HYDROGEOLOGY OF HIGH OCEANIC ISLANDS

Frank L. Peterson[1]

Freshwater development on small oceanic islands is one of the most difficult problems facing hydrogeologists today. The task is made especially difficult by adverse geologic conditions and the ever-present threat of salt water intrusion. The Pacific Ocean alone contains more than 30,000 islands, and the Indian and Atlantic Oceans have many thousands more. To better understand the problems of occurrence and development of fresh water in this environment, knowledge of the geology of small oceanic islands is a necessity.

Islands are often conveniently separated into two broad groups: "low" islands and "high" islands. The high islands are primarily comprised of volcanic rocks, but also often contain substantial quantities of sedimentary materials, including raised coralline limestone and debris. The high islands are older and much larger than the low islands, and generally contain developable quantities of surface water and groundwater. The low islands, which are mainly comprised of coralline atolls and reef material, are very small and usually stand only a few meters above sea level. They have little if any surface water, thus, users must rely on direct rainfall catchment and a thin, often brackish, groundwater lens. The remainder of this paper will describe the geology and water-bearing charactertistics of the high volcanic islands; the geology of atolls and raised coral reef islands is described in other papers.

The high volcanic islands of the Pacific, and all oceans for that matter, fall into two major provinces, the andesitic and the basaltic or oceanic. As described by Mink (in United Nations 1983, p. 260), islands of the andesitic province are associated with island arc volcanism and lie on the continental side of deep ocean trenches within the zone of lithospheric plate subduction. As such, they have typically continental affinities, thus, the term andesitic province. In earlier literature the term "andesite line", which is coincident with the trenches, has been used to separate the andesitic and oceanic provinces. Typical examples of Pacific Ocean island groups within the andesitic province are the Northern Marianas, Guam, Palau, the Solomons, Vanuatu, Tonga, Fiji, and parts of the Cook Islands (Fig. 1). Volcanic rocks in the andesitic province occur as lava flows and pyroclastics, and range in composition from basaltic to trachytic; however, submarine pyroclastics predominate. The permeability and water-bearing properties of volcanic rocks in the andesitic province are generally poor, and little usable groundwater can be developed from them. Instead, most groundwater is developed from limestone and raised coral reefs that are often associated with these islands.

Islands of the oceanic province are typically basaltic, although composition may range to andesitic, and lava flows rather than pyroclastics predominate. The islands occur on the ocean side of trench/subduction systems and are associated with intraplate volcanism, thus, the name basaltic or oceanic province. Islands in this province are generally comprised of large, gently dipping shield volcanoes. The lavas, if young and basaltic, such as those found typically in the Hawaiian Islands, French Polynesia, and Samoa, are extremely permeable and make up the principal aquifers. Conversely, on islands where the lavas are older and contain more pyroclastic material, such as on Yap, Truk, and Ponape in the Trust Territory of the Pacific, the volcanics are poorly permeable and the most productive aquifers are sedimentary deposits and weathered lavas. Oceanic islands are generally submergent and many ultimately

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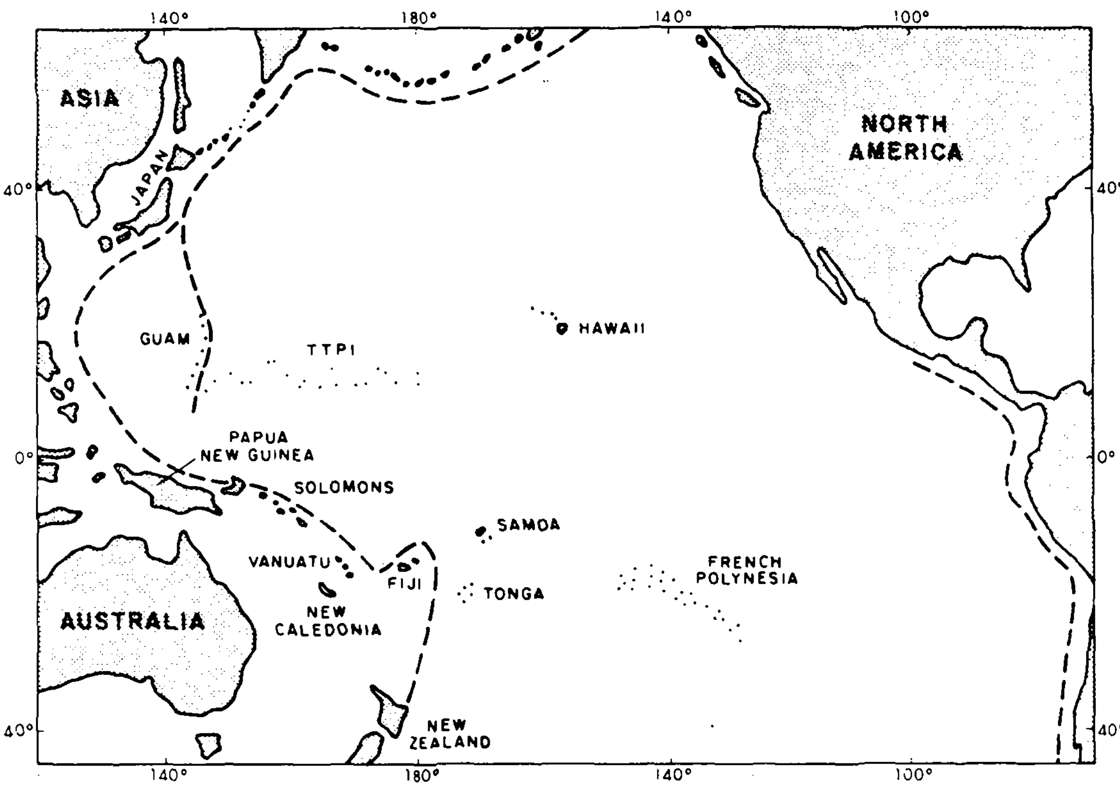

Figure 1. Location map of Pacific Ocean Basin with oceanic trench/subduction zones shown by heavy dashed lines

form atolls.

The remainder of this paper is devoted to a more detailed description of the hydrogeology of the highly permeable basaltic islands, and since I am most familiar with the Hawaiian Islands they will be used as a typical example. Parts of what follow have been previously published (Peterson 1972).

The high permeability of the rocks and soils in Hawaii and, indeed, the entire mode of groundwater occurrence can best be understood by consideration of the geology. All of the major islands in the Hawaiian chain consist of essentially of one or more shield volcanoes which are primarily composed of extremely permeable, thin basaltic lava flows. Interbedded with the flows are a few ash beds.

Basalts are ordinarily among the most permeable rocks on earth. The basalts which comprise the Hawaiian islands are especially permeable due to their very young age and, probably even more important, to the thin layers of individual lava flows. The lavas which stand above sea level are thought to range in age from over five million years to only a few tens of years, and, in fact, on the island of Hawaii new lava flows are still being formed. The flows range in thickness from a few centimeters to several tens of meters, but most are 6 meters or less. This is especially important as many of the water-bearing structures in lava flows are associated with the surface and near-surface portions of flows. Depending on their physical state and the environment in which they cooled, the flows solidified into either pahoehoe, which is a very liquid, smooth-flowing lava, or aa, which is a very viscous, blocky, slow-flowing lava. Pahoehoe flows often grade into aa flows. Their chemical composition is remarkably uniform, however, their physical characteristics, including the water-bearing properties, are quite varied on a coarse scale. The high permeability results primarily from major flow structures, the most important of which include clinker zones in aa, lava tubes and gas vesicles in pahoehoe, vertical contraction joints formed by the cooling of lavas, and irregular openings associated with the surface between flows. The horizontal component of lava flow permeability probably exceeds the vertical; however, permeability in both directions is so great and so subject to local deviations that any difference between them is difficult to assess.

The lava flows were erupted from central calderas and from fissures in linear rift zones along the volcano flanks. As a result, the rift zones contain many vertical or steeply dipping dikes which cut through the gently sloping lava flows. In the central portions of the rift zones, the dikes are closely spaced and almost completely replace the lava flows. Toward the outer edges of the rifts, the dikes are more widely spaced and form large compartments which enclose permeable lavas. Because the dikes are dense and have low permeabilities, groundwater may be impounded within these compartments.

On most of the older islands, the margins of the volcanic mountains are overlapped by coastal plain sediments of alluvial and marine origin which were deposited during periods of volcanic quiescence. The greatest thickness of coastal plain sediments occurs on southern Oahu where the sediments have a maximum thickness of over 350 meters. Although the permeability of the sediments varies widely, the overall effect is one of low permeability compared to the basalts. The coastal sediments contain large quantities of water, varying from fresh to sea water. Compared to the basalt aquifers, however, the capacity of the sediments to store and transmit water is small. Consequently, the sediments act as a caprock retarding the seaward movement of fresh groundwater from the more permeable underlying basaltic aquifer.

Rainwater percolating through the rocks may accumulate in two principal types of groundwater bodies: (1) high-level bodies impounded within compartments formed by impermeable dikes that have intruded the lava flows, and, to a much lesser extent, high-level bodies perched on ash beds or soil interbedded with flows on unconformities, or other relatively impervious lava flows, such as the dense cores of aa flows; and (2) basal water bodies floating on and displacing salt water. The occurrence and development of these groundwater bodies are illustrated in Figure 2.

Springs issuing from perched and dike-confined groundwater bodies repre-

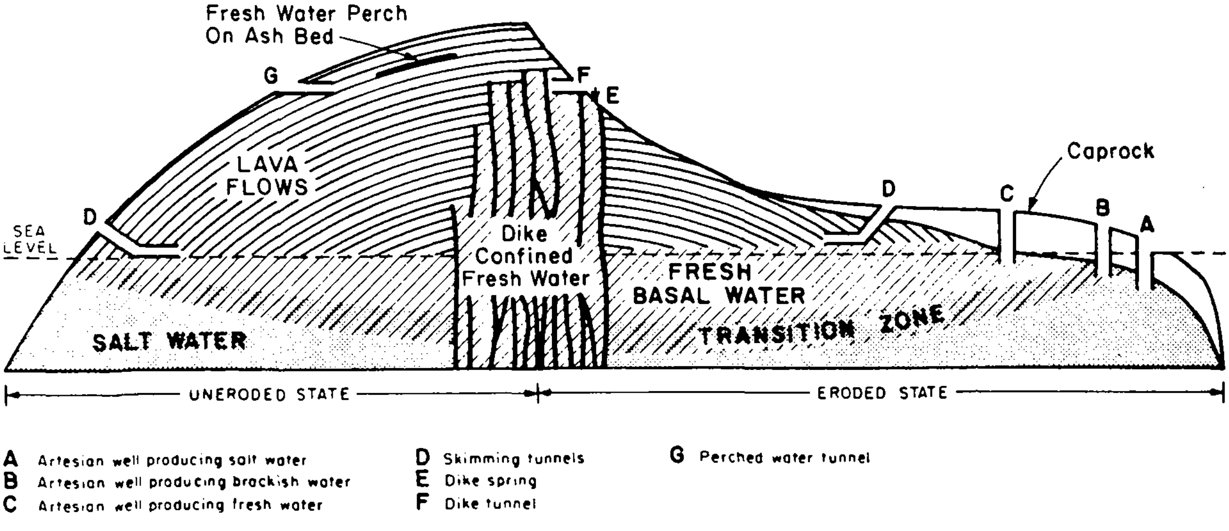

Figure 2. Cross section of typical volcanic dome showing occurrence and recovery of groundwater

sent natural discharge of excess storage from these high-level aquifers and are of great importance in providing a large portion of low water flow of many streams. Without them, most streams would be almost without value as sources of water supply. The natural surface discharge from many of these high-level water bodies has been artificially increased, steadied or diverted to economic advantage.

Natural storage in perched aquifers is generally small and the flow of perched water springs tends to be relatively unstable. Perched groundwater has been primarily developed by tunnels along the perching members. The tunnels serve mainly to collect or divert flow to perched springs and rarely increase either the storage or the natural spring discharge. As a result, perched water is important primarily because of its high elevation and is only a very small part of all high-level groundwater developed.

Similar to perched water bodies, dike-confined groundwater bodies are usually identified by natural spring discharges. The compartments formed by dikes may be commonly saturated with fresh groundwater to levels a few hundred meters above sea level. The volume of water stored in dike-confined aquifers is large compared to other sources of high-level water and, furthermore, dike aquifers provide a relatively stable source of water supply. Compared to the total volume of fresh basal groundwater, however, the amount of dike-confined water is small.

Dike water has been primarily developed by horizontal or inclined tunnels which penetrate one or more dike compartments and, to a much lesser extent, by vertical wells drilled into individual dike compartments. Few dike-development tunnels have permanent equilibrium flows appreciably greater than those which were available from the springs when they drained the dike compartment. On occasion, bulkheads have been used in some tunnels in an effort to replenish the storage capacities within dike compartments.

The principal source of fresh groundwater in the Hawaiian Islands, as it is for most young basaltic islands, is the roughly lens-shaped basal water body floating on and displacing denser sea water. Recharge of the basal water body results directly from percolating rainwater or by underground leakage from perched-water bodies and bodies impounded by dikes. Where the permeable lava flows containing basal water extend to the coast without a cover of sediments, the head above sea level is generally small. Where the basaltic aquifer is directly overlain by the less permeable sedimentary caprock along some of the coastal margins, artesian heads of a few meters to over 10 meters above sea level may occur. In Hawaii the depth to the bottom of fresh water is normally a few tens of meters to several hundred meters, and the thickness of the transition zone varies from only a few meters in relatively undisturbed areas to as great as 300 meters in parts of southern Oahu where extensive development of the basal lens has occurred. In some of the drier coastal areas in Hawaii and, even more commonly, on many of the smaller Pacific islands where heads may be less than one meter above sea level, tidal fluctuations very rapidly mix all the fresh rainwater with the underlying sea water so that only brackish water occurs.

In Hawaii basal groundwater has been primarily developed by drilled wells in artesian and unconfined aquifers and by skimming tunnels in unconfined aquifers (Fig. 2). The skimming tunnels consist essentially of a vertical or inclined shaft constructed from the ground surface down to about the water table and one or more horizontal, or nearly horizontal, tunnels constructed laterally at, or just below, the water level to collect water.

The fundamental advantage of skimming tunnels over conventional wells is their capability to produce large quantities of fresh water from lenses so thin that drilled wells would recover only brackish water. For this reason, skimming tunnels are especially useful in some of the dry coastal areas of

Hawaii, as well as on many small oceanic islands with extremely thin freshwater lenses. Furthermore, in thick basal groundwater bodies, skimming tunnels are capable of producing exceedingly large discharges. For example, a 500 meter long tunnel in southern Oahu is capable of producing almost 200 million cubic liters of water a day, and a skimming tunnel on Maui produces a maximum discharge of almost 175 million cubic liters per day from only 200 meters of tunnel. Due primarily to economic considerations and also to the greater flexibility of modern deep-well pumping stations, only one new skimming tunnel has been constructed in Hawaii in the last 40 years. However, the city of Honolulu still relies on several large tunnel pumping stations for a significant portion of its domestic water supply, and many other skimming tunnels throughout the state produce large amounts of water for agricultural use.

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DEVELOPMENT OF GROUNDWATER RESOURCES ON CORAL ATOLLS: EXPERIENCES FROM TARAWA AND CHRISTMAS ISLAND, REPUBLIC OF KIRIBATI

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1. INTRODUCTION

Recent studies of water resources aspects, including the development of groundwater resources, have been undertaken on Tarawa (DHC, 1982) and Christmas Island (Falkland, 1983) in the Republic of Kiribati. Some aspects of these studies are presented in this paper. Firstly, relevant design criteria for water supply projects on these coral atolls are provided. Detailed assessment of factors influencing the type and layout of groundwater extraction systems from the freshwater lenses are then presented. Various energy options, including the use of renewable energy sources, are discussed and compared on an economic basis. Finally, an economic comparison of a number of water supply options is presented.

2. DESIGN CRITERIA

Some basic criteria used in the design of groundwater supplies on Tarawa and Christmas Island (Figures 1 and 2) are listed below. These criteria are considered appropriate, in general, for the design of groundwater supply projects on coral atolls.

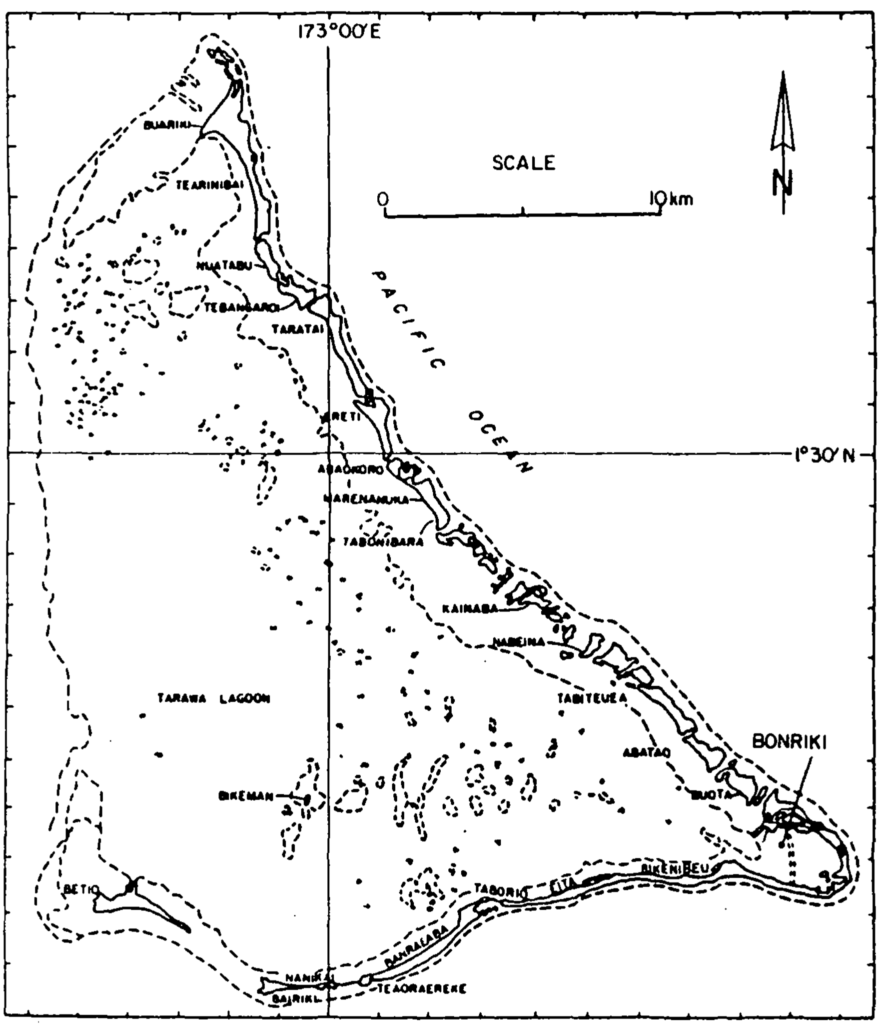

FIG.1 MAP OF TARAWA

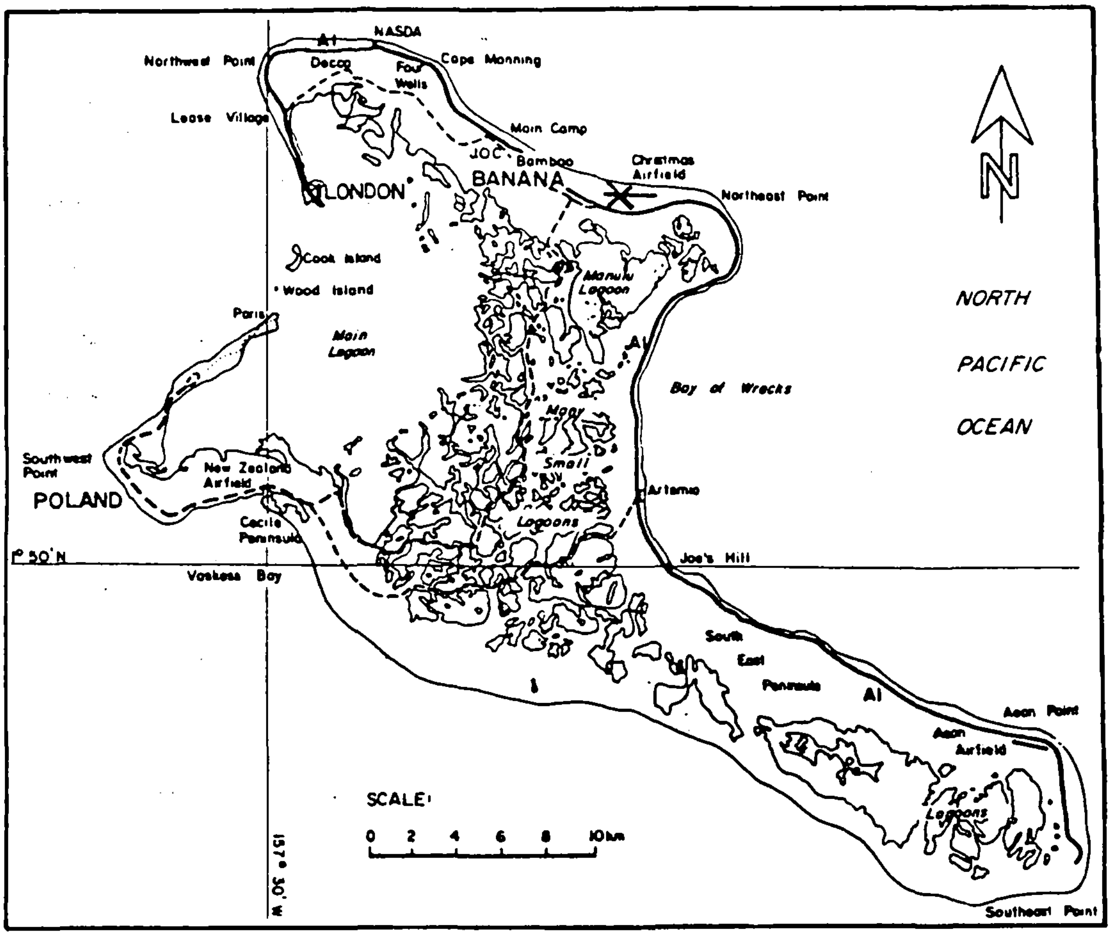

FIG.2 MAP OF CHRISTMAS ISLAND

- simplicity. Designs should allow, wherever possible, the use of simple system components. As much of the construction work required is done by relatively unskilled local labour, components should be easy to install. In general, sophisticated technology is not appropriate for such locations.

- low maintenance requirements. All equipment should be relatively easy to maintain.

- Use of local materials where possible. This has obvious benefits by saving costs on purchasing and transporting materials from overseas. Examples of local materials which may be used are crushed coral aggregate for use in concrete, coral slabs for building blocks and coconut trees for timber construction.

- Other materials and equipment should be corrosion resistant. The relatively high humidity and temperatures combined with moderate wind speeds and close proximity to the ocean combine to make the prevailing conditions highly corrosive. Severely rusted components from previous galvanised steel installations, often less than 10 years old, bear testimony to this problem. Standard galvanised coatings on steel structures are generally inadequate in these locations.

- Availability of spare parts. This is a most important consideration which has often been overlooked in the implementation of some projects, not necessarily related to water supply, in the past.

- Renewable energy sources should be considered. Imported fossil fuels (diesel, petrol and others) are expensive. As there are high levels of solar radiation and often moderately high wind speeds, both solar and wind energy options for pumping should be considered. As it is often desirable for at least the operating costs of water supply projects to be recovered by charging for water, systems with lower operating costs have definite advantages.

- Freight costs of imported materials and equipment should be considered in total costs. Often freight costs constitute a greater proportion of total costs than do purchase costs. It is, therefore, imperative that freight costs be considered so as proper economic comparisons or appraisals can be made.

3. EXTRACTION SYSTEMS

3.1 Basic Principle

If freshwater supplies are to be maximised, the type of extraction system adopted should be capable of extracting the sustainable yield from each freshwater lens. This means that water must be pumped out with the least amount of disturbance to the lens so as to minimise movement at the base of the freshwater zone. This, in turn, will minimise mixing with the underlying transition zone and seawater. If less than the sustainable yield of a freshwater lens is needed for water supply, the same basic principle of minimising disturbance to the lens still applies.

3.2 Possible systems

There are three main alternatives for extracting water from the lenses:

(a) borehole or tube
(b) large diameter well
(c) infiltration gallery.

The disadvantage of the first two is that unless the freshwater lenses are very thick, or very small flow rates are required, there is a considerable chance of causing local upconing of the underlying transition zone and seawater. Also, a large number of them would be required in order to effectively extract water from over the full area of the lens. Infiltration galleries offer probably the best solution since they allow the water to be "skimmed off" the surface of the lens. This tends to minimise local drawdown and, hence, mixing at the base of the lens. This method of extraction has been used successfully in a number of islands in the Pacific Ocean including Tarawa, Kwajalein, Hawaii and Guam.

3.3 Preferred system

The infiltration gallery is considered the best approach for the theoretical and historical reasons above. It should be noted that the term extraction gallery is also used to describe this system. In effect, water infiltrates into the gallery from the surrounding aquifer and is extracted from one or more points by pumping.

3.4 Gallery design

Theoretically, to optimise extraction efficiency in freshwater lens situations, water should be skimmed off the top of the entire lens. Such extraction is effectively a subtraction from recharge. In practice, however, it is not possible to extract water in a completely uniform manner over the whole lens. Rather, extraction is confined to a number of locations within the aquifer with pipes or other conduits being used to draw water to central pumping pits or sumps.

In order to design an efficient and economic extraction gallery system, the following factors must be considered:

- drawdown
- pump rates and operation
- permeability of upper aquifer material
- shape of the lens
- depth to water table
- nature of unsaturated zone material
- mean sea level
- type of gallery
- construction materials
- other land uses

These factors are discussed, in turn, below.

(a) Drawdown

A maximum drawdown at the lens surface of 30 mm is considered a reasonable figure to minimise the pumping effect on the freshwater lens. Such a drawdown, according to Ghyben-Herzberg theory, would result in a local rise of about 1.2 m at the freshwater - seawater interface. In practice, mixing occurs between the freshwater and transition zones causing the transition zone to widen. The value of 30 mm was previously suggested by Mather (1975) for selecting pump rates and distribution of extraction systems in freshwater lens situations.

(b) Pump rates and operation

Pump rates for a specified drawdown have a direct bearing on the length and spacing of gallery systems. For otherwise constant conditions, higher pump rates require galleries to be longer to prevent drawdown within the aquifer exceeding the maximum level. Pump rates used for each lens should not exceed the equivalent sustainable yields.

The type of pumping system and operating policy used can have considerable effect on the lens behaviour. Constant pumping rates are preferable since intermittent pump operation will cause fluctuations in the water table with consequent mixing effects at the base of the freshwater zone.

(c) Permeability of upper aquifer material

This also has a direct effect on the layout of gallery systems. Darcy's law for groundwater flow indicates that flow rates are linearly related to the permeability of the aquifer material. Thus, for a given drawdown and pump rate, higher permeability material would allow greater spacing between galleries as each one would tend to have a greater area of influence.

(d) Shape of the lens

Elongated lenses provide opportunity for long linear type galleries. Broader lenses may be better developed by some form of ring pattern. It is important that the design of the gallery does not allow "draining" of the lens. Interconnected gallery systems linking the centre of the lens to the outer edges, for instance, could allow water to flow out to the edges because the hydrostatic head is slightly higher in the centre. This would allow a redistribution of water at the base of the lens causing the loss of substantial volumes of freshwater in the centre. In the long term, it could even lead to destruction of the lens. To avoid this potential problem, galleries should tend to follow the lens thickness contours. This would tend to prevent "draining" from deeper to shallower parts of the lens.

(e) Depth to water table

This influences the amount of excavation required in order to construct the galleries. Typical depths to water table on Christmas Island, for instance, are 2 to 2.5 m in most freshwater lens areas. However, some locations show deeper depths largely because of inland dune formations. The maximum measured depth from surface to water table was about 4.5 m. Typical depths encountered during construction work on Bonriki, Tarawa were 2 to 3 m.

(f) Nature of unsaturated zone material

In some areas where freshwater lenses occur, layers of cemented calcareous material or 'hardpan' are found in the unsaturated zone. At one location on Christmas Island the material was sufficiently hard to make digging by conventional backhoe difficult. Normally, this hardpan was found to be about 200 to 500 mm thick and at a depth of about 2 to 2.5 m or just above the water table. In some cases conventional backhoes are unsuitable and larger excavators or hand operated air equipment may be required.

(g) Mean sea level

This factor influences the depth at which gallery collection systems are installed. If the collection systems are placed too low there is always a possibility that inappropriate high capacity pumping equipment could be installed at a later date which could adversely affect the long term integrity of a freshwater lens. Also, construction costs would be increased unnecessarily due to deeper excavation. On the other hand, if the system is too high then under certain conditions it may run dry. Groundwater movements are influenced primarily by tidal fluctuations, barometric changes, recharge events and long term variations in mean sea level. The first three influences can be relatively easily recognised from continuous recording of groundwater movements in the short term.

It is generally recommended that the invert of gallery collection systems be placed at mean sea level. This should ensure that galleries will not run dry under any conditions (other than heavy pumping) during their economic lives.

As a further precaution against disrupting the freshwater lenses, pump inlet or suction pipes should be placed at about 150 mm above mean sea level.

(h) Type of gallery

A number of different types of gallery using different materials have been used. The present system on Christmas Island using open trenches covered with corrugated aluminium covers are particularly unsuitable because they provide easy entry to sources of contamination such as crabs, birds and even humans. Also, as the system is relatively open direct evaporation can occur. This tends to increase the rate of withdrawal from the freshwater lens. The original gallery systems on Tarawa, built in the early 1970's, used horizontal rows of butt-jointed hollow concrete blocks leading to a central pit. These were completely backfilled and the only access to the water is at the central pumping pit over which a building stands. The design for the new galleries, currently being installed at Bonriki, Tarawa, makes use of 100 mm diameter slotted PVC pipes.

(i) Construction materials

It is considered that 100 mm diameter PVC slotted pipe provides a cheaper and more effective solution from a maintenance viewpoint than concrete blocks. Manholes and pumping pits could be made of flat coral slabs concreted together where these are available locally (for example, on Christmas Island). On Tarawa the gallery construction program has used locally fabricated ferro cement cylinders for such purposes.

(j) Other land uses

In some places where freshwater lenses are known to exist, it may be impossible, without large scale alterations to existing land use, to construct galleries. An obvious example is Banana village on Christmas Island which is constructed over the southern portion of the Banana lens (Figures 2 and 3). It would not be good policy to construct a gallery in that location knowing that there is some pollution of the lens there due to septic tank effluent.

3.5 Details of galleries

(a) Layout

The suggested layouts for galleries at two major lenses under present vegetation conditions on Christmas Island are shown in Figures 3 and 4. A pump rate of 0.3 l/s or about 26 m^3/day was adopted for each gallery. This was based on the results of modelling the freshwater lenses under different extraction rates (Falkland, 1983). It is also considered a reasonable value and well within the capacity of a number of different types of pumps powered from various energy sources. In general, elongated gallery systems were selected where possible. In all cases, compromises between the extraction patterns developed from modelling, topography, and lens shapes were required. An approximate formula, based on Darcy's law for groundwater flow, was developed for linear gallery systems as follows:

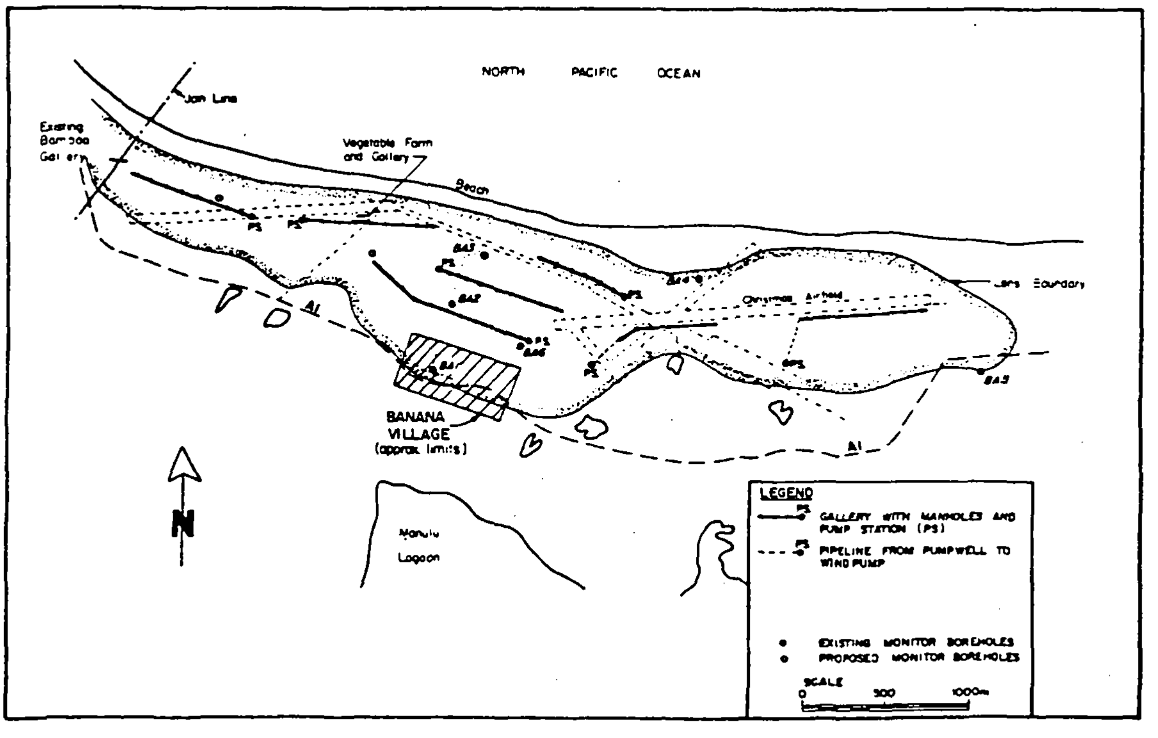

FIG.3 BANANA LENS, EXTRACTION GALLERY PATTERN PRESENT VEGETATION CONDITIONS.

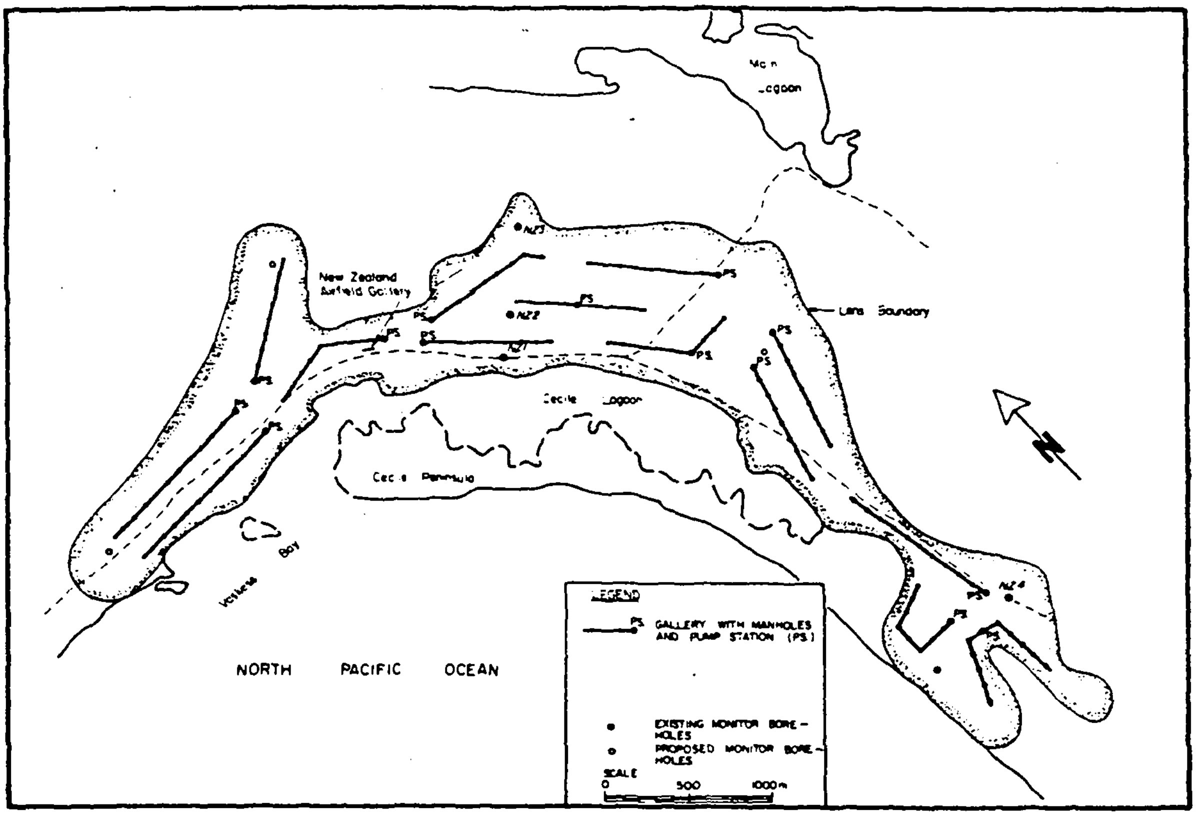

FIG. 4 NEW ZEALAND AIRFIELD LENS EXTRACTION GALLERY PATTERN, PRESENT VEGETATION CONDITIONS.

$$h = \frac{QW}{8(L-W)kD}$$

where h = drawdown at gallery collection pipe (m)
Q = pump flow (m^3/day)
W = width of 'extraction area' (m)
L = length of 'extraction area' (m)
k = permeability (m/day)
D = approximate depth of freshwater lens (m)

The 'extraction area' was obtained by dividing the selected pump flow into the sustainable yield. This gave the area in terms of equivalent square nodes with sides equal to 100 m. The extraction gallery layout for the two cases considered are described below:

(i) Banana (Figure 3)
The total gallery length for the 7 galleries, each with a pump rate of 0.3 l/s, is about 6350 m. The total pump rate of 2.1 l/s or 180 m^3/day is equivalent to the sustainable yield.

(ii) New Zealand Airfield (Figure 4)
In all, 14 galleries with a total length of about 13,100 m would be required. The total pump rate of 4.2 l/s or about 360 m^3/day is slightly less than the sustainable yield for the lens of 380 m^3/day.

On Tarawa, the galleries presently under construction at Bonriki, consist of both the linear type described above and a cruciform type. A plan and section of the typical layout for this latter type is shown in Figure 5. The sectional view is also typical of the linear type of gallery.

(b) Other structures

Pump wells should be constructed using flat coral slabs, ferrocement cylinders or other suitable non-coroding materials. The location of pump stations are largely dictated by:

- ease of access for construction and later maintenance
- proximity to coconut trees, especially if wind and solar energy sources are considered.

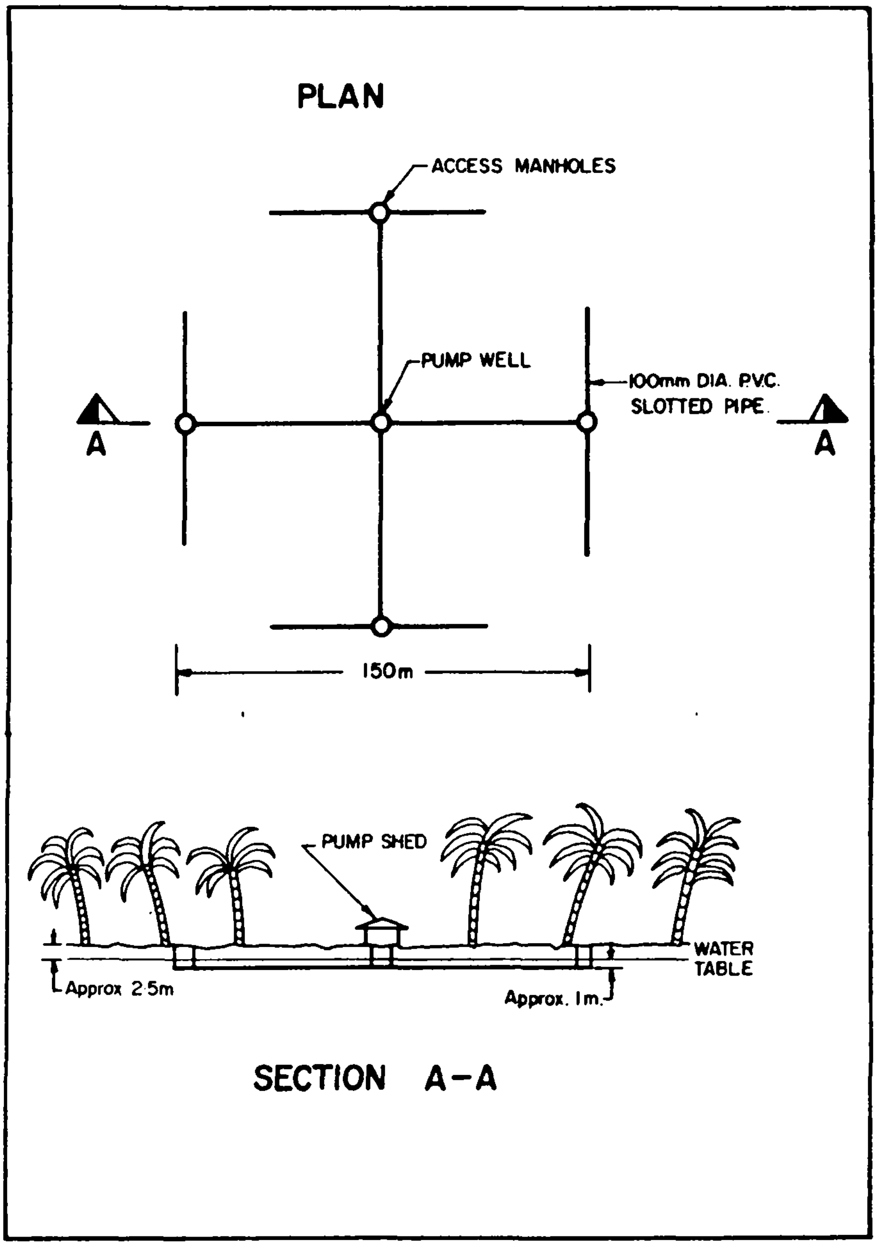

FIG. 5 CRUCIFORM TYPE GALLERY, BONRIKI, TARAWA.

Manholes should be located at approximately 100 m intervals to allow later maintenance to be carried out. These should be of similar materials to pump wells and measure approximately 1 m in diameter. Secure covers should be placed on top to prevent entry of potential contamination sources.

4. ENERGY SOURCES

4.1 Introduction

In this section, the emphasis is on energy sources for relatively remote village locations where energy from electric generating plants or other centralised energy sources is not available. While there are quite a large range of potential energy sources, the ones usually considered for such locations are:

- diesel energy
- wind energy
- solar energy

Other forms of energy, such as wave energy, and ocean thermal energy conversion are not normally considered relevant as they are primarily concerned with electricity generation. Also costs and the sophisticated technology involved generally place currently available methods beyond the financial resources of small island nations.

Some details of the available energy options for Christmas Island including costs in terms of Australian dollars, are presented below. Full details are provided in Falkland (1983). At Bonriki, Tarawa the most appropriate energy source was found to be electricity which is generated from power stations on South Tarawa (DHC, 1982). This latter case is not considered typical of many coral atolls where energy is not available from such sources.

4.2 Diesel energy

This source of energy can be used directly to drive water pumps or, alternatively, diesel powered generators can supply electric power to pumps. The latter option is relatively inefficient and has greater component requirements. Thus, both capital and operating costs would be higher than for the first option. The latter option is, therefore, rejected for extraction gallery pump purposes.

Advantages of this energy source are:

- relatively unsophisticated technology.
- generally a local familiarity with diesel engines.
- relatively constant pump rates can be achieved which avoids drawdown fluctuations at the freshwater lens surfaces. This, in turn, minimises the mixing between the freshwater zone and underlying transition zone. Constant pump rates also reduce capacity requirements of pumps, pipelines and reservoirs to meet given demands.

Disadvantages are:

- high cost of imported fuel.
- relatively high maintenance requirements in the prevailing conditions.

For Christmas Island, the unit cost of pumping using diesel energy was determined as $0.63 per m^3 of water pumped. This cost, which takes account of capital, operating and maintenance expenses, is a more expensive option than other alternatives (see Table 1 for comparison).

4.3 Wind energy

(a) Introduction

Wind can be used to, either pump water directly, or produce electric power by means of wind generators.

(b) Direct water pumping

A number of different pumping systems are now available including:

(i) conventional fan type windmill linked to a positive displacement piston type pump.
(ii) "wind turbine" using one or more Savonius or S-type rotors connected to a positive displacement helical rotor type pump.
(iii) another "turbine" type consisting of a multi-blade fan within an aerodynamically shaped shell linked to either a piston or helical rotor type positive displacement pump.

Wind speeds on Christmas Island from 12 years of records obtained from London on the west side of the atoll are relatively constant. The average annual value is 4.4 metres per second at a height of 2 m with an average maximum in January (4.9 m/s) and an average minimum in June (4.0 m/s). Independent measurements from the east side of the atoll during a different eight year period tend to confirm these results. There are some periods of in excess of 1 week, particularly during the onset of El Nino events, when wind speeds drop to near zero.

Based on the "wind turbine" option, the unit cost on Christmas Island was determined as $0.47 per m^3 of water pumped and compares favourably with other possible options. This cost includes a back-up diesel motor for use when wind speeds are insufficient for pumping.

(c) Wind generation of electricity

Wind energy can be converted to electrical energy using wind generators and stored in a battery system for use by electrically driven water pumps. Unit costs in terms of m^3 of water pumped is about $0.59 for Christmas Island which is more expensive than the direct wind pumping and solar options. The disadvantage of high maintenance requirements for batteries also acts against this option.

4.4 Solar energy

(a) Introduction

This form of energy can be converted using solar or photovoltaic cells into electrical energy which can be either used directly for driving electric motors, or stored in batteries for later use. Either direct current (DC) or alternating current (AC) electric motors can be driven by solar energy. The latter motor-type requires an inverter to convert the DC produced by the solar cells, or supplied from batteries, to AC. Such electric motors can be used to drive water pumps. The field of solar powered water pumping systems is a rapidly developing one and a number of systems are currently available. Some of these are considered below.

Solar energy can also be converted using other techniques to useful mechanical or electrical energy. For example, solar collectors consisting of reflecting parabolic dishes have been used to convert water to steam. The steam can drive a turbine which in turn can drive a generator to produce electricity. A number of such systems are available but are normally considered to be beyond the scope of water supply projects, as they are primarily associated with electric power generation.

(b) DC motors

(i) without storage batteries

The most widely used solar water pumping systems involve the direct connection of solar panels to a 24 volt permanent magnet DC motor coupled to a centifugal or positive displacement pump. No storage batteries are used and, hence, the pump can only operate during periods of solar radiation or insolation. For Christmas Island, using the average radiation value of 5.6 kWh/m^2 determined from 5 years of record, pumping at full capacity could be anticipated for about 8 hours each day based on an average solar intensity of about 0.7 kW/m^2.

The advantages of such a DC no-battery storage system are:

- no requirement for additional equipment such as an inverter, which is required if AC motors are used.
- no requirement for relatively expensive battery systems which also have high maintenance requirements.

Disadvantages are:

- intermittent rather than continuous pumping which can have adverse effects on the freshwater lenses. This is also a disadvantage of the AC no-battery storage system yet to be considered.
- pump, solar array, pipe and water storage capacities have to be about three times the capacities required for a continuously operating pump. This increases capital costs.

A number of such systems are currently available in Australia and elsewhere. One Australian manufacturer, has recently started supplying a system using solar panels linked to a 24 volt DC permanent magnet type electric motor. This, in turn, drives a helical rotor positive displacement pump. Another company offers a similar arrangement.

In order to cost a solar system without battery storage, a pump rate of 1.0 l/s was used. This is about 3 times greater than the standard pump rate of 0.3 l/s on a continuous basis and allows for the fact that pumping would, on average, occur for one third of the time. Thus, pumping is intermittent and also at a greater rate than would be the case for continuous pumping. Close monitoring would be required, as it may be damaging to the freshwater lens in the long term.

Also, as days of low or virtually no effective insolation occur, it is necessary to provide standby power sources such as diesel motors for such occurrences. Alternatively, provision for additional water storage to satisfy demand during these periods should be made. From available records and information, the maximum period without sunshine is not more than 2 to 3 days and such occurrences are rare. They are normally associated with high rainfall periods.

The unit cost for such a system on Christmas Island is about \$0.47 per m^3 of water pumped. As with the wind pumping option, this system includes a back-up diesel motor for periods when solar radiation is inadequate to enable pumping.

(ii) <u>with storage batteries</u>

If batteries are incorporated in the system, electrical energy can be stored and used to provide continuous pumping from the lens galleries. This has the distinct advantage of having less effect on the lens behaviour, but has the disadvantage of higher capital costs and maintenance requirements. While a variety of different batteries are available, the ones most commonly used for solar powered installations are deep cycle lead-acid batteries.

To cost a solar powered pumping system using batteries, a period of three days without solar radiation was assumed. As mentioned before, this period is considered the maximum such period likely to occur. The battery capacity must be capable, therefore, of providing sufficient power for three days operation. In the battery system, less solar panels and smaller pumps and motors are required. Offsetting this to some extent is the cost of batteries. The unit cost for this system was determined to be \$0.53 per m^3 of water pumped on Christmas Island.

(c) AC motors

These systems use inverters to convert the DC output from the solar panels or photovoltaic arrays to AC. No batteries are incorporated in the presently available systems and, hence, pumping can only occur during sunlight hours. The unit costs of such a system is $0.44 per m^3 of water pumped which is slightly cheaper than the equivalent DC option. Most of the cost advantage is in the pump and motor units and solar panel mounting frames for the AC option.

4.5 Summary of Results

The cost comparisons of the various energy options for pumping water from freshwater lenses on Christmas Island are summarised below:

TABLE 1: COMPARISON OF UNIT PUMPING COSTS FOR ENERGY OPTIONS ($AUSTRALIAN PER CUBIC METRE OF WATER PUMPED: 1983 PRICES)

ENERGY OPTION	COST
. Diesel	0.63
. Wind-direct pumping	0.47
. Wind-generation of electricity	0.59
. solar-no batteries-DC pump	0.47
. Solar-no batteries-AC pump	0.44
. Solar-with batteries	0.53

On an economic basis alone, the solar pumping option using AC pumps and no storage batteries is the most appropriate. The direct wind pumping option is ranked second along with solar pumping using DC pumps. The possible disadvantage associated with intermittent pumping with the solar option would need to be ascertained using a trial scheme before it could be favoured before the more continuous wind pumping option. If this possible disadvantage is found to be minor then obviously the solar option would be the most favourable.

In the longer term as prices for solar panels are gradually dropping, the solar option will become even more cost competitive with the relatively fixed price of the wind pumping option.

5. COMPARISON OF WATER SUPPLY DEVELOPMENT OPTIONS

In addition to the study of groundwater lenses, other water supply development options were considered to determine which option was the most economical. The results for the Christmas Island study (Falkland, 1983) are tabulated below. The costs are based on the supply of 50 m^3 (50,000 litres) per day which is equivalent to 50 litres per person for a population of 1000 people.

TABLE 2: COMPARISON OF COSTS FOR WATER SUPPLY DEVELOPMENT OPTIONS, CHRISTMAS ISLAND ($AUSTRALIAN PER CUBIC METRE OF WATER SUPPLIED:1983 PRICES)

METHOD	COST
. Extraction gallery	3.72
. Desalination (conventional reverse osmosis plant)	6.41
. Solar still	4.27
. Rainwater collection	20.00*
. Importation (tug and barge)	9.31

Notes: (a) The above costs include capital, operating and maintenance and replacement costs. A discount rate of 10 percent was used.

(b) * indicates that the cost of rainwater collection systems exceeded $20.00 per m^3 of water supplied. Also, it was found that such systems would 'fail' (not provide water supply) more often than the others. This is directly related to the relatively low rainfall at Christmas Island.

From the above table, it can be seen that the extraction gallery option involving the development of groundwater resources is the cheapest option. A similar conclusion was reached in relation to a water resource study for Tarawa (DHC, 1982).

6. CONCLUSIONS

The studies of water resources on two coral atolls, some details of which are provided in this paper, indicate that the development of freshwater lenses is a more economic option than other available water supply methods. The use of renewable energy sources is seen to be a viable alternative to conventional energy sources for the provision of energy to pumping systems. A number of important design criteria have been outlined. Also, the various factors involved in designing extraction systems for the freshwater lenses have been discussed in some detail.

7. ACKNOWLEDGEMENTS

The work outlined above was carried out on behalf of the Australian Development Assistance Bureau (ADAB) by the Department of Housing and Construction (DHC) for the Government of the Republic of Kiribati. The author wishes to thank DHC for allowing the use of material prepared within the Department and ADAB for providing funds for attendance at the Workshop.

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(summarised version)

DESALINATION IN TONGA

Filipe F. Koloi B.E. (Civil) N.Z.
Manager-Engineer
TONGA WATER BOARD

Typical costs for desalination units are quoted around US$ 0.5 million or upwards, depending on quantity and quality of the produced water.

The Report is concerned with Reverse Osmosis and quotes a technical information leaflet from the Clearwater System Ltd. of Portsmouth, Guildford, United Kingdom.

"In a practical Reverse Osmosis System therefore a proportion of the feed water is allowed to flow along the membrane and then to waste. This flow is called the concentrate OR reject. The concentration of the salt in it depends upon the initial salt concentration and what proportion of the input water and salts pass through the membrane.

The salt passage is given by:

$$SP = \frac{CP}{Cf} \times 100 \qquad \ldots\ldots (1)$$

where SP = % salt passage
CP = salt concentration in the Product stream
Cf = salt concentration in the feed stream

The term salt rejection is often used and is simply (100 - SP).

The Recovery Y is given by:

$$Y = \frac{QP}{Qf} \times 100 \qquad \ldots\ldots (2)$$

where QP = Product water flow rate
Qf = feed water flow rate

The concentration factor is therefore given by:

$$Cf = \frac{\text{concentration in the concentrate}}{\text{concentration in the feed}}$$

$$= \frac{100 - (Y \times SP)}{100 - Y} \qquad \ldots\ldots (3)$$

To a first approximation two equations define the passage of water and salts through the Semi-permeable membrane:

$$QW = \frac{KW\ (P - \pi)\ A}{t} \qquad \ldots\ldots (4)$$

$$QS = \frac{KS.\ C.\ A.}{t} \qquad \ldots\ldots (5)$$

where Q = water or salt flow through the membrane
K = membrane permeability coefficient for water or salt
P = applied pressure
π = Osmotic Pressure differential
C = salt concentration differential
A = membrane area
t = membrane thickness

There are three main components of the system - pressure provided by a pump, a membrane and the solution (sea or brackish water). A membrane was purchased from Australia for US$ 1000 and the rest of the essential equipment assembled locally. At the time of the report preparation (July 1984), the unit had been operating successfully since November 1983 producing better quality water than the local well water. Output is some 400 gallons a day using a 3.5 HP diesel engine and 0.5 gallons of fuel daily.

Attempts are now underway to make the membrane in Tonga using a local Tongan cotton dried overnight in a copra drying shed (variable temperature) as the basic material. Water, acetic anhydride, acetic acid and sulphuric acid were subsequently added (in fixed volumes) to the cotton and shaken vigourously. When a viscous solution was obtained in which all the cotton fibres had been dissolved, concentrated hydrochloric acid was added and the product was precipitated in distilled water, washed and stabilised.

The resulting precipitate is dissolved in known volumes of hydrochloric acid, formamide, acetone and magnesium perchlorate. The mixture was well stirred and poured onto a glass plate which was then immersed in very cold water. The acetone vapourises and other solvents are leached leaving a film of cellulose acetate. The film was subsequently tested for salt water rejection ability under high pressure. The results demonstrate a similar performance both in salt and pathogen rejection as those made by Loeb and Sourirajan at University of California. Design construction proposed which should provide 50,000 gallons per day of 50 ppm output from 2,700 ppm brackish source and using 1.5 gallons of diesel daily. Estimated cost of plan is Tonga Dollars 60,000.

For further details of the design and operations process, those interested can apply to Mr Koloi in Tonga.

C.S.C. WORKSHOP ON WATER RESOURCES OF SMALL ISLANDS

2-9 july 1984 , SUVA , FIJI

HYDROGEOLOGICAL FACTS ABOUT DIKE AQUIFERS AND UNDERGROUND WATER CIRCULATION IN TAHITI

by Jacques A. GUILLEN *

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ABSTRACT

Hydrogeologists have demonstrated the existence and importance of groundwater resources of dike aquifers in OAHU (HAWAII) . Arguing about the geological similarities between the volcanism of TAHITI and OAHU , a drilling campaign was carried out between 1969 and 1972 in the dike zone of the FAUTAUA valley under the sponsorship of the city of PAPEETE , in order to provide an extra flow of gravity water for the urban area . 47 boreholes were drilled through 10 selected zones , 12 of which were developed to supply the city water mains .

Drilling logs and flow measurements have proved the insignificance of dikes in the control of large water bodies . Water-gushing is mainly in relation to joints or voids between lava flows .

A computation method is proposed to determine the recharge flow of aquifers using the recorded data (open flow measurement and closed flow pressure recording) .

Underground water circulation is mainly governed by high permeability along sequentially piled aquifers interconnected by open fractures and joints . Near the coast aquifers are under artesian conditions due to inter-lava beds weathered layers . The feet of large lava slopes are the most promising areas for developing underground water .

1 . INTRODUCTION

TAHITI is the main island of French Polynesia (Tahiti area = 1,000 km2) . It lies between lat.17°30' and 17°55' S and long. 149°05' and 149°40' W, in the tropical zone of the southern Pacific (Fig.1) . Tropical oceanic conditions prevail with an average temperature of 26°C at sea level and a high air moisture content . Rainfall varies greatly according to altitude and exposure to eastern tradewinds . Average is about 2m along the leeward shore and may reach 8m near the crest of the ranges where moist tradewind air is orographically lifted (max. altitude is 2240m) .
Distinction is made between a dry and cool season from May to November and a warm and humid season from December to April .

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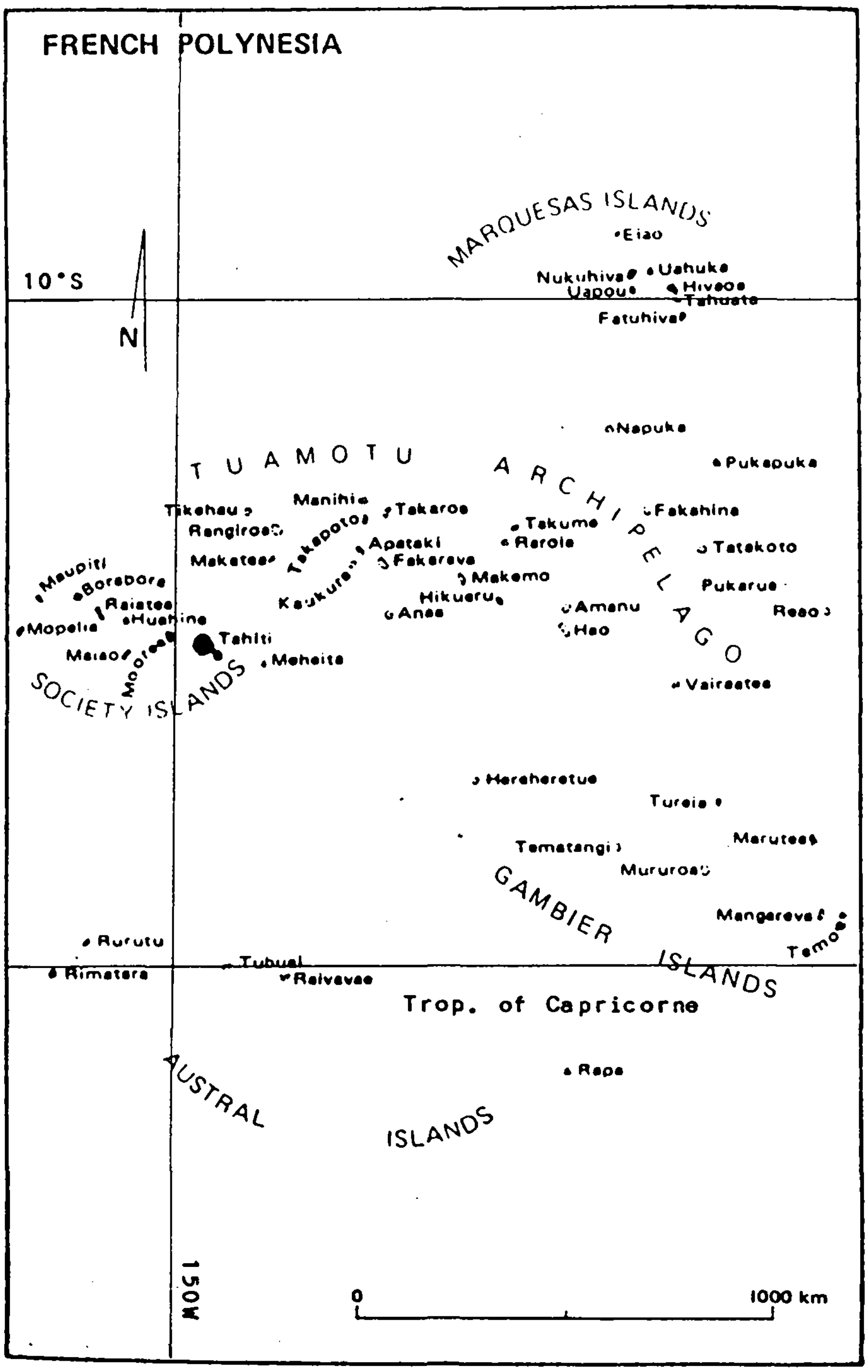
FRENCH POLYNESIA
MARQUESAS ISLANDS
Eiao
Nukuhiva
Uahuka
Uapou
Hivaoa
Tahuata
Fatuhiva
10°S
N
Napuka
Pukapuka
TUAMOTU ARCHIPELAGO
Tikehau
Manihi
Takaroa
Rangiroa
Takume
Fakahina
Takapoto
Apataki
Raroia
Tatakoto
Makatea
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Anaa
Amanu
Reao
Mopelia
Huahine
Tahiti
Hao
Maiao
Moorea
Meheita
SOCIETY ISLANDS
Vairaatea
Hereheretue
Tureia
Tematangi
Maruteas
Mururoa
GAMBIER ISLANDS
Mangareva
Rurutu
Temoe
Rimatara
Tubuai
Raivavae
Trop. of Capricorne
Rapa
AUSTRAL ISLANDS
150W
0
1000 km

Fig. 1

The island is composed of the emersed remnants of two main volcanic systems joined together and stretching along a NW-SE direction for a distance of 60 km. They are hawaian type shield volcanoes , formed by a thick piling of basaltic lava flows (the highest point of the island is 7,000 m above the ocean floor) .
The structure of the emersed part of the island displays two low cones, incised by deep radial L-profiled valleys which delimit gently sloped lava tables (6° to 10°).
Around the island, a coastal plain is bordered by a lagoon separated from the ocean by a more or less continuous reef .
A network of faults oriented E.NE /S.SW or N.NE / S.SW cuts through the volcanic formations . Along the fault system, a dike complex can be observed . The dikes are forby a microcristalline lava, generally less permeable than the lava flows they intersect .

Some hydrogeologists (1) have conjectured that dike aquifers may exist in a similar way as those found on the island of OAHU (HAWAII) where they play a major role in retaining water . In the "marginal zone of dikes" where spacing of dikes allows for the storage of water, galleries driven through these dikes have been able to provide a lot of water . The main advantage of such an exploitation is to provide gravity water of excellent quality .
It has been noticed that the volcanoes of OAHU and TAHITI present several similar geological features :
- hawaian type of volcanic activity
- same age of volcanic systems
- same kind of lava flows
- existence of dikes
However, the rainfall is 4 or 5 times higher in TAHITI than in OAHU and recharge of dike aquifers may seem much better there .

With the aim of providing water by gravity flow for the rapidly growing urban area of PAPEETE, the valley of FAUTAUA was first selected to carry out a survey on dike aquifers and to begin extensive exploitation .

2 . INVESTIGATIONS IN THE VALLEY OF FAUTAUA

2.1. Geological survey

A preliminary survey of dikes (orientation,dip) was carried out inside the marginal zone of dikes . The direction of vertical dikes is more or less radial, i.e. almost parallel to the valley axis . The direction of drillings is perpendicular to the direction of dikes, i.e. almost at right angles to the valley sides .

2.2. Drillings (3) Fig. 2 and 3

The horizontal drilling campaign was carried out from sept. 1969 to dec.1972. Three types of boreholes were drilled :
- 22 survey drillings (R) , by means of a small drilling machine (Winkie GW 10) with AX and BX diameters (35 and 45 mm), and lengths up to 50m . The purpose of such drillings was to determine the thickness of outcropping dikes and to give a preliminary indication for the location of future deep boreholes .
- 13 test drillings (T) , by means of a CRAELIUS XCH 60 machine with a maximum diameter of 6" for depths up to 300 m . The purpose of T drillings was to determine deep dike aquifers for exploitation and allow for the setting of recording pressure gauges.
- 12 exploitation drillings (E) , by means of a heavy machine (CRAELIUS XH 90 or LONGYEAR 44) with a maximum diameter of 8" for depths up to 400 m . These drillings were made after T drillings had demonstrated the existence of productive aquifers .

The main results obtained from T and E boreholes are displayed in Fig.4 & 5.

FAUTAUA DRAINAGE BASIN

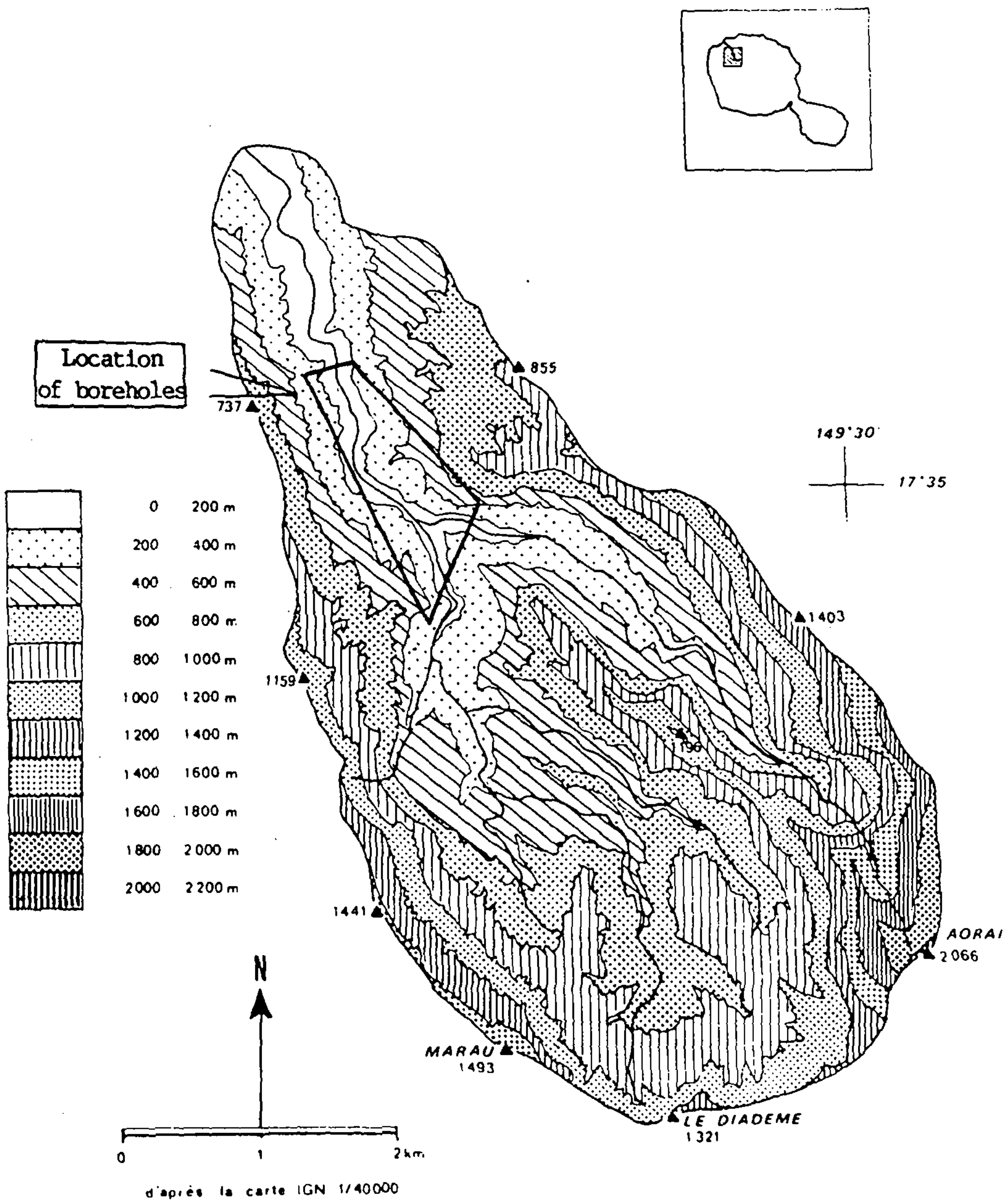

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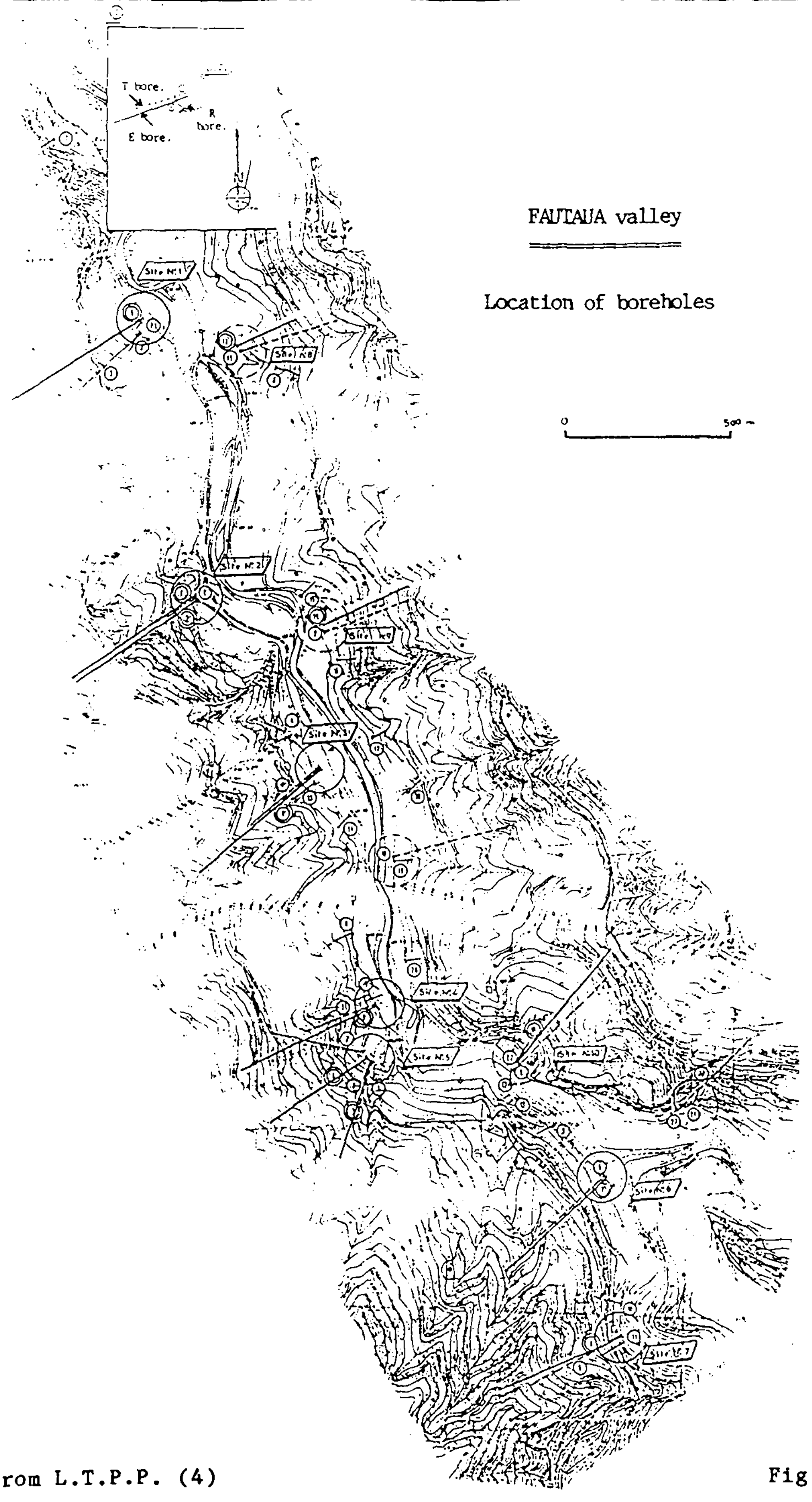
Fig. 2



from L.T.P.P. (4)

Fig. 3

Fig. 4 . T Boreholes

Borehole n°	River Bank	Elev. (m)	Orient d°/N	Depth (m)	Ø (mm)	Casing (m)	Depth of first water gushing (m)	Max. outflow (l/s)	Outflow after compl. (l/s)	Specific Outflow of prod. zone (l/s/m)	Number of water gushing	Nb of water leakage	Nb of dikes with water	Total nb of dikes
T0	Left	118.82	226	110.00	220/95	2.50	1.70	77	50	0.46	Sev.	Sev.	2	2
T1	"	167.48	187	212.20	165/75	3.00	6.00	29	29	0.14	16	0	2	4
T2	"	167.71	273	239.00	195/75	-	41.60	15	15	0.08	7	0	0	3
T3	"	114.00	227	210.00	165/75	17.70	31.50	24	23.2	0.13	6	3	0	4
T4	"	131.22	230	201.00	165/75	43.30	43.60	34.4	17	0.11	11	8	3	6
T5	"	175.00	216	211.00	145/75	26.00	129.50	70.80	50	0.39	5	3	1	9
T6	"	193.00	228	253.25	145/85	19.20	103.50	20	18	0.13	9	2	1	7
T7	"	144.00	239	258.45	145/65	25.00	68.30	32	32	0.17	8	3	2	5
T8	right	150.00	35	296.30	145/75	24.50	32.25	37	37	0.14	LI	LI	LI	LI
T9	"	110.00	60	218.80	145/75	-	108.30	11	10.4	0.10	LI	LI	LI	LI
T10	"	150.00	65	289.80	145/75	32.60	117.60	30	30	0.17	LI	LI	LI	LI
T11	"	87.00	60	236.35	145/75	-	26.20	60	58	0.28	LI	LI	LI	LI
T12	"	208.00	35	249.50	145/75	-	122.10	10	10	0.08	LI	LI	LI	LI

LI = Lost information

Fig. 5 . E Boreholes

Borehole n°	River Bank	Elev. (m)	Orient. d°/N	Depth (m)	Ø (mm)	Casing (m)	Depth of first water gushing (m)	Max. outflow (l/s)	Outflow after completion (l/s)	Specific outflow of prod.zone (l/s/m)	Number of water gushing	Nb of water leakage	Nb of dikes inter water	Total number of dikes
E1	Left	118.84	226	350.00	220/95	127.70	3.00	85.5	47.7	0.14	23	2	3	5
E2	"	118.81	226	350.00	220/95	81.00	3.00	61	28	0.18	12	2	0	0
E3	"	167.53	187	251.10	220/75	14.40	86.00	80	80	0.48	12	1	1	3
E4	"	167.77	227	273.15	220/85	19.00	97.90	106	106	0.60	11	1	1	3
E5	"	99.44	215	374.30	220/75	20.00	106.00	42	38	0.14	12	6	0	7
E6	"	136	230	386.50	220/95	39.15	90.00	56	52.5	0.18	16	1	3	16
E7	"	169	220	336.00	220/101	30.00	127.60	55	17	0.06	10	6	2	17
E8	"	193	228.30	306.00	220/85	30.75	37.80	15	15	0.08	11	7	1	7
E9	"	144	235	357.80	220/85	15.30	70.40	88	88	0.31	LI	LI	LI	LI
E10	Right	150	30	356.30	220/145	-	52.50	37	37	0.12	LI	LI	LI	LI
E11	"	LI	LI	243.60	220/145	17.00	LI	5	5		LI	7	3	LI
E12	"	LI	LI	176.50	220/145	17.00	LI	42	38		LI	11	3	LI

LI = Lost information

3 . RESULTS OF INVESTIGATION

3.1 Geology

Each horizontal drilling bears witness to the great heterogeneity of coring as a result of the dip of lava flows (10 to 15°) . The main rock formations consist of :
- dense basalt usually moderatly to poorly permeable with the exception of vacuolar beds
- clinker beds most often weathered and thus poorly permeable
- breccia
- fine grained dike basaltic lavas

Features that most contribute to high permeability are voids between lava flow surfaces along with joints and fractures . All the lava beds are more or less weathered and contain secondary mineralizations (zeolites) . Homogeneous cores are usually less than 5 m . Thickness of dikes varies from a few centimeters up to 4 or 5 m . Several boreholes didn't cross any dike .

3.2 Hydrogeology

Results of boreholes lead to the following conclusions :
- water-gushing related with certainty to dikes represented no more than 10% of the total while 90% was not dike related .
- water-gushing appeared to occur mainly in relation to joints or voids in lavas or between lava flows .
- the average flow of water-gushings was 5 l/s .
- total cutflow of water was variable while the drillings were in progress . Usually it increased but sometimes it decreased rapidly due to water losses through highly permeable beds .
- average specific discharge from productive zones through T and E boreholes was 0.20 l/s/m with a standard deviation of 0.15 l/s/m .

The above values for flow rate were encountered whether or not dikes were intersected.

4 . MEASUREMENT DATA

Two kinds of data were recorded for T and E boreholes :
- total discharge out of E boreholes during the work phase and after drilling was completed .
- water pressure at the head of T boreholes after corresponding E boreholes had been closed up .

4.1. Discharge

Outflow was recorded for E boreholes :
- while the drilling was in progress to measure discharge out of every productive intersected zone .
- after the drilling was completed to record total discharge during the flow recession period

4.2. Pressure

Water pressure was recorded at the head of casings driven through T boreholes for several meters . Few pressure recordings were made during the open flow of E boreholes . After E boreholes were closed , water pressure was permanently recorded during variable periods of time by means of MAXANT pressure recording gauges .

The following chart displays significant values taken from the recording diagrams.

T borehole	Corresponding E borehole	Maximum waterhead (m)	Steady waterhead (m)
T0	E1,E2	15 & 30	12.5
T1	E3,E4	80	75
T2	E9	70	70
T3	E5	0	0
T4	E6	10	25
T5	E7	70	70
T6	E8	46	45
T7	E9	65	62.5
T8	E10	67.5	20
T9	E11	4.5	4.5
T10		12.5	1.5
T11	E12	30	15
T12		10	6

We noticed that :

- water head varied greatly from one borehole to another
- maximum water heads were low, the highest value being no more than 80 m
- when E taps were opened and closed shortly there after, water head increased rapidly. This means that aquifer inertia is low, as is the potentiality of such aquifers.

4.3. Rainfall records. River gaging stations (fig. 6)

The drainage basin of the FAUTAUA Riv. was equiped with :

- 1 monthly rainfall recorder SIAP (1000 cm^2)
- 1 weekly rainfall recorder SIAP (1000 cm^2)
- 1 weekly rainfall recorder CERF (400 cm^2)
- 3 rain gauges (400 cm^2)
- 1 gaging station equiped with a water level recorder (OTT).

4.4. Interpretation of results (4)

One of the problems of water management is the balancing of supply and demand. The following organigram (fig. 7) displays the method used in order to determine the average recharge flow of aquifers using all the recorded data. It allows for the determination of storage to be depleted by development in an average year.

The organigram is divided into 2 sections :

- the one on the left concerns outflow data during the open flow period
- the one on the right concerns water pressure data during the closed flow period.

During these 2 periods, rainfall was also recorded.

4.4.1. Open flow calculations

The flow recession from a water reservoir can be represented by the equation

FAUTAUA DRAINAGE BASIN

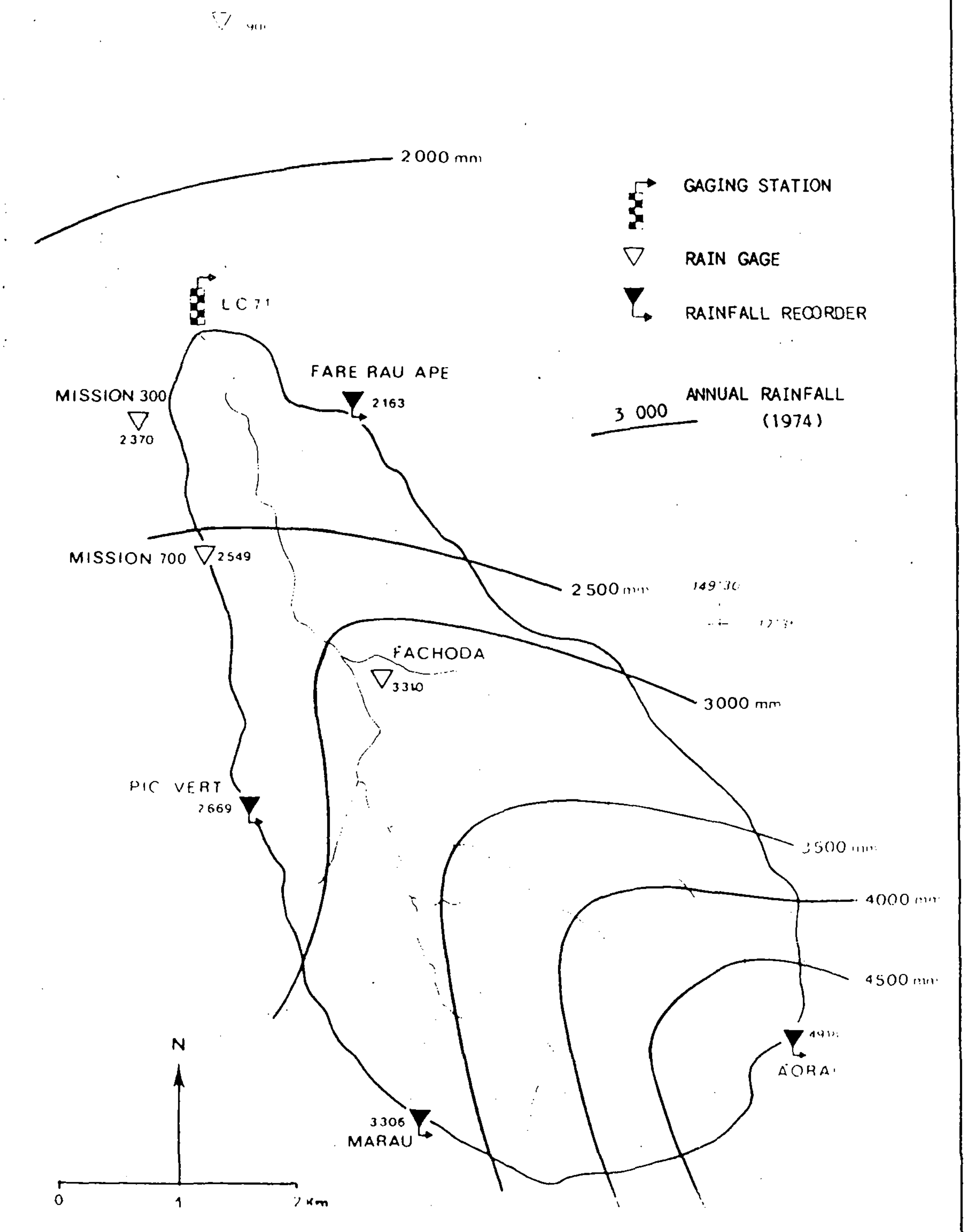


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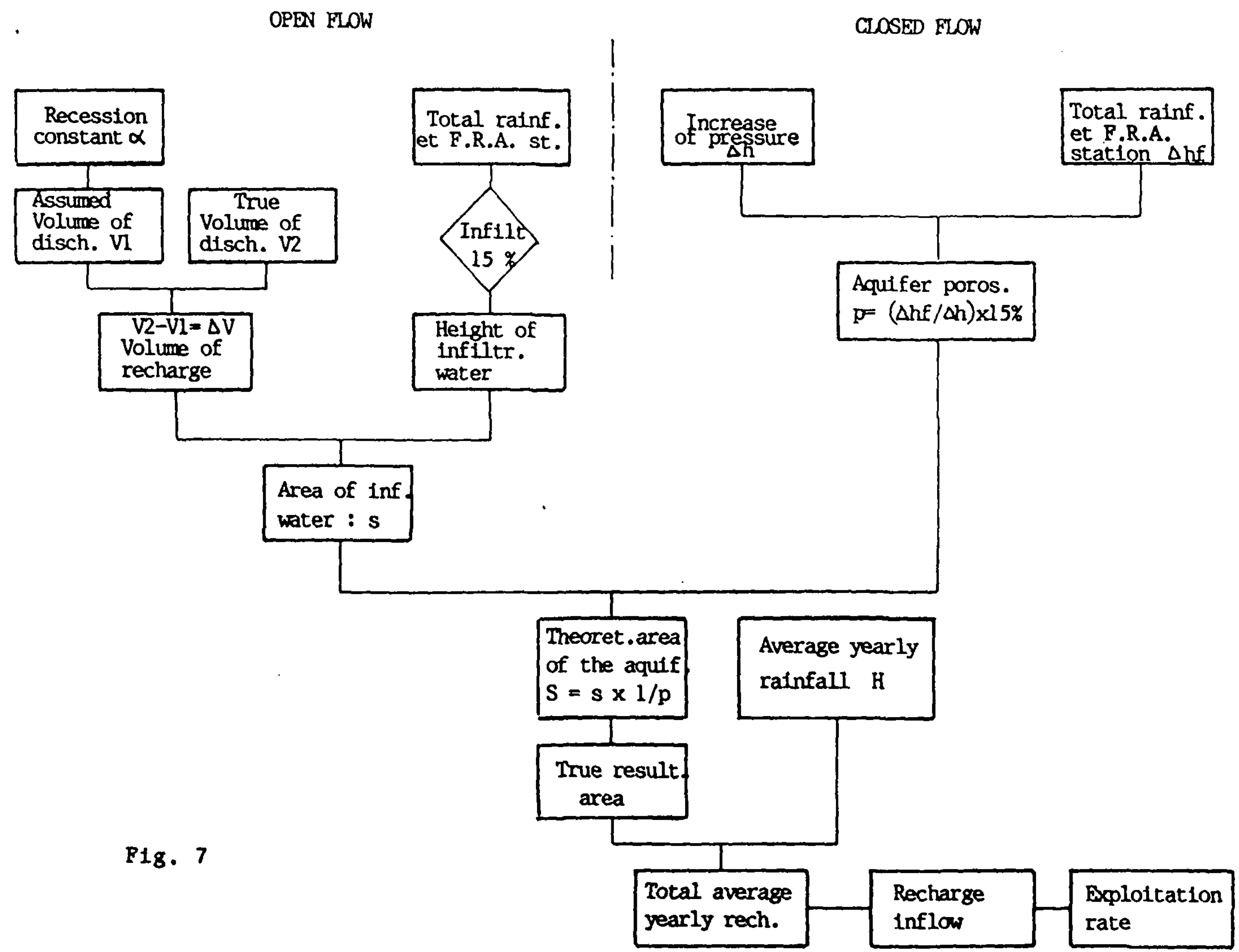
Fig. 6



OPEN FLOW
CLOSED FLOW
Recession constant α
Total rainf. et F.R.A. st.
Increase of pressure Δh
Total rainf. et F.R.A. station Δhf
Assumed Volume of disch. V1
True Volume of disch. V2
Infilt 15 %
V2-V1= ΔV Volume of recharge
Height of infiltr. water
Aquifer poros. p= (Δhf/Δh)x15%
Area of inf. water : s
Theoret.area of the aquif. S = s x 1/p
Average yearly rainfall H
True result. area
Total average yearly rech.
Recharge inflow
Exploitation rate

Fig. 7

$$Qt = Qo\ e^{-\alpha t}$$

Where Qt = discharge at any time, t
Qo = discharge at some initial time, to
t = time
α = recession constant

The recession constant α , determined during a period with little or no rainfall, allows for the determination of final discharge Qf, designated "assumed discharge", from Qo.

The assumed volume of water discharged is obtained by integrating the recession curve during the period of steadily declining discharge.

$$V1 = \int_p Qo\ e^{-\alpha t}\ dt = \frac{Qo\ e^{-\alpha t}}{-\alpha} + C$$

At initial time (t = o) $\frac{Qo}{-\alpha} + C = o$ so $C = \frac{Qo}{\alpha}$

$$V1 = \frac{Qo\ e^{-\alpha t}}{-\alpha} + \frac{Qo}{\alpha} \quad \text{and} \quad V1 = \frac{Qo - Qt}{\alpha}$$

If we consider the volume V2 of water discharged at the same time,
$\Delta V = V2 - V1$ is the restored volume.
If we know the height of infiltrated rainfall during the same period of time, we are able to determine the area of water stored corresponding to a reservoir of 100 % porosity.
Valus of α determined during little or no rain periods are the followings :

Bore-hole n°	River side	α	Recording period	Initial discharge Qo l/s	Depleted volume V1 (10^3 m^3)
E1	Left	0.005267	12/02 to 12/10/71	85	1,300
E2	"	0.002392	18/02 to 25/10/71	70	1,080
E3	"	0.001100	01/03 to 24/10/71	80	3,320
E4	"	0.00135	25/05 to 24/10/71	100	3,300
E5	"	0.00269	19/05 to 26/10/70	35	685
E6	"	0.00230	14/06 to 11/11/71	50	770
E7	"	0.000960	11/10 to 02/12/71	14	90
E8	"	-	unsignificant	-	
E9	"	-	"	-	
E10	Right	0.01482	25/07 to 29/08/72	37	8.580
E11	"	0.01393	25/01 to 22/03/72	5	28.676
E12	"	0.00253	20/05 to 29/09/73	38	1.024

4.4.2. Closed flow calculations

T boreholes were equiped with recording pressure gauges in order to follow the change in water pressure inside aquifers exploited by corresponding E boreholes.

Using variation curves of pressure versus time, we are able to determine the increase of waterhead ΔH from the time the flow is interrupted to an assumed stabilization. If we have an estimation of the increase of rain water infiltrated at the same time, we can deduce the value of the aquifer porosity p , as $p = \Delta hf / \Delta H$

4.4.3. Synthetical computations

We can compute the assumed area of the aquifer for each borehole by dividing the assumed area of the water table by the porosity p.
Thus we obtain for each borehole the area of infiltrated rainfall. However as the aquifers are more or less interconnected, there is a resulting zone of infiltration which envelopes all the areas. Each one may be considered as a hemicircle. If the average yearly rainfall is measured we can infer the average yearly recharge and therefore the exploitation rate for each borehole.

The following chart (fig. 8) summarize the main results of these computations and infers the allowed discharge rate for each exploitation borehole.

However, the following limiting remarks upon assumptions can be made :

- Rainfall : The rainfall station selected has the longest recording period. However, rainfall varies greatly according to the direction of drainage basins and even within the basin itself.

- Recession constant

α has been computed over a period of supposed no rainfall. Absolutely dry sequences do not exist because a more or less steady rain falls on the upper reaches of the valley; thus the computation method gives an underestimation of recharge.

- Infiltration rate

A uniform 15 % infiltration rate has been considered. It is a rough estimation ; no direct measurement of infiltration rate is avalaible for Tahiti.

- Water head measurement

Pressure gauges were fitted at the head of T boreholes. The measured pressure is the resultant pressure of all the aquifers near the valley slope. However, the depth of T boreholes is less than that of corresponding E boreholes, we can assume that measured water figures are lower than would be expected - thus, the method gives an underestimation of computed porosity.

- Resultant area

The assumption of a hemicircular drainage area around a borehole has no true hydrogeological meaning. It represents an extension of the classical circular influence area around a pumping well.

Borehole n°	Assumed volume V1 (10^3 m^3)	Outflow volume V2 (10^3 m^3)	V=V2-V1 (10^3 m^3)	Rainfall during open flow period (m)	15 % Infilt. rate during open flow period (m)	Assumed water area 10^3 m^2)	Porosity % $\frac{hf}{H}$ x 15 %	Aquifer area S (10^3 m^2)	Exploitation rate (1/s)
E1	1300	1600	300	6	0.9	334	0.07	4770	17
E2	1080	2400	1320	5.65	0.85	1553	0.37	4200	15
E3	3320	3900	580	3.14	0.47	1234	0.25	4936	18
E4	3300	4200	900	3.14	0.47	1915	0.25	7660	27
E5	685	760	75	2	0.30	250	Indet.	Indet.	1.8
E6	770	850	80	1.1	0.165	485	0.69	705	2.5
E7	90	105	15	0.8	0.12	125	0.35	355	1.3
E8	non signif.	41.5	41.5	0.6	0.09	460	0.05	9580	34
E9	non signif.	250	250	0.52	0.075	3340	0.53	6325	22
E10	8.6	8.6	0	0.04	0.006	indet.	0.11	indet.	0
E11	28.67	28.7	0.03	1	0.15	160	2.07	78	0
E12	1024	1250	226	3.3	0.5	452	2.63	172	1.4

Fig. 8

According to the resultant computed drainage area influenced by the boreholes, the yearly average recharge during the period considered is 160 l/s, i.e. very close to the figure of measured discharge at the same time (170 l/s).

As a result we concluded :

- the assumptions made were rather realistic
- the inertia of aquifers is low which confirms the concluding remarks made concerning the rapidly changing water pressure .

4.5. Water quality

Chemical analysis of water depleted was systematically carried out during the drilling works and after completion of boreholes during the open flow period. Results of analysis are very constant ; differences appear to be related to sample processing.
The following average values can be considered :

pH : 7.9	Silicium : 9.5 ppm
TH : 5.8 d°F	Iron : 0.3 to 0.6 ppm
TA : o d°F	Ammonic : o ppm
TAC : 8.5 d°F	Organic matter : < 0.5 ppm
Chloride : 2.5 d°F	Suspended matter : < 0.2 ppm
Co2 : 4 to 17 ppm	Total dissolved solids : 158 ppm
Nitrite : < 0.1 ppm	

Analysis also show a very low mineralization and the water is free of any bacterial contamination.

5. SURVEY OF DIKES AQUIFERS IN THE VALLEY OF TIPAERUI

The valley of TIPAERUI is another radial valley in the urban area of PAPEETE. Geological conditions are the same as those encountered in the valley of FAUTAUA : Thick series of basaltic lava flows (orientation N150°, dip 10°) and vertical dikes oriented N140° i.e. almost parallel to the valley slopes.

Two horizontal drillings were driven through assumed productive zones. Boreholes characteristics and results are as follows.

Borehole	Elevation (m)	Orientation d°/Nm	Depth (m)	Ø (m)	Total outflow l/s
Tipaerui 1	220	40°	280	195/115	ε
Tipaerui 2	140	31°5	347.20	195/115	0

Although geological features may have appeared in favor of the existence of dike aquifers, the two boreholes were dry.
In both boreholes a permanent water leakage was noticed during the drilling work.

6. CONCLUSIONS

The following main points can be deduced from the FAUTAUA exploration :

- water gushing is almost independant from dikes. It is found in connection with particular types of rock formation such as fractured lava beds or open surfaces between lava flows. Several drillings which intersected dikes were dry whereas others which did not were procutive.
- water head measurements are generally low and the figures are far less that the altitude of perched springs which are supposed to represent the overflow of dike aquifers-
- the specific discharge of E and T boreholes is 0.14 l/s/m (compared to their total length). The specific flow of the Fautaua river is 0.15 l/s/m, i.e. a figure of the same level.
- total exploitation rate for the 12 E boreholes has been estimated to be 140 l/s, according to the results of the above computation, i.e. a specific discharge rate of 0.04 l/s/m.

By comparison, the specific discharge rate of the WAIHEE tunnel (KOOLAU Range-OAHU) is 1.33 l/s/m i.e. 33 times greater after only 2 dikes were penetrated. (2)
- after 10 years of exploitation, total discharge from E boreholes has decreased to 95 l/s i.e. only 68 % of the expected outflow.

The most productive boreholes are E3, E4 and E9 which deliver about 20 l/s each.

What can be concluded from these results ?

First of all it must be pointed out that the drilling work took place more than 15 years ago. It was part of a general hydrogeoligical survey of Tahiti and, at the time, the preliminary conclusions of the survey were in favor of the exploitation of dike aquifers.

Since that time, several geological surveys and drilling projects have allowed for a better knowledge of underground water in Tahiti. We have now been able to confirm the high permeability of lava flows and the increase of such a permeability in the outer parts of the volcanic systems. On the other hand, thick piling of lava beds of different permeability creates a vertical heterogeneity of levels of more or less easy flow.

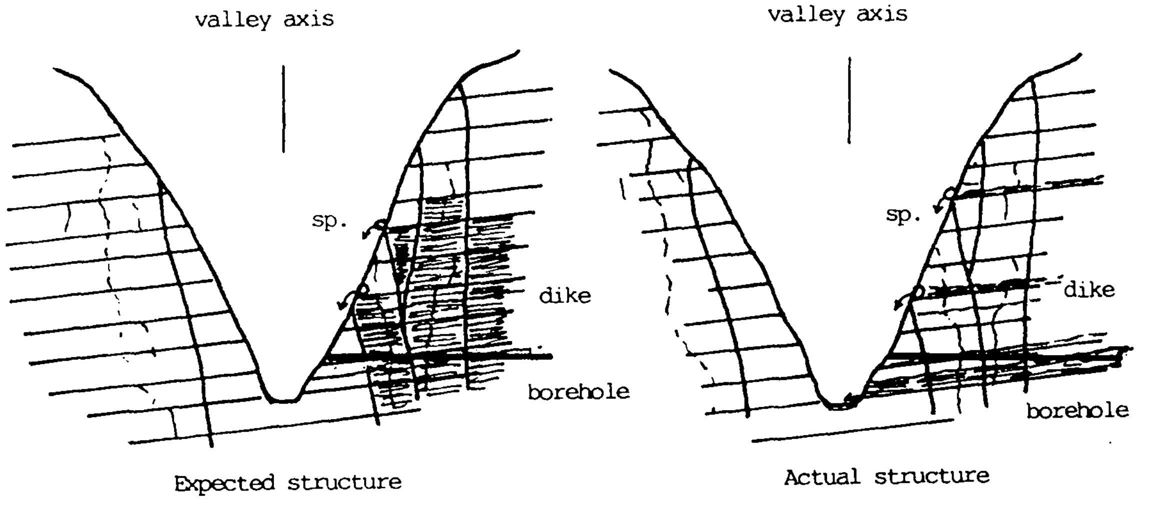
Such piled aquifers are interconnected by open fractures and joint networks, but permeability in the flow direction, Kh, is much higher than the one at right angles, Kv, and allows for the existence of aquifer levels. $Kh \gg Kv$ through voids between lava beds and creates a sort of plane aquifer.

Flat radial valleys cut deeply through lava beds and play a major role in the drainage of volcanic series as they successively intersect the aquifers whose dip is steeper than the valley profile.

Such a regular drainage is obvious when measuring base flow upstream - downstream ward during the dry season, i.e. when runoff is non existant. Base flow measurements show a steady increase along the stream direction, i.e. when the different aquifers are intersected. No high gain in discharge is noticed as it is noticed in OAHU as rivers cross the marginal zone of dikes.

Unlike OAHU, where dikes are at right angle to the direction of the rivers, the dikes of FAUTAUA valley are parallel to the river. Such a feature is not in favor of a retardation of flow along the drainage direction.

As the direction of lava flows is oblique to the valley axis, horizontal drillings successively intersect levels of different permeability : some of them are water-bearing structures, others are dry or create leakage. Horizontal boreholes play the same role as the valley itself and identical specific discharges in both cases just confirm the point : the valley is a sort of "horizontal drilling" in the open air.



The general picture of groundwater movement in Tahiti is ruled by a stratification of aquifers more or less interconnected. On the upper reaches of the valleys, almost persistant rainfall creates perched water bodies at the origin of waterfalls. Water percolates through joints and provides for base flow of rivers through highly permeable lava beds.

Near the shore, lava beds are less dense and more weathered. The reduction of permeability due to weathering allows for the existence of artesian water. Water development is most promising in this area where ground water flow is high.

At present, several pumping stations have been installed for the exploitation of basal water near the shore, at the foot of large lava slopes. The altitude of water level is low : it ranges from 2 to 3 m.

Specific yield of the vertical boreholes which intersect aquifers about 30 m below sea level is high, or about 10 l/s per cm of drawdown. Many high discharge springs can be seen along the coast all around the island. They represent the normal outflow of basal water.

7. ACKNOWLEDGMENTS

The investigations discussed in the paper were undertaken by the Laboratoire des Travaux Publics de Polynésie on behalf of the city of Papeete. The author wishes to thank both of them for agreeing to presentation of the paper.

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OPTIMIZATION OF RAINFALL STORAGE FACILITIES

by Jean SILVESTRO * and Jacques A.GUILLEN **

ABSTRACT

In the atolls of the TUAMOTU archipelago, the collection and storage of rainwater is usually carried out under poor conditions .
To the numerous problems of faulty maintenance of roofs and gutters and of dirty, unprotected cisterns built out of poorly - adapted materials, can be added the important factor of inadequate dimensioning of the cisterns . In general, their volume is too small to meet consumption needs . Certain households dispose of only a few hundred liters in reserve, stocked in discarded fuel drums . Only rarely does one encounter cisterns whose volume is greater than the roofing run-off capacity.

This report describes a simple method for the rational calculation of dimensions for rainwater collection and storage facilities as a function of rainfall measurement data . The method is illustrated by an example utilised for the atolls of the western part of the TUAMOTU archipelago .

1 . PRINCIPLE OF METHOD USED

This method was developed with the aid of a micro computer, type TRS-80 . Knowledge of significant daily pluviometric data (i.e. covering a maximum of years) is necessary .

The method consists of simulating the evolvement of water level in a cistern by using data on : roofing surface area, consumption, volume of storage, and daily rainfall . The level of satisfaction is then deduced, that is the ratio of the number of days that consumption is assured to the number of days in the year .

On varying the ensemble of these parameters, the year with the most unfavorable rainfall condition can be determined along with the values for roof area-consumption-level of satisfaction linked to the pluviometric data .

1 . 1 Basic program

Let the following symbols represent :
- household roofing area : S
- " cistern volume : V
- " daily consumption : C
- daily rainfall measurement for one year : Pj

1.1.1 Effective measured rainfall

For convenience, it is assumed that the measured rainfall for day "j" fall only

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once at midnight of the day considered, since only total daily rainfall is measured . Certain installations include a by-pass device to deviate the initial rainfall which has served to "clear off" the roof . This requires eliminating a certain height of water which is designated as "NE" .
The yield of installations is never perfect because of leaks . This yield is designated as "R" . Thus, the effective measures rainfall is equal to : R (Pj - NE) , accepting by convention that Pj - NE = 0 if Pj $<$ NE .

1.1.2. Results for a day

If the volume of water in the cistern at midnight on day "j" is designated "Vj", the two possibilities arise :
- either Vj $<$ C , where the desired consumption can not be assured up to day j+1 and :
  Vj+1 = R (Pj+1 - NE) S
- or Vj $\geqslant$ C , where the desired consumption is assured up to day j+1 and :
  Vj+1 = Vj + R (Pj+1 - NE) S - C

The value for Vj+1 is then deduced . The maximum stockable volume of water is V i.e. the volume of the cistern . Thus , if the calculation of Vj+1 $>$ V then Vj+1 = V .

1.1.3. Results for a year

Let N be the number of days in the year . The number of days in the year when consumption is not assured is counted assuming a hypothetical situation where the pluviometric year under consideration repeats itself indefinitely . This amounts to letting the program run until VN remains the same . If the number of days when there is water is designated as "I" and the level of satisfaction as NS, then :

$$NS = 100 \times I / N$$

Thus the chart for calculation is deduced (fig. 1) .

1 . 2 The search for a representative rainfall metering station

This situation does not arise when a pluviometric station already exists in the location under consideration . However if one does not exist, or if it is desirable to cover an entire region, it is necessary to proceed to a collection of all pluviometric data available in order to find the most representative . When in doubt, of course, the least favorable is selected .

1 . 3 Selection of the year with the most unfavorable measured rainfall

Let Pi (i=1 to n) represent the annual n values of known effective measured rainfall , then :

$$Pi = \sum_{j=1}^{N} R (Pij - NE)$$

If "C" represents daily consumption, the minimum roofing area necessary to insure a level of satisfaction of 100% can be deduced :

$$S = Pi / (N \times C)$$

If Pk represents the least of the Pi, then the minimum roofing area necessary for a given consumption rate can be determined by :

$$Sm = Pk / (N \times C)$$

Volume - level of satisfaction curves are then plotted for Sm and C and for all pluviometric years :

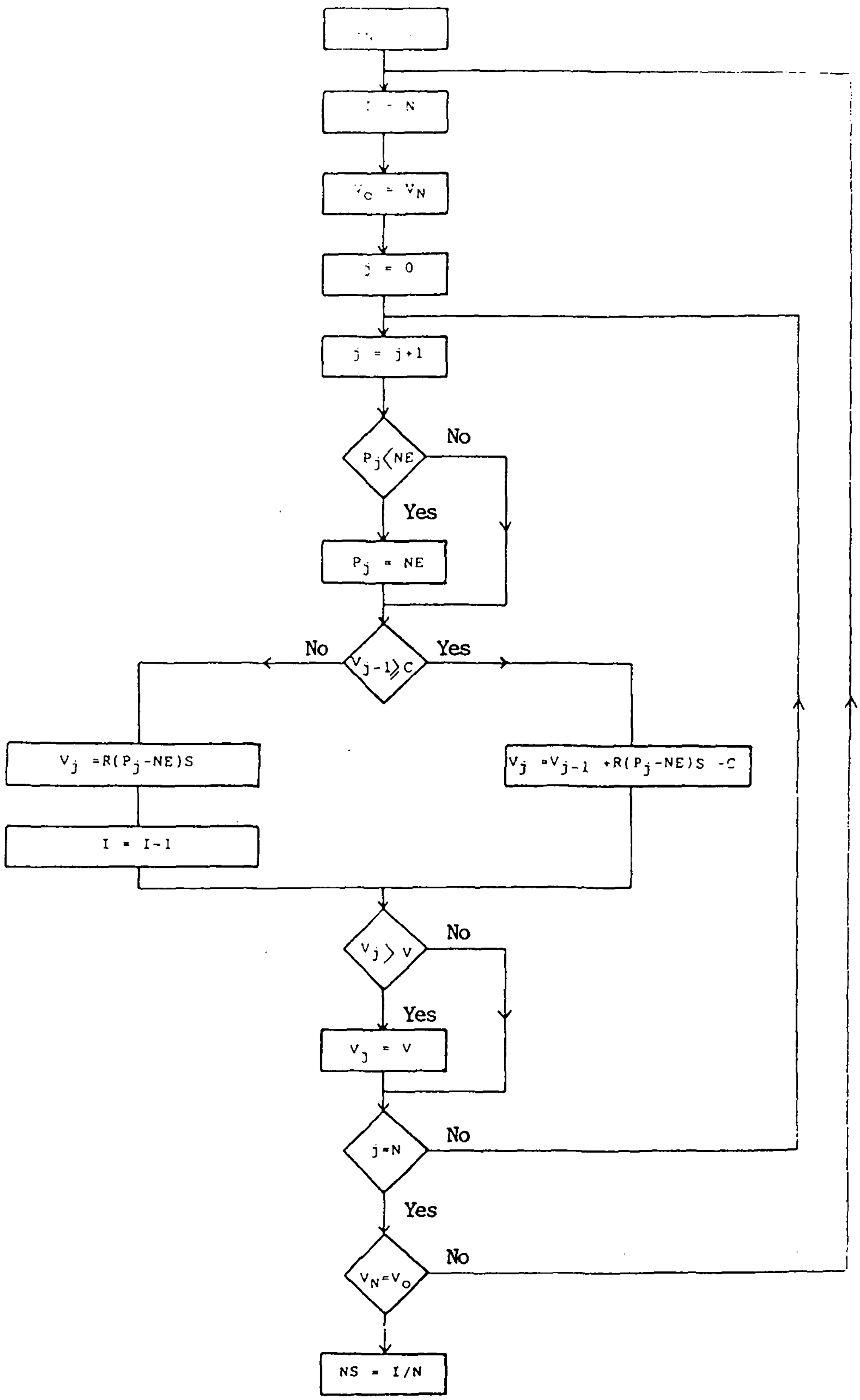
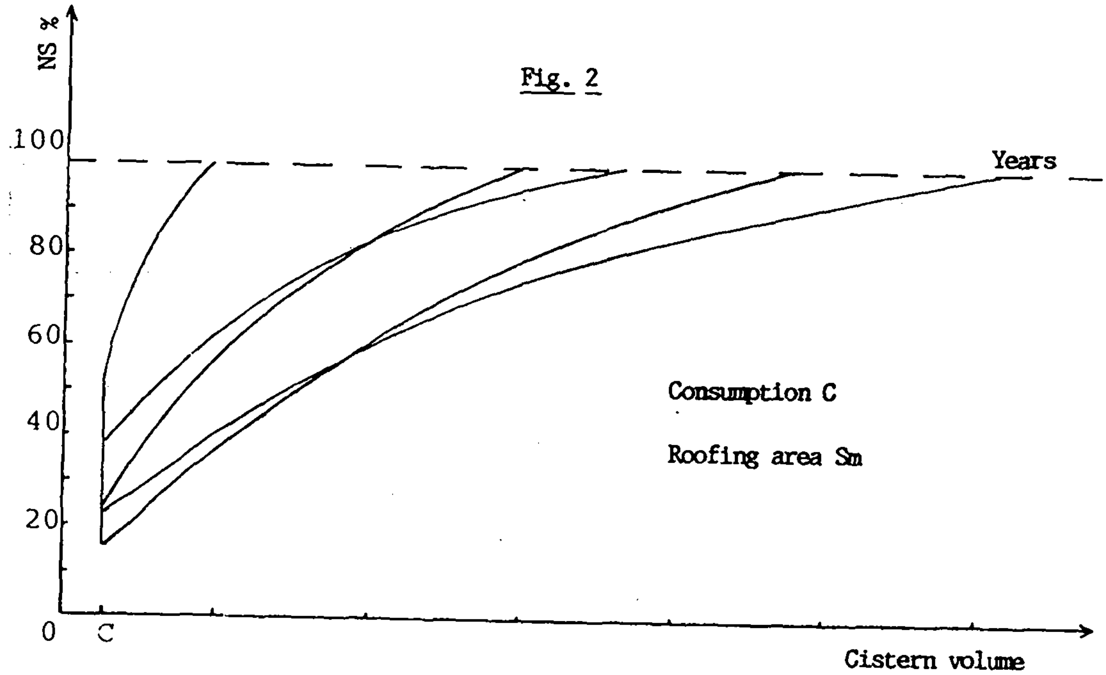


Fig. 1 CHART OF CALCULATIONS

A set of curves is then deduced (fig 2)

Fig. 2

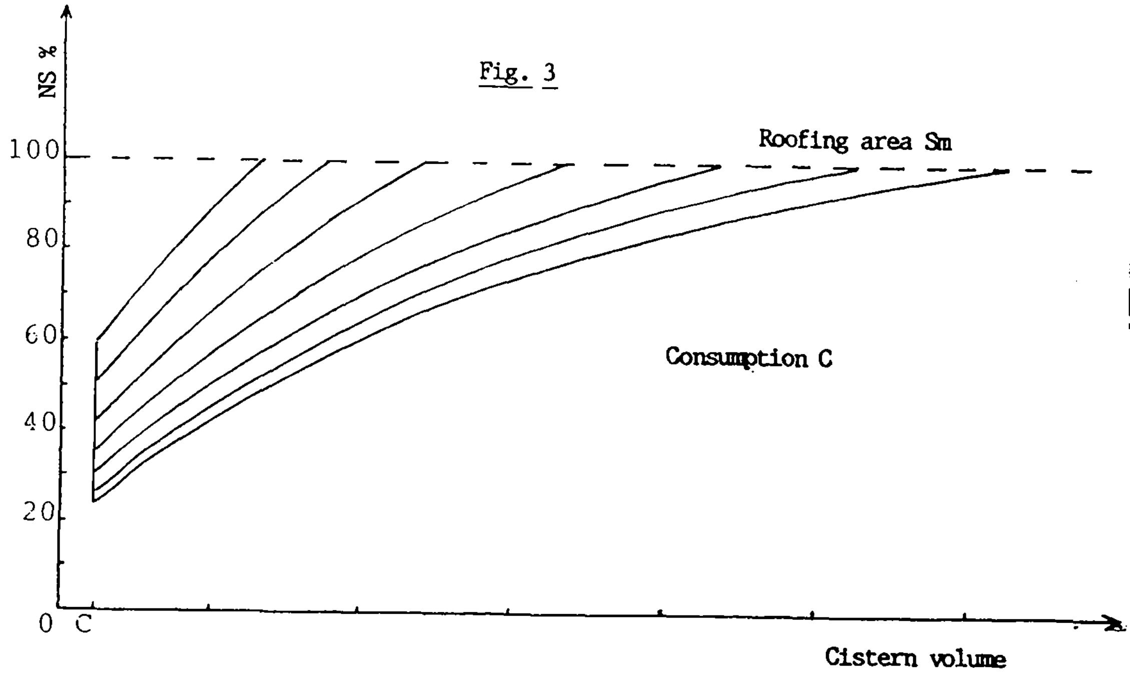


Two remarks can be made :
- the curves can overlap . Effectively, the distribution of rainfall throughout the year is of fundamental importance . For example, in a pluviometric year during which rain falls regularly every day, the volume of storage required is equal to the daily consumption, whereas for a year when it rains only one day the storage required equals the annual consumption .
- the portion of the grouped curves to the right is the most interesting since it represents the most unfavorable portion and, hence, regroups the values to be considered . Thus the most unfavorable pluviometric year(s) can be determined .

Note, in general, that the highest values for level of satisfaction are obtained during the same pluviometric year which is used for the remainder of the calculations.

1 . 4 Calculation of relationships between the different parameters

Once the pluviometric year has been selected, volume-level of satisfaction curves are plotted for the selected value of consumption C and for different values of S assuming $S > Sm$. A set volume-roofing area-consumption can then be deduced for each level of satisfaction (fig.3) . Note that the curves can not overlap since they are derived from the same pluviometric distribution .



I . 5 Development of the computed models (abacus) for utilisation

1.5.1 Let the triple set Cb , Vb , Sb represent a given level of satisfaction . If Vj is the volume of water in the cistern on day j , then :

$$Vj = Vj\text{-}1 + R\ (\ Pj - NE\ )\ Sb - C \quad \text{if}\ \ Vj\text{-}1 \geqslant C$$
$$Vj = R\ (\ Pj - NE\ )\ Sb \quad \text{if}\ \ Vj\text{-}1 < C$$

We assume that Vo = VN (level at the beginning of the year = level at the end of the year) and let "I" be the number of days the alimentation is assured .

1.5.2 Let z represent any positive real value . Let's show that the triple set zCb , z Vb , zSb gives the same level of satisfaction as the triple set Cb , Vb , Sb .

Let V'j be the volume of water in the cistern on day j . Prove by recurrence that V'j = zVj and that I' = I , assuming V'o = zVo .

* If V'k = zVk

\- If Vk ⩾ Cb then Vk+1 = Vk + R (Pk+1 - NE) Sb - Cb but also zVk ⩾ zCb so V'k ⩾ zCb from which V'k+1 = V'k + R (Pk+1 - NE) zSb - zCb = z Vk + R (Pk+1 - NE)Sb - Cb and so V'k+1 = zVk+1 .

\- If Vk < Cb the day k+1 is a day without water for the triple set Cb , Vb , Sb and then Vk+1 = R (Pk+1 - NE) Sb . But also zVk < zCb so V'k < zCb then the day k+1 is a day without water for the friple set zCb, zVb , zSb and then V'k+1 = R (Pk+1 - NE) Sb = zVk+1

\- If Vk+1 > Vb , then Vk+1 = Vb but also zVk+1 > zVb then V'k+1 > zVb and V'k+1 = zVb

It has then been shown that for every j we have the relationship : V'j = zVj

* If the day j is a day without water for the triple set Vb , Cb , Sb it is equally so for the triple set zVb , zCb , zSb from which I' = I . We have V'o = V'N because Vo = VN so zVo = zVN .

As a result, the triple set zVb , zCb , zSb gives the same level of satisfaction as the triple set Vb , Cb , Sb .

1.5.3 As a result , it can be inferred that from a triple set Vb , Cb , Sb and for a level of satisfaction NS , an infinite number of the triple set V , C , S for the same level of satisfaction can be deduced, verifying the relations :

$$V = zVb \quad C = zCb \quad S = zSb \quad \text{from which :}$$

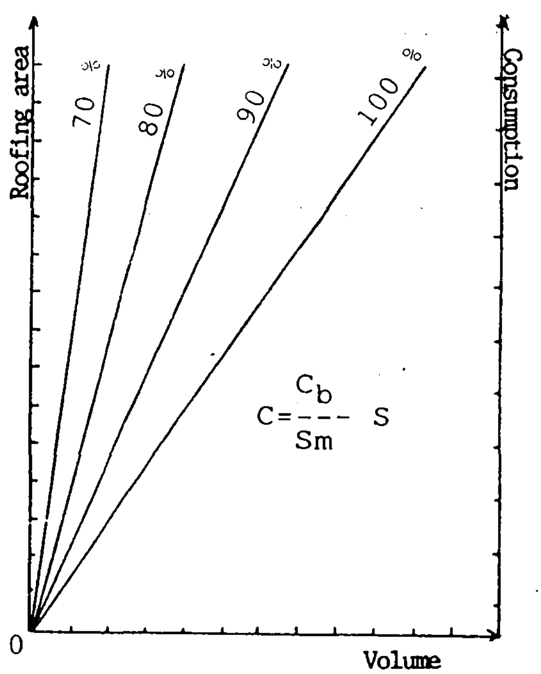
$$V = C \cdot Vb/Cb \quad , \quad V = S \cdot Vb/Sb \quad , \quad C = S \cdot Cb/Sb$$

as $V/Vb = C/Cb = S/Sb$.

Then from volume-level of satisfaction curves for a given value of consumption C and for different values of roofing area S, we can deduce a whole set of three relationships for each level of satisfaction desired .

1.5.4 Abacus 1

For different levels of satisfaction, this abacus gives the maximum consumption rate which can be expected for a given roofing area and the corresponding volume of cistern required .



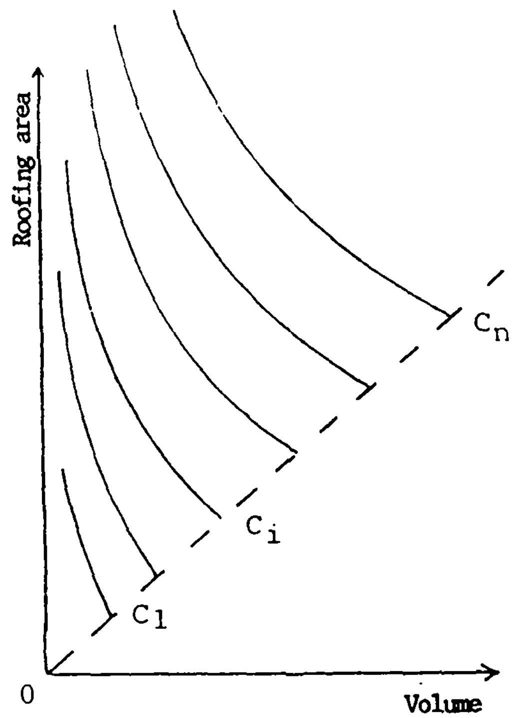
These straight lines are derived from the curve corresponding to the minimal roofing area Sm (see § 1.3) . For example, this abacus is to be used when , for a given roofing surface one wants to benefit from the greatest possible consumption , even if it is done at the expense of an important storage volume .

1.5.5. Abacus 2 , 3 , 4 .

These abacus are plotted from the series of three relationships in § 1.5.3 They can be plotted for any level of satisfaction . Those which correspond to a level of satisfaction of 100% are to be plotted whenever rainwater constitutes the main source of household alimentation .

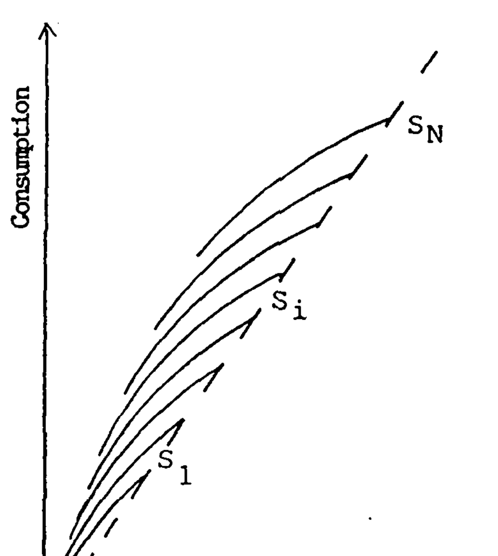
1.5.5.1 Abacus 2

Is to be used whenever one wants a precise individual consumption for a given household alimentation .



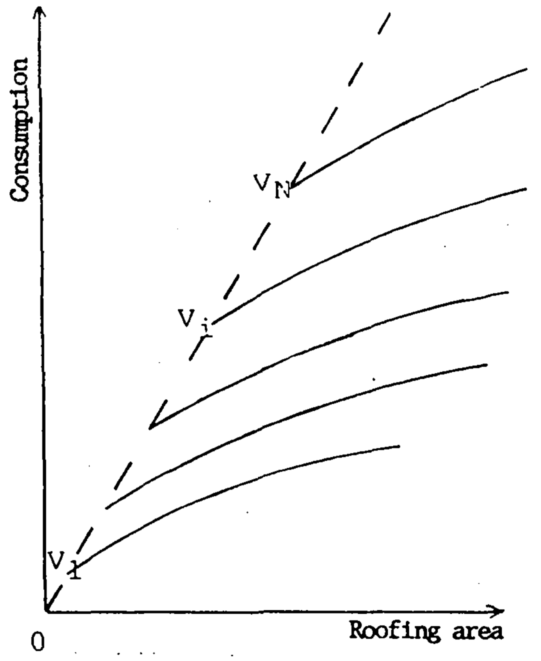
1.5.5.2 Abacus 3

Is to be used whenever one wants to know the relation between consumption and volume for a given roofing surface area



1.5.5.3 Abacus 4

Is to be used whenever one wants to know the consumption allowed by a given roofing surface area, for a given reservoir volume .



1.5.6 Interpolations

The abacus 2 , 3 and 4 are actually the graphic interpretation of the same relations . By way of interpolation, we can thus recover a curve from an abacus, or resolve problems which can not be resolved directly by means of the abacuses . the following figure (fig.4) illustrates the method of interpolation .

2 . EXAMPLE OF THE USE OF THE METHOD FOR THE WESTERN TUAMOTUS

The TUAMOTU archipelago are low islands (atolls) where the collection of rainwater constitutes the main water supply . Without prejudice to the improvements which can be provided by exploiting the fresh water lenses, the improvement of the conditions of collection, storage and treatment of rainwater remains a priority for these islands .

The development of abacuses for determining the optimal volume of water cisterns correlates well with such an objective .

The archipelago extends over a distance of more than 1,600 km and decreasing rainfall is encountered as one proceeds from West to East . Thus , the archipelago has been divided into three zones of identical rainfall pattern . The following example concerns the western part of the TUAMOTUS .

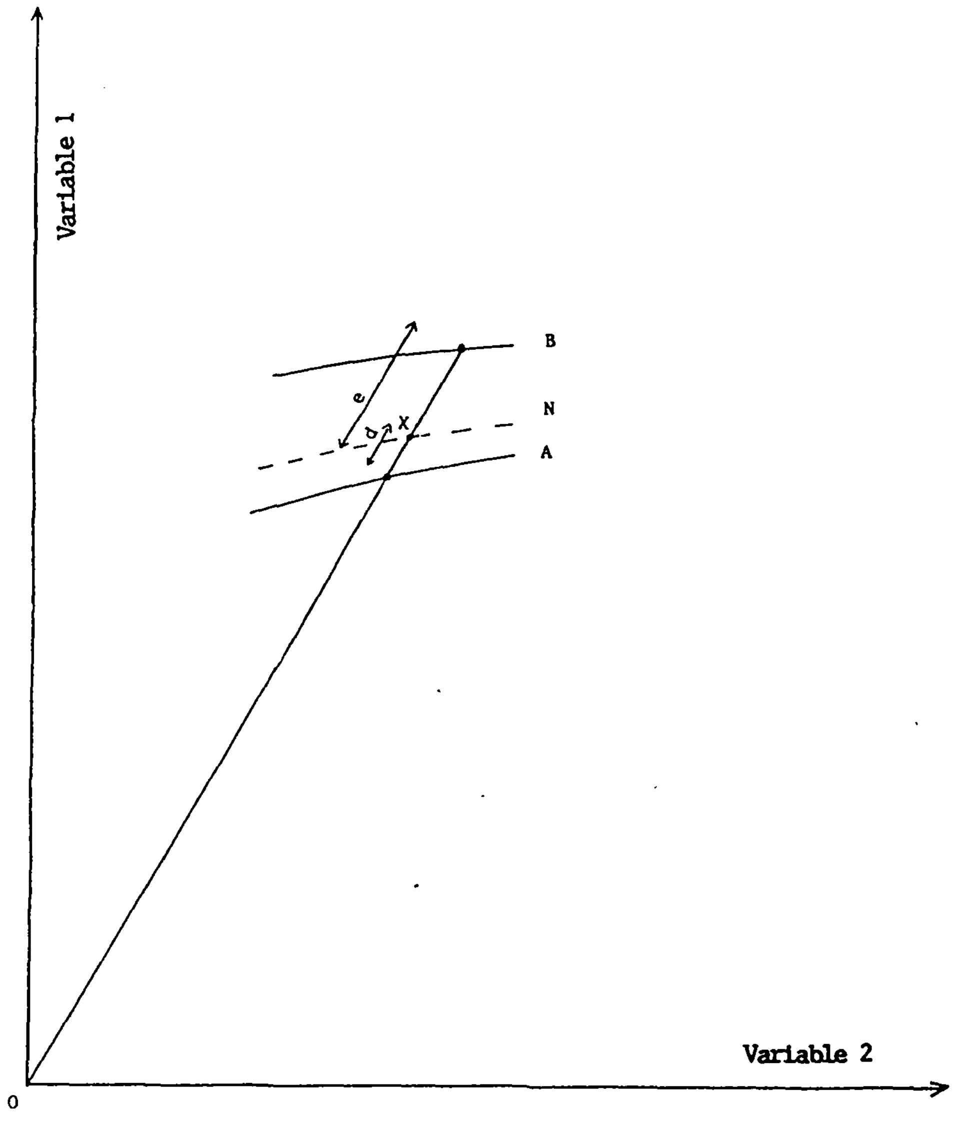


Fig. 4 METHOD OF INTERPOLATION

(to be used with abacuses 2 , 3 , 4)

Given X located between levels A and B, find the level N corresponding to point X.

1 - Plot the straight line passing through X and starting at 0
2 - Measure distance d and e
3 - Calculate the level N

$$N = A + (B - A) \times d/e$$

2 . 1 The search for a representative pluviometric station

In the western TUAMOTUS, daily rainfall is recorded by the meteorological stations on the islands of RANGIROA and TAKAROA . Statistical tests of significance applied to the observed differences between the rainfall measurements of the two stations show that the measured values belong to the same population . For the calculations which follow, we have chosen the station on TAKAROA where the rainfall recordings are of the longest duration (1958 - 1983)
The average value is Pt = 1616.97 mm and the standard deviation St = 478 .
Graphic verification of the statistical distribution of annual pluviometric data show that the adjustment following Gaussian law is valid excepting for the highest and lowest values of the modulus (see fig.5) . The TAKAROA station also provides the year with the lightest measured rainfall, that of 1976 with 977.2 mm for an appearance probability of less than 5% .

2 . 2 Selection of the year with the most unfavorable measured rainfall

2.2.1 Minimal roofing surface

For a given consumption, there is a minimal roofing surface which can assure 100% of satisfaction for alimentation throughout the year (see § 1.3) . For the purpose of this study, we have retained :

cleansing of the roof NE = 0
yield of installation R = 80%

These values are those recommended by the World Health Organization (W.H.O.)
Annual consumption = 366 x C / 0.8 = 457.5 x C (C = daily consumption)
The minimal surface thus is : Sm = 457.7 x C / 977.2 = 0.4682 x C

2.2.2. Pluviometric year chosen

To identify the most unfavorable year for rainfall, calculations were carried out for 9 years of rainfall measure : the three driest years (1976,1971,1959) , the rainiest year (1977) and five average years (1967,1980,1981,1982,1983) .
Results are presented on fig. 6 and 7 in the form of curves and tables . It would appear that the most unfavorable year was 1976 . Thus ,it is that year which is utilised for the calculations . It can be seen from § 2.1 that it represents a good security for the dimensioning .

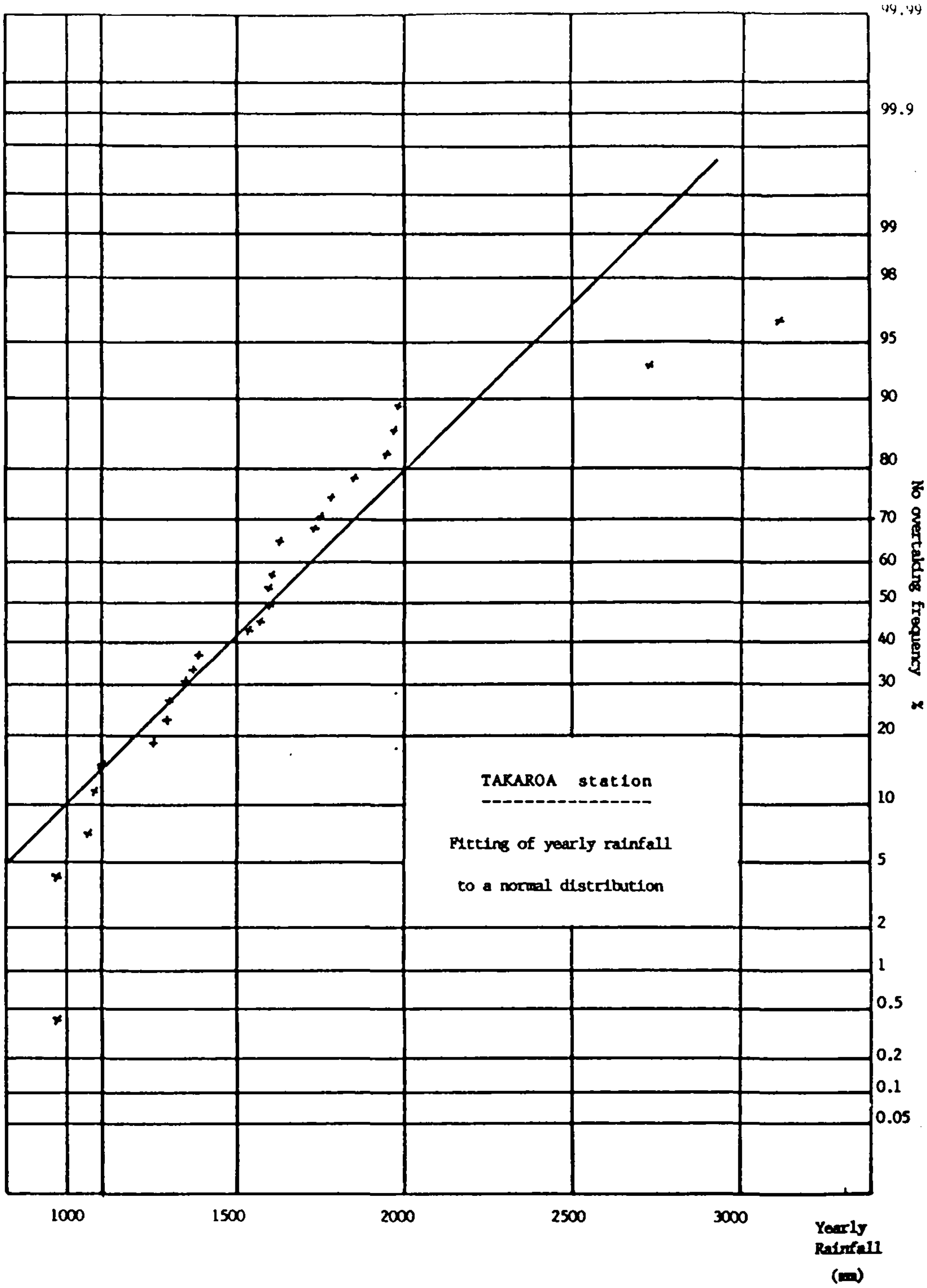
2 . 3 Calculation of relations between the different parameters .

The aim of the study being abacuses which cover most cases, the roofing surface area required for a given consumption has been varied . Volume-satisfaction curves were plotted for a given consumption-surface relationship . The main interest of the study being the determination of the parameters leading to 100% satisfaction, a set of relationship linking all the parameters was deduced .

On fig.8 and 9 can be found the set of volume-satisfaction curves as well as the ensemble of relations which drawn from them .

2 . 4 Development of the abacus

When one parameter is fixed, the relationships found allow for the plotting of the curve linking the two others . On fig. 10, 11 , 12 and 13 can be found 4 sets of curves :
- Abacus 1 : These curves offer, for several levels of satisfaction (70,80,90,100%) the maximal consumption which can be expected for a fixed roofing area and the cor-



99.99
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
No overtaking frequency %
TAKAROA station
Fitting of yearly rainfall
to a normal distribution
1000
1500
2000
2500
3000
Yearly
Rainfall
(mm)

Fig. 5

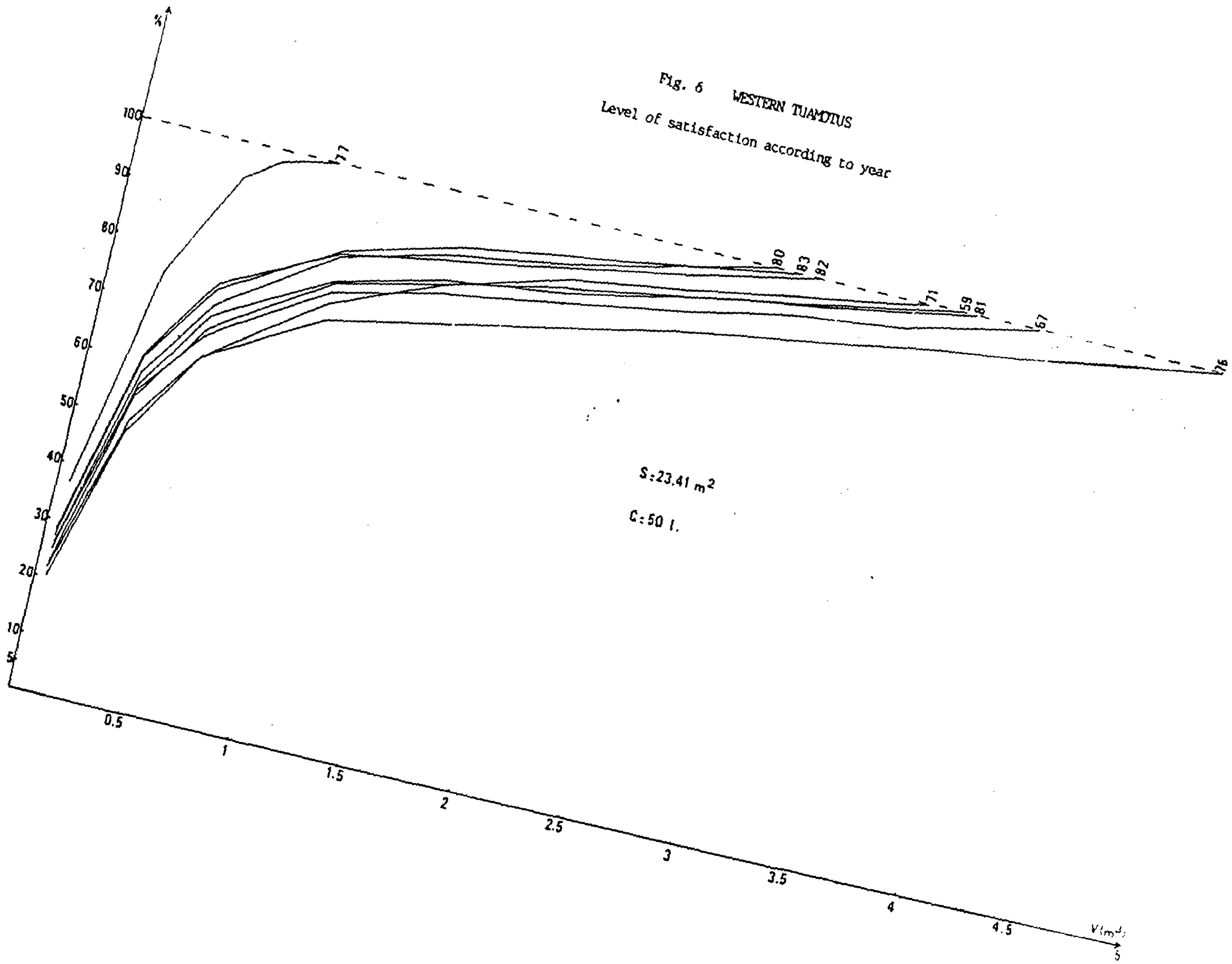


Fig. 6 WESTERN TUAMOTUS

Level of satisfaction according to year

Fig. 7 WESTERN TUAMOTUS

Level of satisfaction according to year with Sm = 23.41 m2 and C = 50 liters

Volume (m3) \ Year	76	67	81	59	71	82	83	80	77
4	94.26	99.17	100	100	100				
3.5	91.53	95.34	97.80	98.35	99.17	100			
3	88.25	92.60	94.52	94.79	96.16	99.17	100	100	
2.5	85.24	88.76	91.23	91.23	92.32	95.34	97.26	97.26	
2	81.14	85.47	87.67	88.21	89.58	91.50	93.69	92.34	
1.5	77.32	82.46	84.93	84.11	84.10	88.21	90.68	89.07	
1	73.22	78.08	80	79.72	76.43	84.93	85.47	84.15	100
0.5	62.84	66.57	69.86	67.67	62.73	75.34	74.24	71.58	93.69
0.25	49.45	54.79	55.61	53.69	47.67	61.09	60.82	57.65	75.06
0.05	21.85	25.20	25.75	22.73	20.27	28.49	27.39	26.22	36.71

Fig. 8 WESTERN TUAMOTUS

Level of satisfaction with consumption = 50 l

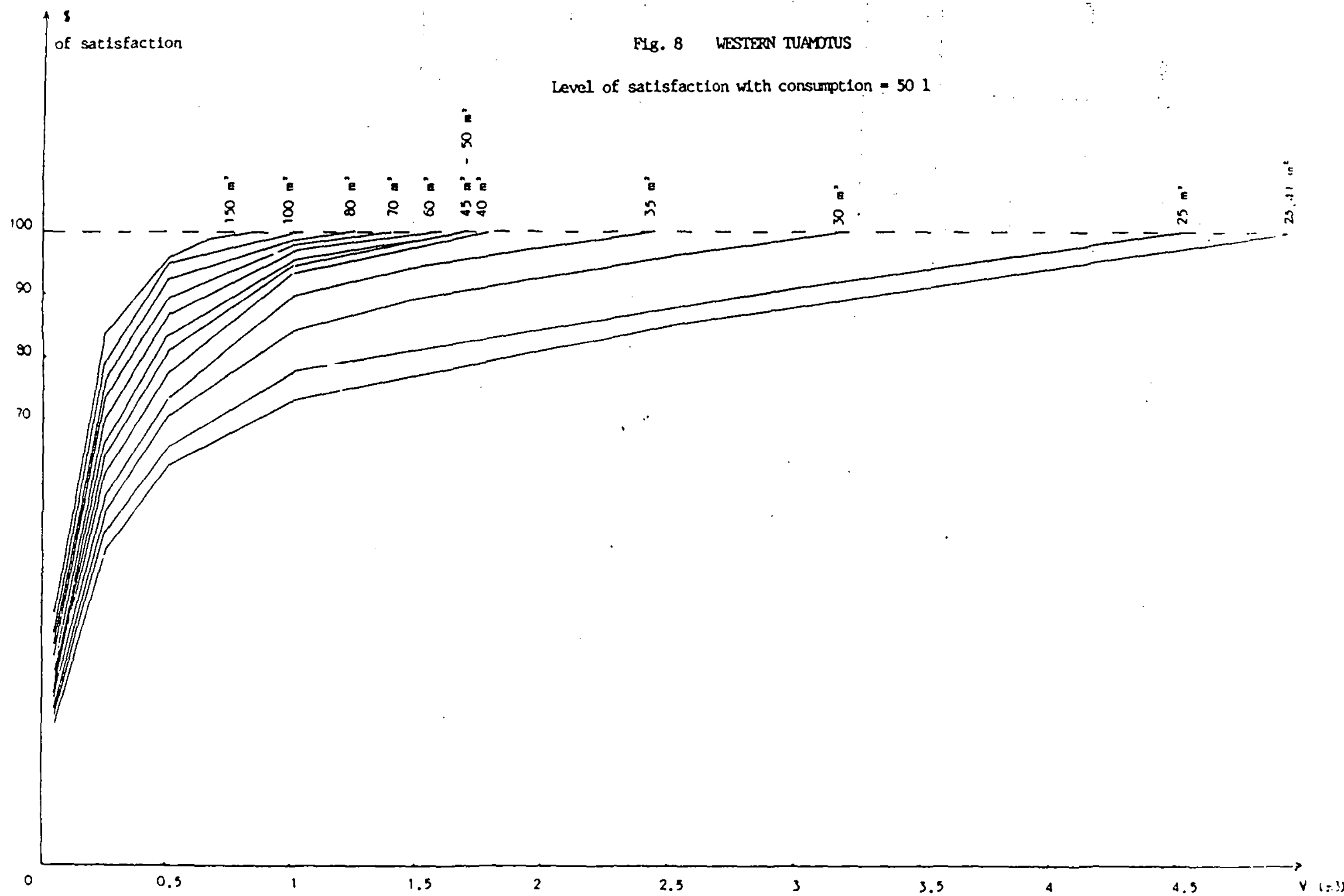


Fig. 9 WESTERN TUAMOTUS

RAINWATER STORAGE

VOLUME DIMENSIONS FOR CISTERNS

C = 2.136	S	V = 0.208	S	C = 10.24	V
C = 2	S	V = 0.18	S	C = 11.11	V
C = 1.66	S	V = 0.105	S	C = 15.75	V
C = 1.43	S	V = 0.07	S	C = 20.51	V
C = 1.25	S	V = 0.045	S	C = 28.09	V
C = 1.11	S	V = 0.038	S	C = 28.87	V
C = 1	S	V = 0.035	S	C = 28.90	V
C = 0.83	S	V = 0.027	S	C = 31.32	V
C = 0.71	S	V = 0.02	S	C = 35.50	V
C = 0.63	S	V = 0.016	S	C = 40.32	V
C = 0.5	S	V = 0.01	S	C = 48.54	V
C = 0.33	S	V = 0.006	S	C = 55.61	V

ponding necessary volume .

- Abacus 2 : these curves offer for a fixed consumption, the relationship between surface and volume .
- Abacus 3 : these curves offer, for a fixed surface, the relationship between consumption and volume
- Abacus 4 : these curves offer, for a fixed volume, the relationship between consumption and surface .

2 . 5 Examples of use of the abacuses

2.5.1 Abacus 1

Example : a household of 70 m2 with 5 people .

Roofing area = S = 70 / 5 = 14 m2 . The maximal consumption per capita is 29.9 l and the total reserve per capita should be 2.91 m3 or a total reserve of 14.55 m3 for the household .

2.5.2 Abacus 2

Example : a household of 60 m2 with 4 people needs a daily consumption of 20 l per capita . Roofing area = S = 60 / 4 = 15 m2 . V = 0.88 m3 or a total volume of 3.52 m3 .

2.5.3 Abacus 3

Example : a household of 50 m2 with 4 people .

Roofing area = S = 50 / 4 = 12.5 m2 . The curve 12.5 expresses the relationship C=f(V). For example , an individual volume of 1 m3 (or 4 m3 for the household) allows for an individual daily consumption of 18.8 l .

2.5.4 Abacus 4

Example : a cistern of 4 m3 and a household of 100 m2 with 8 people .

V = 4 / 8 = 0.5 m3

S = 100 / 8 = 12.5 m2

A daily individual consumption of 14 l can be expected .

2.5.5 Interpolations

Example , abacus 4 . Given a household of 120 m2 with 4 people . Want a daily consumption of 24 l per capita .

S = 120 / 4 = 30 m2

The volume is situated between 0.5 and 1 m3 .

V = 0.5 + 25/65 x 0.5 = 0.7 m3 . Thus a volume of 2.8 m3 is required .

— o —

Fig . 10

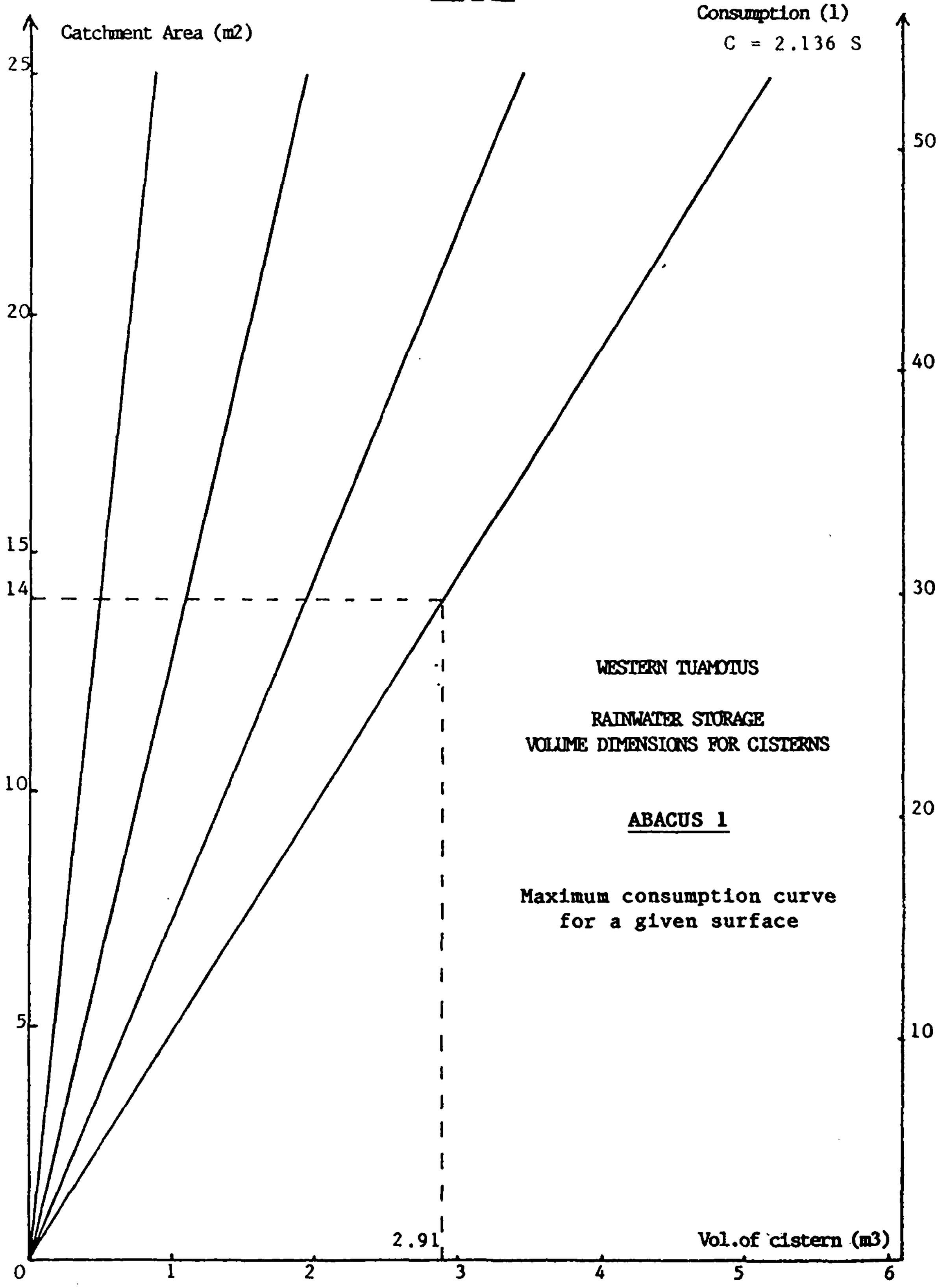
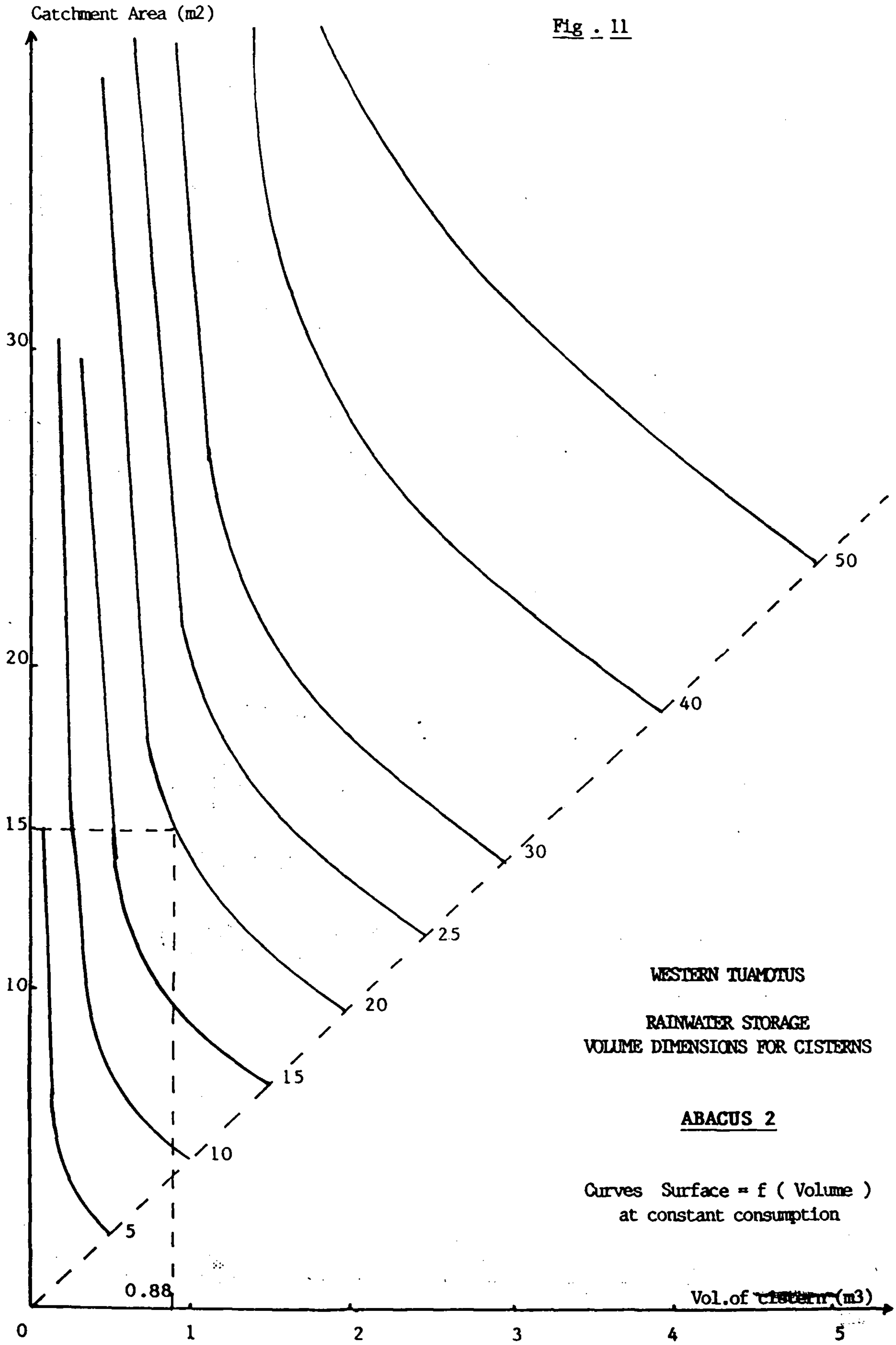
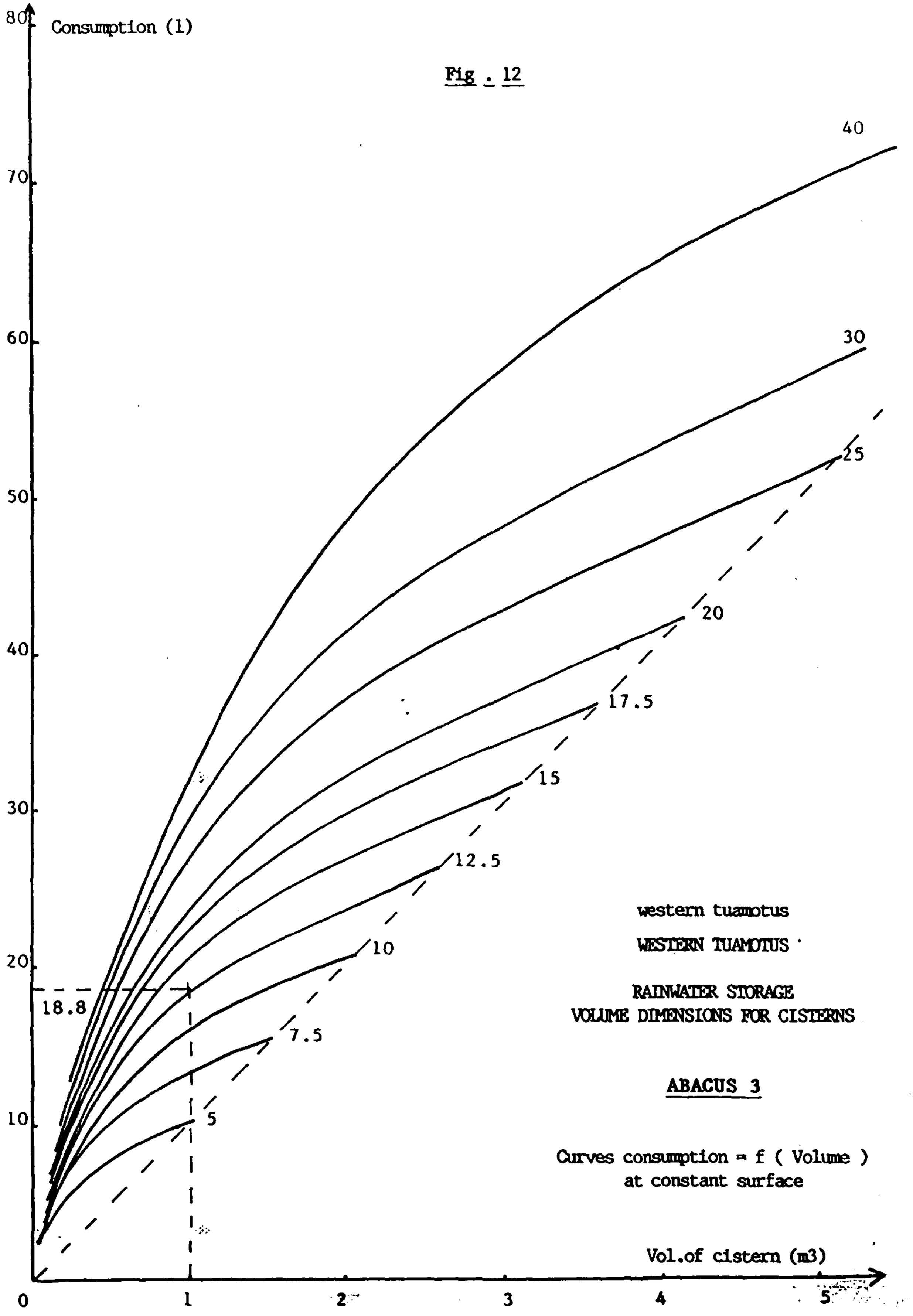

Catchment Area (m2)
Consumption (l)
C = 2.136 S
25
20
15
14
10
5
0
50
40
30
20
10
WESTERN TUAMOTUS
RAINWATER STORAGE
VOLUME DIMENSIONS FOR CISTERNS
ABACUS 1
Maximum consumption curve
for a given surface
2.91
Vol.of cistern (m3)
1
2
3
4
5
6

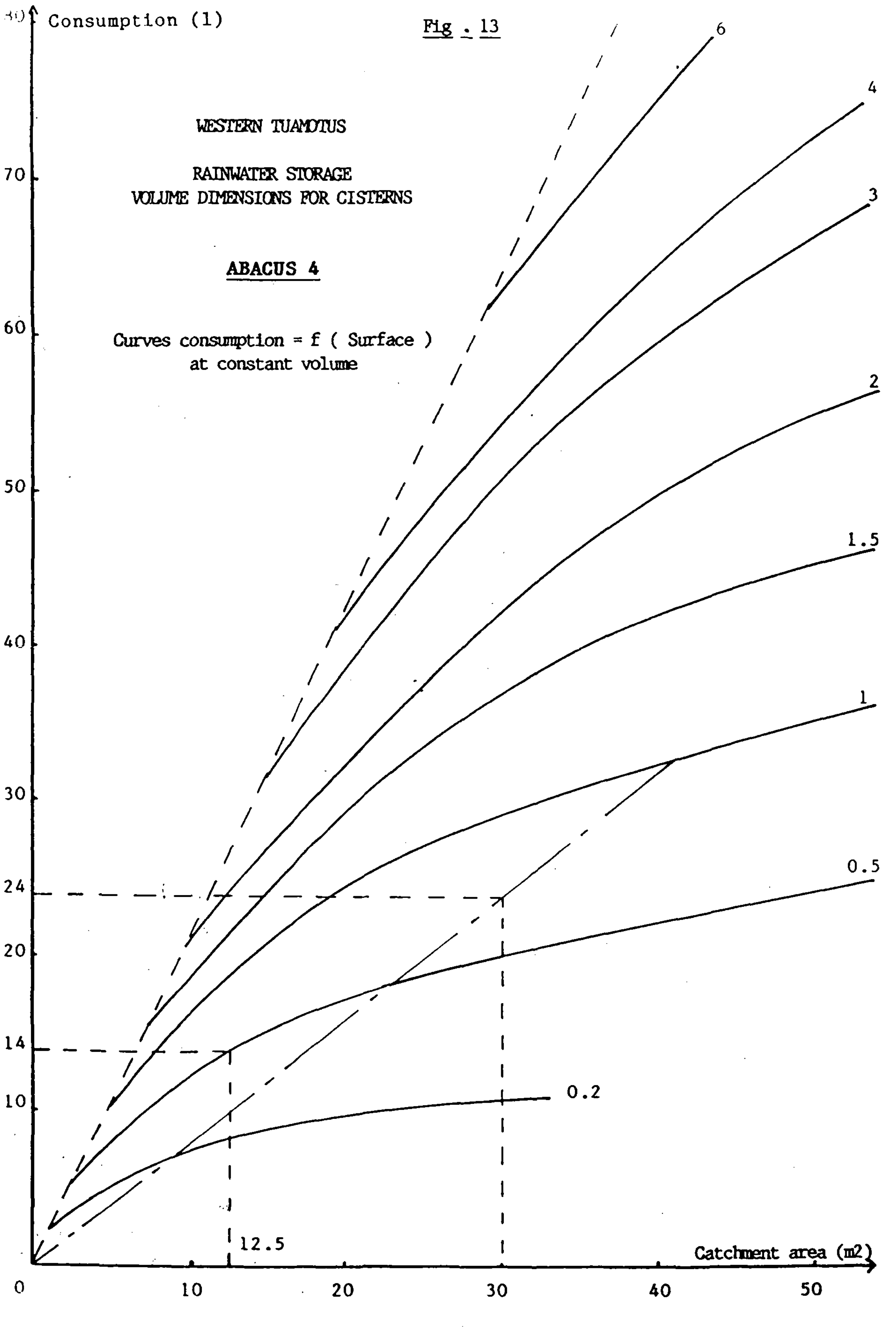
Fig . 11



Catchment Area (m2)
30
20
15
10
0
0.88
1
2
3
4
5
Vol.of cistern (m3)
5
10
15
20
25
30
40
50
WESTERN TUAMOTUS
RAINWATER STORAGE
VOLUME DIMENSIONS FOR CISTERNS
ABACUS 2
Curves Surface = f (Volume)
at constant consumption

Fig . 12


Consumption (l)
80
70
60
50
40
30
20
10
0
1
2
3
4
5
18.8
5
7.5
10
12.5
15
17.5
20
25
30
40
Vol.of cistern (m3)
western tuamotus
WESTERN TUAMOTUS
RAINWATER STORAGE
VOLUME DIMENSIONS FOR CISTERNS
ABACUS 3
Curves consumption = f (Volume)
at constant surface


Consumption (1)
Fig . 13
WESTERN TUAMOTUS
RAINWATER STORAGE
VOLUME DIMENSIONS FOR CISTERNS
ABACUS 4
Curves consumption = f (Surface)
at constant volume
6
4
3
2
1.5
1
0.5
0.2
70
60
50
40
30
24
20
14
10
12.5
Catchment area (m2)
0
10
20
30
40
50

CONSERVATION OF WATER RESOURCES -

A LOOK AT WAYS TO REDUCE DEMAND FOR POTABLE WATER

By

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18 July 1984

ABSTRACT

Many towns and countries are faced with a water supply inadequate to meet the demand. These same towns and countries investigate and develop water resources which are expensive to build and/or operate and are probably unwarranted. An in depth study of the metering and rating system and the unaccounted-for-water will often reveal a large wastage of existing resources. Positive steps to reduce the wastage will be economical to implement and will conserve water resources.

INDEX

INTRODUCTION

The development of water resources for water supply schemes can require expensive and/or long term investigations. The resultant water supply schemes which are implemented often require a large capital investment or else have high operating costs if pumping is involved. The schemes are often implemented too early because the water undertaking has not assessed the amount and breakdown of its unaccounted-for-water.

Unaccounted-for-water has been known to exceed over twice the quantity metered at consumers premises. Analysis of unaccounted-for-water with follow-up action to reduce it will have major benefits:

1. The income of the water undertaking will increase
2. The total water consumption will decrease, resulting in decreased operating costs.
3. Costs will be saved by deferring and saving on capital expenditure.

The reduction in metered (accounted-for) water can also be investigated with similar benefits especially with regard to deferred capital expenditure, and saved water resources.

REDUCING UNACCOUNTED-FOR-WATER

Unaccounted-for-water is the difference between the quantity of metered water at the water sources and the quantity of water metered at the points of consumption.

Unaccounted-for-water can be subdivided into the following categories:

- Metering and meter error
- Leakage (from the water undertakings own distribution system)
- Illegal connections
- Miscellaneous

Metering and Meter Error

Establishing a reliable estimate of the unaccounted-for-water requires a well metered system.

The most important meters are the source meters as errors in these can grossly effect the water balance account. There are many documented cases where errors in the estimate of unaccounted-for-water due to source meter error has led undertakings to either:

- implement action where action on a lesser scale or even none at all would have been appropriate or

- fail to take any action because there was no apparent problem. In fact, these undertakings were losing money and possibly having pressure put on their water resources because of their inaction.

In any water supply system it is necessary to have accurate source meters. The practice of estimating water comsumption by multiplying pump hours run by pump nominal capacity should be avoided for this reason.

The purposes of metering consumers is to ensure that equitable charges are made proportional to the water used. All industrial premises should be metered as they will generally account for about 30% of the consumption though only 5% of the service connections. Whether to meter or not to meter domestic premises is debatable. In the United Kingdom, very few supply areas are completely metered, yet the average domestic consumption at 100 litres per capita per day is low for an industrialised nation. Studies show, however, that the introduction of a comprehensive metering system will result in a decrease in consumption in excess of 25% (ref 1). Developing countries or countries with limited water resources cannot afford to construct works which are oversized by 25%. Therefore in these cases complete metering is advised. Disadvantages with metering all consumers are meter installation and maintenance costs, associated headloss through the meter and to a certain extent increased leakage at the fittings.

In a fully metered system the meter under registration can be very significant due to meter wear and incorrect sizing. Meters have a finite life, and after a period of time their accuracy falls off or else they fail completely. Meters must be overhauled overy 5-8 years to ensure that they retain their accuracy. Even new meters can under-read particularly at low flows. Domestic meters must be accurate at flows as low as 20 litres per hour. Industrial meters need to be chosen with care. The cheaper helix type meters are unsuited to some applications.

Accurate but more expensive meters are warranted in many cases, as low flows, which fail to register on a helical meter, can be significant.

Leakage

In a well metered and maintained system, the majority of the unaccounted-for-water will be leakage.

Leakage is caused by many factors: high pressures, pipe or fitting corrosion, poor quality pipes and fittings, poor construction methods, traffic, soil movements and water hammer among them. Pressure is the most significant of these as for any leal;

- Leakage increases with increased pressure

- The occurrence of leaks increases with increased pressure.

Further, internal consumption increases since increased pressure increases flow through the consumers pipes and fittings. A reduction in average zone pressure from 60m head to 40m will result in a reduction of leakage to 40% of that existing previously. Therefore, pressure control should always be considered in the first instance, using either pressure reducing valves or break pressure tanks. Both have their advantages and disadvantages with regard to site, maintenance requirements and costs.

There are a number of methods which can be utilised to reduce leakage. The decision to implement a method depends on an economic evaluation and the various local constraining factors. The returns from implementing any of the possible methods must be carefull evaluated. The aim of an active method of leak detection, as for introducing a good metering system is to achieve a return on investment, in the form of reduced operation costs, deferred capital works and conserved water resources.

To assess the economics of leakage control and the appropriate methods to be used the following calculated:

1. The amount of leakage

2. The unit cost of leakage

3. An estimate of the amount of leakage which could be saved by implementing each method of leakage control.

4. The cost (capital and annual) to implement each method.

From these calculations the most economic method(s) are selected and the one best suited to the local conditions implemented.

Details of the above calculations may be found in reference 2.

The alternative methods which can be implemented each have a net benefit and a net cost to implement. The simplest have the least cost to implement and are suited to cheaper water. For more expensive water that is water which has a higher marginal production costs, or a high costs due to impending captial works (which could be deferred) more concentrated methods are used to locate the leakage. The methods rely on either acoustic techniques or flow metering techniques, and are briefly described below. They are listed in order of increasing effectiveness at reducing leakage and increasing cost to implement.

Method	Description
Passive	Leaks are located and repaired as they become obvious due to visible water or low pressure problems.
Regular Sounding	Simple listening sticks or electronically amplified microphones are used to listen for the characteristic sounds made by water as it escapes through a leak. All accessible water works fittings are listened to.
District Metering	Meters on pipes which feed permanently isolated districts are read regularly. When one district shows an increase in flow not parallelled by similar increases in other districts and cannot be explained other than by leakage, then the leakage is located either by sounding or by waste metering.
Waste Metering	Recording flowmeters are installed so that they monitor the entire night flow into (temporarily) isolated district. If the night flow is high, indicative of leakage, the districts is sequentially shut down by valve closure. The times when large decreases in flow are recorded on the flowmeter will correspond to times when valves are closed and the approximate location and the size of the leak(s) will be known.

In any water works systems with high operating costs or proposed capital works regular sounding will be justified as a first step to reduce leakage. Physical quantitive figures cannot be given regarding the water which could be saved ad the intrinsic leakage level will be different in each water supply system dependant on pressure, constructtion materials and corrosion etc.

The highest level of leakage is associated with passive control. The following table shows the reduction in leakage to be expected should a method other than passive control to be introduced (adopted from reference 1)

Method of Leakage Control	Level of leakage	Probable reduction from Maximum
Passive	Maximum (100%)	0
Regular Sounding	(55%)	45%
District Metering	(45%)	55%
Waste Metering	(30%)	70%

Design and construction practice may be utilised to reduce leakage in the long term:

- Design of low pressure zones where ever possible
- use of non-corroding pipes and fittings
- good supervision
- the use of higher strength and better quality materials, especially where good supervision is lacking.
- accurate as built drawings and operating plans.

Apart from the tangible cost benefits of reducing leakage there are a number of other benefits:

- improved supply pressures
- a safer water supply; with higher average pressures there is reduced chance for backflow of contaminated groundwater into the distribution systems at times of low pressure.
- improved operations control (valves and meters are regularly cleaned and inspected).
- improved knowledge of the water supply system (as wrong way valves and buried valves etc are located).
- improved public relations. The water undertaking is seen to be trying to reduce costs. The undertaking also identifies and in some cases will repair the consumers own leaks.

Illegal Use

Illegal use usually does not form a significant part of unaccounted for water though there are many means of obtaining water illegally. Tampering with hydrants or air valves, illegal connections and reversing some types of water meters are a few. Tampering is very difficult to stop without assistance from the public.

Meter readers often do not detect illegal connections as they work during the day to regular schedules which are easy to avoid. More often illegal connections are found by leakage detection teams who work at night. Even if illegal use is not a problem stiff penalties should be imposed as a deterrent.

Other Unaccounted-for-water

Mains flushing, fire fighting, street cleaning all may contribute to unaccounted for water. Normally water used for these legitimate purposes is small enough to be negligible. Mains flushing, unavoidable where colour and odour cause problems due to stagnation, can be minimised by providing a clean treated water, and eliminating dead ends. Water used for street cleaning, where significant, should be metered.

REDUCING EXCESSIVE CONSUMPTION

A reduction in consumption by consumers can be achieved in various ways:

- increasing the unit cost of water
- public education campaigns
- reducing supply pressures
- use of water saving fixtures
- identification of large consumers by their billings.

Increasing the unit cost of water has the most immediate impact on reducing consumption provided the cost increase is significant and relevant to the average income. Rates will need review particularly if certain sections of the community use excessive water. Public education campaigns have best long term results with children. Advises with meter billing giving information on the water supply system and ways to cut down wastage, newspaper and radio messages can also have an effect, but this is generally short term.

Mandatory use of water saving fixtures can substantially reduce consumption. Toilet use and washing typically account for 70-80% of the total domestic use. Lual flush toilets and shower head restrictors should always be considered. In public and commercial buildings spring loaded taps, water timers are useful provided that they are adequately maintained. Much scope for reduction lies in the elimination of automatic flushing urinals which require high maintenance and use excessive amounts of water if improperly adjusted.

Large water bills will identify large consumers as well as some who have leakage on their premises. These consumers should be given additional publicity materials to encourage conservation.

In considering the reduction of metered consumption. other factors must also be examined such as the effect on revenue, and the effect on the sewerage system which will require certain water velocity to prevent the settling of grit and organic material in the sewers.

APPLICATION TO GROUND WATER RESOURCES DEVELOPMENT

Most of the above have direct application to island countries with limited water resources. In particular, the implementation of good conservation practice will, as well as reducing operating costs and deferring capital expenditure have benefits:

1. There will be reduced chance of groundwater depletion or saline intrusion due to overpumping.

2. The implementation of a water conservation policy to reduce demand will allow sufficient time for data collection, evaluation and modelling of the groundwater extraction scheme is implemented rather than one hastily designed and based on insufficient data.

CONCLUSION

A water system with low unaccounted-for-water is indicative of a well managed system. Each of the major factors making up accounted for and unaccounted for water can be analysed economically, socially and from an engineering point of view to determine what forms of control are justified.

Source meter accuracy, reliable estimates of actual consumers' consumption and leakage levels are essential pre-requisites. All can be utilised to assess the benefits of reducing the supply to lower operating costs and in particular to delay proposed capital works and conserve our most valuable resource, water.

Typical savings of the order of 15% from effective leakage control and 25% from a good metering-rating system would allow most communities to utilise their existing water resources for at least an extra 10 years without the need for the development of new sources.

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WATER RESOURCES OF SMALL ISLANDS

WORKSHOP

FIJI

1984

PAPER ON

DESALINATION OF SEA WATER

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INTRODUCTION

On first impression a great deal of information is available on the subject of desalination and especially of reverse osmosis, the only technology which will be considered in the paper. On closer investigation it becomes apparent that very little concrete data exists which relates to the particular circumstances of Fiji, and similar Island groups, and that what does exist is discouraging. In the absence of data based on experience are claims and inferences, estimates and proposals which conceal more than they reveal and are as much the product of salesmen as of technicians. That is not to say the information supplied is of itself incorrect, only that for the most part it cannot be related to our requirements.

Nevertheless to anticipate a little my conclusions it is recommended that equipment be purchased so that first hand experience can be obtained. This recommendation reflects the seriousness of the emergency water supply problem, the high cost of present solutions, the need to test data against local conditions before it can be applied to final decision making and the opportunity to participate in international development of this advanced technology with a view to making it practicable for the South Pacific area.

In preparing this paper contact was made with or data obtained from firms or authorities in Australia, America, Japan and Germany. Discussions were held with officers of other interested departments and organisations in Fiji and information was exchanged.

RESTRICTION OF PAPER TO REVERSE OSMOSIS METHOD

Sea water is 96½% water, 3½% salts.

Methods available for the desalination of sea water are:
distillation, crystallisation, solvent extraction, ion exchange resin, electrodialysis and reverse osmosis.

The first two processes, distillation and crystallisation, utilise the fact that water can exist as a vapour, a liquid and a solid (ice) and by changing the salty liquid into one of the other forms and then back to water the salts can be left behind. Solvent extraction removes the water from the salts by dissolving the water into another chemical and then releasing it. The ion exchange resin process removes the salts from the water by absorbing them into a special resin. Electrodialysis used electricity to pass the salt ion through a membrane. The reverse osmosis process uses pressure to form the sea water against a semi-permeable membrane so that the salt is held by the membrane and the water passes through.

All of the methods have advantages and disadvantages and all require high inputs of energy. The selection of method depends on an appraisal of all the circumstances. From a preliminary study it appears that the most recent advances in desalination have taken place in the Reverse Osmosis system. For this reason and as the data available on other systems indicates that they are more expensive, or even more technological, or require extensive local works, this discussion has been limited to Reverse Osmosis plant.

TECHNOLOGY

From the positions of directors and managers of organisations responsible for balancing the conflicting interests of budgets,priority and especially resources the general impression to be gained from studying the publications of both the manufacturers and researchers is that technologically the operation and maintenance of a reserve osmosis plant are beyond normal resources and the benefit - cost ratio is low. The manufacturers and their salesmen use such terms as "reliability and maintenance free performance" and "low maintenance and service schedule", but these claims must be read in terms of a high technology society: the authors of such claims would scarcely have contemplated an environment where conditions dictate a three year life for an ordinary pump. A reverse osmosis plant includes filtration systems, low and high pressure pumps, membranes, and numerous valves and meters, backwash controls and so on. These factors put desalination into a special category and limit locations to those with reasonable access to at least moderately skilled labour while experience is built up. It would be the acme of optimism to install a desalination plant on an island remote from servicing and expect it to function.

ECONOMY: General

In view of the manner of presentation of data by the suppliers of the plant, lack of practical experience of what ancillary equipment and power is in fact required, and of the variety of desk studies carried out with pessimistic results, no firm advice can be offered in regard to likely cost of either the capital or running costs of a reverse osmosis plant on an island.

ECONOMY: Capital

The suppliers are intent on presenting a minimum capital cost, and this leads to advertisements which quote prices and then list options which close reading suggests are in practice necessities for satisfactory operation. Such optional items include pre-filters, while the notes say "Particles of mud, clay etc. suspended in the feedwater will foul the membrane". Iron is common in Fiji water and this is known to shorten membrane life, indicating that the feed might require spraying into an extra storage tank before use. The need or cost of such unknowns cannot be theorised with any degree of accuracy and only trial and error will close the gaps in our knowledge.

ECONOMY: Operation

It is suspected that the power supplies quoted against the water outputs are minima under ideal conditions and that by the time the systems are operating under real-life conditions with the options, boosters etc. found to be necessary the requirements will bear little resemblence to those quoted. It seems likely that the outputs quoted per day are for perfect operation for close to 24 hours per day. If it turns out to be practical to operate only 8 hours a day the rated output required is tripled, with appropriate power demand.

The running costs therefore are indeterminate. If diesel power is used te real cost of fuel will vary for each location. Desalination plants are reported as very heavy on fuel but almost no figures have been quoted. Figures calculated from theoretical power requirements are only as reliable as the power estimates. There are few islands with electricity supplies of sufficient reliability of power and the effect of fluctuating power is another uncertainty.

STAFFING

Discussion of staffing might be thought outside the scope of this paper but it has two important aspects. Firstly the skilled attention required may be infrequent but when required it may be technically critical. Thus it is suggested that the local attendants should be able to do only routine tasks, such as operate backflow systems, but should be instructed to call on highly skilled mechanics for anything requiring dismantling or suchlike steps. The second point follows from the first and is that the opportunity can be taken to select and develop both local labour for routine tasks and special skills with upgraded technology in base workshops. Obviously, if the locally recruited attendants prove adept the opportunity would be taken of advanced training, with mutual benefits.

SELECTION OF PLANT

The operation of potable water producing plant must be regarded as a new level of technology in the context of the Pacific Islands. Taking into account that usually there are alternatives available, such as wells, collection and conservation, it is prudent to consider the scale on which the first experience should be gained. In other parts of the world the circumstances are different and the total absence of alternatives other than bulk transport may justify the installation of massive systems, often fuelled by comparatively cheap fuel sources.

Although economies of scale may be lost it is recommended that as the basic technology does not change with size the first steps should be taken with small inexpensive units. There is the advantage also that if successful the small units may be suitable when dispersed among single villages and linked into the expanding electricity supply.

QUANTITY OF WATER

Relevant to the selection of plant is a decision on the quantity of water to be purified. Clearly it will not be practical to attempt to provide for full demands of normal usage. On the other hand a minimum survival consumption of, say, a litre a day would not be acceptable. Taking a figure of 2.25 litres (½ gallon) per head, and applying this to a village of 300 inhabitants gives a requirement of $0.675m^3$ per day. A figure in this range can be provided by any of several well developed units by several manufacturers.

COSTS

The most that can be hoped for in any discussion on costs is that they will be roughly of the right order at the time and under the conditions given. On this understanding a typical appropriate small unit may carry a basic price of about $5000, which could be doubled on the addition of options, supplementary plant, storage and delivery and installation costs. The amortisation depends on anticipated life and this may be as short as two years or as long as ten for reasons largely out of the proposers hands.

Direct operating costs are subject to local prices for fuel and labour and little would be served by offering a figure in this paper.

I feel that I should draw to attention that the points presented in this paper are firstly largely theoretical, perhaps conjectural would be a better word, since there is virtually no practical experience in Fiji to call upon, and, secondly is based on an appraisal of average levels of procedure, skills and resources. I am well aware that under different circumstances quite different results may be obtainable. An extraordinary capacity for improvising, special skills and fabrication capacity, innovation and enthusiasm have shown that practical results can be achieved which far exceed my modest anticipations. These successes will be the subject of other talks during this Workshop and I would be pleased to have some of my pessimism proved wrong or at least discounted.

CONCLUSION

1. Desalination of seawater can be a practical proposition for small islands but its technical effectiveness will depend largely on the infra-structure available. That is the routine operation and maintenance labour at one end and the high technology skills as required.

2. Unless special circumstances prevail the economics are not

likely to compare favourably with alternatives such as well, reservoirs, roof tanks, etc.

3. There are the advantages of local employment, social developments and widening of technological skills to be considered.

4. It would be prudent to start small to gain experience.

Single Well Pump Tests on Small Islands

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Abstract

Two selected single well pump test analyses from tests conducted during a water supply drilling programme in the Southern Cook Group, SW Pacific, are given. Constant Discharge and/or Constant Drawdown tests indicated a limited aquifer in holes drilled in volcanics on the islands of Atiu and Mangaia. Transmissivity is low at between 5.7 m^2/d and 0.6 m^2/d but the recommended pumping rates (2500 l/hr and 1600 l/hr) and long term predictions appear to have been maintained after four years of pumping.

Keywords Cook Islands, hydrogeology, pump tests

Introduction

During a New Zealand Bilateral Aid water resources drilling programme carried out on four outer islands of the Southern Cook Group, SW Pacific between 1978-80, single well pump tests were made in 16 holes in an attempt to determine long term yields.

Although not entirely suitable for long term predictions, single well pump tests can be used as a rough guide to future performance of drillholes if only one hole can be drilled within the prevailing constraints of time and money. In the Cook Islands, if the hole contained even small amounts of water that appeared to be sustainable after testing, it automatically became a production hole.

From the time of completion of the project in 1980, unconfirmed reports suggested that the predictions made by Waterhouse and Petty (in press) based on single well pump tests have stood up in practice. It is suggested that these simple pump tests may have application in other small islands in the Pacific and could be used to determine elementary aquifer characteristics and for comparative purposes on an island to island basis.

Selection of Drill Sites

Drill sites were selected according to proximity to villages, geology, height above sea level and distance from shore. Ground level at each site was determined from traverses with level and staff from known datum heights or from mean sea level. Target depth was to sea level or slightly below with a limit of 100 m, the maximum of the Longyear 24 drill rig. Most of the holes were drilled in basalt because of the generally better groundwater quality and potentially greater number and thicker aquifers encountered in these rocks, compared to sites close to sea level in the makatea.

Test Procedure

On completion of drilling, standing water levels were measured with an electric probe before setting up the test pump and ancillary equipment. When the pump, rods and rising main were lowered down the hole inside the casing, there was insufficient clearance for the probe to be lowered and raised during the pumping test. As a consequence, water levels throughout the period of testing were measured with foot pump and gauge, and airline taped to the rising main slightly above the pump intake. The test pump unit comprised a 10 hp Lister diesel with belt drive to a Southern Cross deep well pump capable of lifting 2500 l/hr against a head of 60 m. The engine was factory governed to a set speed so no fine control of pumping rate was attainable but slight increases or decreases in engine speed were made by adjusting the throttle.

Drawdown tests were carried out by either Constant Discharge or Constant Drawdown methods depending on whether the hole was slowly or rapidly dewatered. In most cases the tests were of 24 hrs or more duration followed by a usually longer period for recovery.

The procedure for conducting these tests is described in the Drillers Training and Reference Manual compiled by the National Water Well Association of Australia (undated) and Hazel (1975).

Constant Discharge Test

As the name implies this test involves pumping the bore at a constant discharge rate and measuring the varying drawdown throughout the test.

With the discharge held constant, drawdown measurements are taken during the test at the following times after pumping commenced - 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, 30, 45, 60, 75, 90, 100, 120 minutes then each half-hour to six hours and then hourly until the end of the test.

Rate measurements are taken at least at the start of the test, after 15 minutes, 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 or orifice bucket if these are being used.

At the end of the constant discharge test residual drawdown measurements are taken, if possible, at the following times after pumping ceases 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, 30, 45, 60, 75, 90, 100, 120 minutes, then hourly until the water level has recovered to within 15 centimetres of the standing water level. If for any reason a reading at any of the above times is missed, then a reading should be taken as soon as possible thereafter and the actual time of this reading should be recorded. It is more important to know the time when the drawdown was measured than to have the drawdown measured at the exact times laid out in these notes.

Constant Drawdown Test

In this type of variable discharge 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 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 at the pump suction throughout the test.

Because of the air/water mixture for this type of test an orifice meter cannot be used with any reasonable degree of 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 an orifice bucket is used, rate measurements should be taken at the same intervals as drawdowns were taken during the constant discharge test, i.e. 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, 30, 45, 60, 75, 90, 100, 120 minutes, then each half-hour to six hours and then hourly until the end of the test.

Regular checks should be made to see if the pump is maintaining a constant drawdown, i e the pump is breaking suction throughout the test.

On completion of the pumping test, residual drawdown should also be taken, if possible, at 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, 30, 45, 60, 75, 90, 100, 120 minutes, and then hourly until the water level comes to within 15 centimetres of the standing water level. However in many cases, a constant drawdown test is only carried out because it is not possible to measure drawdowns and in these cases, it may not be possible to measure residual drawdowns either.

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.

Abbreviations

In the analyses (Figs. 1, 2) a definition of the terms used and abbreviations are given as follows:

T Transmissivity is the capacity of an aquifer to transmit water. It is equal to the hydraulic conductivity of the aquifer multiplied by the saturated thickness of the aquifer. The units are expressed in m^2/day.

Sw Drawdown is the amount of lowering of the water level in metres in a pumping hole.

Residual Drawdown. The distance that the water level in a drillhole remains lowered from the standing water level after pumping ceases.

V Volume of water collected in a container expressed in m^3.

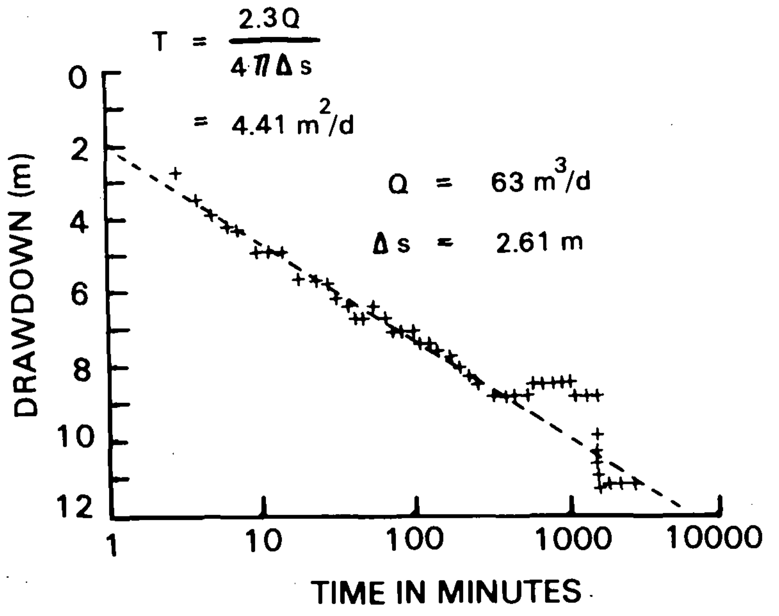
Δ s Slope of the drawdown over one log cycle expressed in metres.

Δ t" Slope of the drawdown over one log cycle expressed in days.

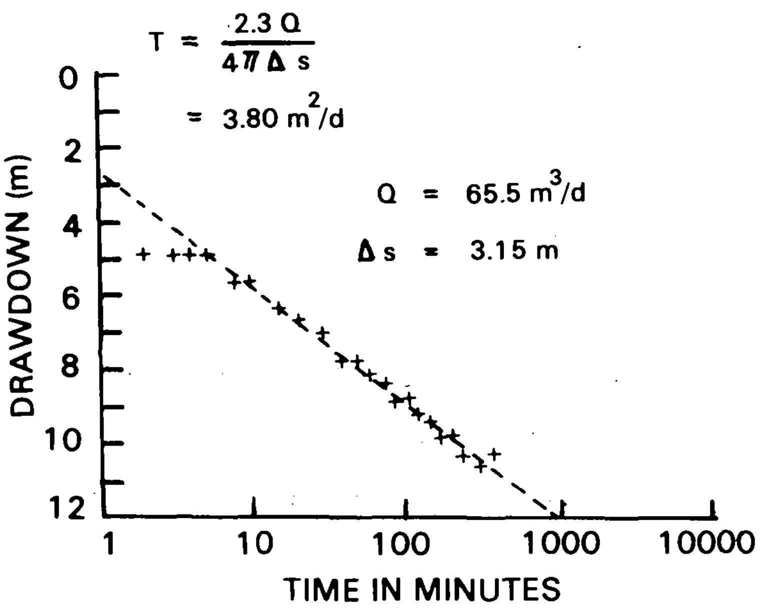
Test Results

On Atiu in the Southern Cook Group, a hole at Matavai was drilled to 63.1 m and three Constant Discharge tests of 46 hrs, 7 hrs, and 53 hrs duration respectively were carried out (Fig 1a-c). The basic data from which one of the analyses (Fig. 1c) was constructed is presented in Appendix 1.

In the first test on 22 April, 1980, static water level stood at 11.75 m b.g.l. and the pump was set to 40.6 m b.g.l. Pumping rate averaged 3450 l/hr till the end of the test at 46 hrs. An immediate response to the increased rate resulted, but the drawdown rapidly flattened out and remained constant for the final 16 hrs of the test. Transmissivity for the first test is calculated at 4.41 m^2/day.

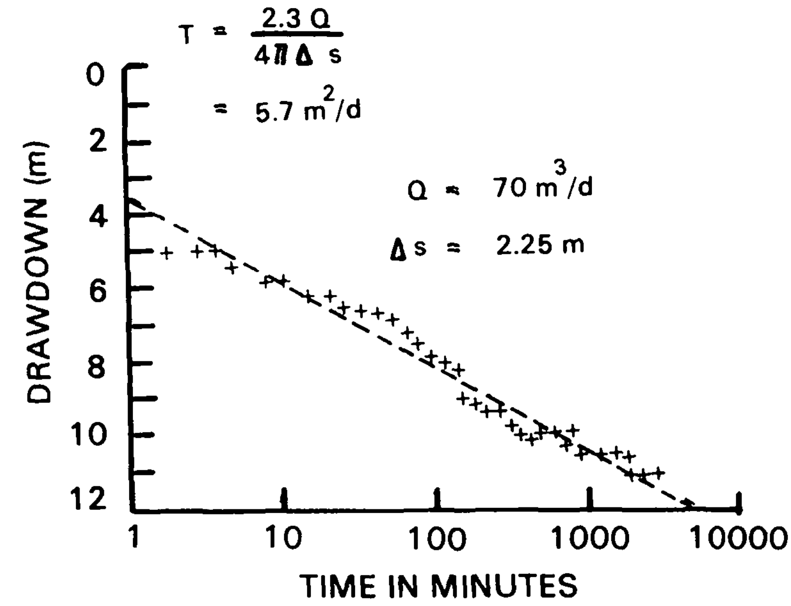


a. Constant discharge test No. 1–drawdown 22 April 1980.



b. Constant discharge test No. 2–drawdown 29 April 1980.

FIGURE 1 Matavai pumping hole tests.



c. Constant discharge test No. 3—drawdown 2 May 1980.

FIGURE 1 (Cont.) Matavai pumping hole tests.

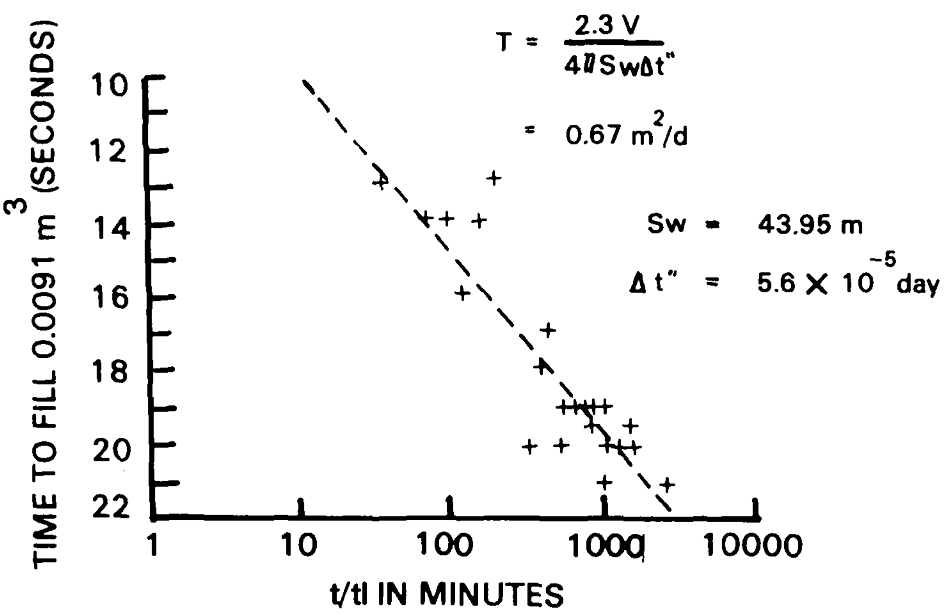


FIGURE 2 Kaauvo No. 1 pumping hole—constant drawdown test 14 August 1979.

In test 2 on 29 April static water level stood at 10.0 m b.g.l. and the pump was set to 52.6 m b.g.l. Pumping at the rate of 2700 l/hr continued for 7 hrs when, because of a pump intake blockage, the test was stopped. Transmissivity from the test is 3.80 m^2/d.

In the third and final test on 2 May, static water level stood at 9.25 m b.g.l. and the pump was set to 55.7 m b.g.l. The pumping rate averaged 2900 l/hr for the 53 hrs duration of the test, and the transmissivity calculated is 5.70 m^2/d.

The improvement in transmissivity is considered to be due to gradual development of the hole, and the flushing and cleaning out during the third test. The practice of completely cleaning out the hole before installing a permanent pump is recommended, and in this instance, it appears the Matavai hole has been improved and could maintain a yield of 2500 l/hr.

On Mangaia a hole drilled in basalt at Kaauvo to 100 m was tested initially by the Constant Discharge method. When the pump broke suction at 76 minutes the test was switched to a Constant Drawdown for a further 41 hrs. The drawdown plot (Fig. 2) is constructed from the data presented in Appendix 2.

The first 9 hrs shows a marked fluctuation in time to fill the contained compared with the remaining 33 hours of the test period when it appears that the hydraulic conditions had more or less stabilised. The initial fluctuations may have been partly caused by differences in permeability of the rock, the presence of hydraulic boundaries, the dewatering of small perched pockets of water, or from recharge from rainfall which fell for much of the time. The peaks and lows in the plot do not appear to be cyclic and cannot be attributed to tidal influences because the pump intake was some 26 m a.s.l.

The hole yielded an average 1940 l/hr for 43 hrs (82 ^{3}m). It is concluded that the pump could be lowered by 26 m to 87 m b.g.l. at which depth the hole could probably sustain a yield of about 1600 l/hr.

Acknowledgement

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Appendix 1. Matavai drillhole, Atiu. Constant Discharge pump test, May 2 1980. Depth of hole 63.1 m. Height asl 61.23 m. Depth to water 9.25 m. Depth to pump intake 55.7 m.

Time (hrs)	Time since pump started (mins)	Pressure reading (lb/in^2)	Drawdown (m)	Time to fill 18ℓ container (secs)	Pump rate gpm	Pump rate m^3/d	Remarks
0830	0	65	9.25				standing water level
	1	59	13.47				
	2	58	14.18				
	3	"	"				water dirty
	4	"	"				
	5	57.5	14.53	20	720	78.48	
	8	57	14.88				
	10	"	"	20.21	685	74.74	water discoloured
	15	56.5	15.24				
	20	"	"	23	626	68.24	
	25	56	15.59	24	600	65.4	
	30	"	"	23	626	68.24	
	40	55.75	15.76	22	654	71.34	
	50	55.5	15.94	23	626	68.24	
0930	60	55	16.29	22.5	640	69.76	
	75	54.5	16.64	24	600	65.4	
	90	54	16.99	"	"	"	water clearer
	105	53.75	17.17	"	"	"	
1030	120	53.5	17.35	"	"	"	
	150	52.5	19.05	22	654	71.34	
1130	180	52.25	18.23	"	"	"	
1200	210	52	18.40	"	"	"	
1230	240	"	"	23	626	68.24	water milky
1330	300	51.5	18.76	23.5	613	66.79	
1425	355	51	19.11	"	"	"	almost clear
1530	420	50.75	19.28	23	626	68.24	
1630	480	51	19.11	21	685	74.74	
1720	530	"	"	"	"	"	
2135	785	"	"	23	626	68.24	
2230	840	50.5	19.46	"	"	"	
2330	900	50.25	19.64	22.5	640	69.76	
0430	1200	"	"	23	613	66.79	3.5.80
0830	1440	"	"	21	685	74.74	
0930	1500	"	"	22	654	71.34	
1530	1860	50	19.81	21	685	74.74	
1935	2105	49.5	20.16	21	"	"	
2300	2320	"	"	"	"	"	
1010	2990	"	"	22	640	69.76	4.5.80
1205	3105	"	"	"	670	73.0	

Appendix 2. Kaauvo drillhole, Mangaia. Constant Drawdown pump test, August 14-16, 1979. Depth of hole 100 m. Height asl 87.3 m. Depth to water 17.35 m. Depth to pump intake 61.3.

Time (hrs)	Time since pump started (mins)	Time to fill 9ℓ container (secs)	Yield (ℓ/hr)	Remarks
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

ECOLOGY AND ENVIRONMENTAL HEALTH IMPLICATIONS OF WATER RESOURCE DEVELOPMENT IN SMALL ISLANDS

William H. Zucker, South Pacific Regional Environment Programme

SUMMARY

Well-maintained water supply systems and sanitary facilities have been correlated with lower rates of infection by pathogens, as shown in the attached tables. There is a general prevalence of water-borne diseases in the Pacific, including hepatitis, gastroenteritis, leptospirosis, and occasionally typhoid and cholera. Common Pacific parasitic infections include amoebic dysentery and various nematode diseases.

Water resource development can also have a pronounced negative effect on environmental health. With increased reticulation of water and waste water systems there is a higher gray water output, with accompanying high phosphate concentrations and eutrophication. Pit latrines or even flush toilets may increase pollution of the lens if they penetrate down to limestone strata or are situated too close to waterways. Also, water supply reticulation requires correct maintenance. Otherwise, pipes may be easily broken, allowing influx of pollution.

Increasing population density can place additional stresses on water resources. Lens location, island geology, and direction of groundwater flow must be considered when siting abbatoirs, cemeteries, rubbish tips, and even swamp taro pits.

There are many potential sources of pollution, some of which are directly linked with resource development. For instance, fish cannery wastes should be disposed of in such a manner that they will not contaminate the water lens and raise the drinking water nitrate concentration to dangerously high levels. There is also the problem of contamination of drinking water from asbestos cement roof catchments, but more research is needed to determine the actual toxicity.

Fresh water resources were ranked highest priority at the SPC Regional Technical Meeting on Atolls (Majuro, 1982), along with environmental health factors which influence water quality[2]. The South Pacific Regional Environment Programme (SPREP) is committed to protection and sustained development of the water resources of the region. SPREP's mandate can be found in the South Pacific Declaration on Natural Resources and the Environment and the Action Plan for Managing the Natural Resources and Environment of the South Pacific Region, promulgated at the ministerial-level Conference on the Human Environment in the South Pacific[3] held in Rarotonga, Cook Islands in March 1982. A number of specific directives regarding water resource development can be found in these documents, which represent the first region-wide legal instruments for environmental management in our part of the Pacific.

Current SPREP water resource projects are funded by United Nations Environment Programme Regional Seas monies as well as country contributions. Similar programmes have been established in the East African and Asian regions. UNEP is also supporting negotiations on a Draft Convention for the Protection and Development of the Natural Resources and Environment of the South Pacific Region, with protocols on combatting pollution emergencies and dumping. These will provide further legal authority once signed by representatives of the governments concerned.

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PREVALENCE OF FAECAL VIRUSES AND PARASITES IN WELL PRESCHOOL CHILDREN (≤ 5 YEARS) IN MELE VILLAGE, (PORT VILA, VANUATU), BY SANITARY FACILITIES OF HOUSEHOLD

Organisms	Outside Toilet No.	%	Inside Toilet No.	%
Viruses		(n=102)		(n=16)
Poliovirus	8	7.8	2	12.5
Enterovirus (untyped)	35	34.3	5	31.3
Adenovirus	6	5.9	1	6.3
Coronavirus	38	37.3	2	12.5
Small virus	18	17.6	3	18.8
Astrovirus	5	4.9	1	6.3
Any virus	72	70.6	11	68.8
No virus	30	29.4	5	31.3
Not examined	22		3	
Total examined	102	100.0	16 (84.2%)	100.0
Total in group	124		19	
Parasites		(n=121)		(n=19)
Ascaris	69	57.0	7	36.8
Trichuris	65	53.7	7	36.8
Strongyloides	5	4.1	-	-
Trichostrongylus	-	-	-	-
Giardia	7	5.8	3	15.8
D. fragilis	9	7.4	1	5.3
E. coli	11	9.1	1	5.3
I. butschlii	1	0.8	-	-
E. histolytica	5	4.1	-	-
E. nana	4	3.3	1	5.3
Any parasites	89	73.6	14	73.7
No parasites	32	26.4	5	26.3
Not examined	3	-	-	-
Total examined	121	100.0	19	100.0
Total in Subgroup	124		19	

Taylor, R. et al. 1984. SPC Infectious Diseases Study of Mele Village, Vanuatu (Preliminary results of baseline study).

PREVALENCE OF FAECAL VIRUSES AND PARASITES IN WELL PRESCHOOL CHILDREN (≤ 5 YEARS) IN MELE VILLAGE, (PORT VILA, VANUATU), BY WATER SUPPLY OF HOUSEHOLD

Organisms	Communal Tap No.	Communal Tap %	Outside Tap No.	Outside Tap %	Inside Tap No.	Inside Tap %
Viruses						
		(n=21)		(n=85)		(n=14)
Poliovirus	1	4.8	7	8.2	2	14.3
Enterovirus (untyped)	10	47.6	30	35.3	2	14.3
Adenovirus	2	9.5	4	4.7	1	7.1
Coronavirus	4	19.0	32	37.6	4	28.6
Small virus	5	23.8	14	16.5	2	14.3
Astrovirus	2	9.5	2	2.4	1	7.1
Any virus	17	81.0	60	70.6	8	57.1
No virus	4	19.0	25	29.4	6	42.9
Not examined	6		16		5	
Total examined	21(77%)	100.0	85(84%)	00.0	14(73%)	100.0
Total in Subgroup	27		101		19	
Parasites						
		(n=26)		(n=99)		(n=19)
Ascaris	14	53.9	59	60.0	5	26.3
Necator	-	-	9	9.1	-	-
Trichuris	11	52.4	58	58.6	5	26.3
Strongyloides	-	-	5	5.1	-	-
Trichostrongylus	-	-	7	7.1	-	-
Giardia	2	9.5	7	7.1	1	5.3
D. fragilis	2	7.7	10	10.1	2	10.5
E. coli	2	9.5	10	10.1	-	-
I. butschlii	-	-	-	-	1	5.3
E. histolytica	-	-	4	4.0	-	-
E. nana	1	4.8	4	4.0	-	-
Any parasites	16	76.2	77	77.8	10	52.6
No parasites	10	37.5	22	22.2	9	47.4
Not examined	1	-	2	-	-	
Total examined	26(96%)	100.0	99(98%)	100.0	19(100%)	100.0
Total in Subgroup	27		101		19	-

Taylor, R. et al. 1984. SPC Infectious Diseases Study of Mele Village, Vanuatu (Preliminary results of baseline study).

DRILLING FOR GROUNDWATER IN THE ISLANDS OF THE PACIFIC REGION

E P Wright

Introduction.

The viewpoint adopted in this report is that of a geologist, hydrologist or engineer who is proposing a programme of groundwater development by drilling and wishes either to purchase suitable equipment or to draw up a drilling contract.

It is not intended to include an exhaustive review of drilling methods which would be a major task. Fuller details are available in the bibliographic references. It is proposed to concentrate more specifically on the issues relating to a drilling programme in the Pacific region.

In making a choice of drilling equipment, whether for purchase or in connection with a contract, there is much to be gained from expert and impartial advice. Drilling is a complex technique and costs for equipment or contractual projects can vary from considerable to astronomical. Planning for cost effective operations is not to be undertaken lightly and without assistance of knowledge based on experience. Numerous instances can be quoted where the purchase of inappropriate equipment has had long term adverse effects on work programmes.

Selection of equipment must be preceded by decisions on the actual work programme and the factors which bear on the selection are listed below:

Depth to be drilled and geological formations to be encountered.

Occurrence of aquifers in the drilled sequence.

Borehole design including hole diameters and construction materials.

Geographical location of drilling area, mainly in relation to position of base workshops and source of materials supply. Transport facilities.

Terrain and local access.

Numbers of holes to be drilled and target rate.

Availability of drilling crew, either trained or potential.

These factors will be looked at in more detail in the context of drilling in the Pacific region but to assist those with negligible background knowledge of the subject a brief review of drilling procedures will be made.

Review of Drilling Techniques.

In drilling, rock formations must be broken or cut and the pieces (cuttings) must be brought to the surface. Rock is a term used loosely for any naturally occurring component of the earth's crust, whether consolidated or unconsolidated, massive such as fresh granite or plastic such as clay.

Rock cutting is achieved in the main by one of three methods:

(i) Percussive which involves either the repeated lifting and dropping of a heavy tool (drill bit) on the end of a wire rope or less commonly by means of a device which impacts periodically on to a length (string) of rigid drill pipe.

(ii) Rotary in which a cutting bit attached to drill pipe is rotated and simultaneously forced downwards under pressure. The action is effectively one of crushing and gouging. The pressure may be exerted by some form of mechanical 'pull down' to increase the loading on a bit or by coupling especially heavy lengths of drill pipe (Drill Collars) immediately above the bit and both techniques are effectively limited by the dead weight of the rig. The drill bit may be a rock roller type with two or three rotating cones for hard rock or winged drag bits for clay or unconsolidated rocks such as sand or silts. Other variations of rotary drilling include auger drilling or coring with a core barrel. The rotating force or torque is a critical factor in the process.

(iii) Rotary-Percussive which is comparable to rotary but associated with a percussive device to increase effectiveness. It is employed most effectively in hard rock and most particularly by means of a hammer operated by compressed air, located generally down the hole (DTH) or less effectively on the surface. The degree of impact is approximately proportionable to the air pressure.

(iv) Other methods employed for drilling are in the main very specialised and sophisticated techniques, such as the thermal drill. An exception is the water jet which may be used to make a hole through very soft and loose, relatively fine grained sediments.

The removal of the cuttings is carried out also by a variety of ways of which the most important are:-

(i) Mechanical: bailing; the use of augers (bucket or continuous flight).

(ii) Circulation: by means of a fluid which carries the cuttings. The fluid may be compressed air, water, foam or drilling mud. Circulation is most commonly direct down the drill pipe and up the annulus but for special requirements (e.g. large diameter hole in unconsolidated sediments), direction of circulation may be reversed.

(iii) Coring: by means of a core barrel with an annular cutting bit (single/double tube); in soft material a tube may be mechanically driven a short distance.

In accordance with these techniques, drill rigs may be referred to as cable-tool, rotary or air hammer. However combination rigs are now frequently used although constraints of cost and design may limit some of the techniques. Cable tool percussion rigs may have a rotary attachment. The wire line and bit may operate over a beam or directly from a pulley. The latter method is more commonly employed on the larger rigs and appears to be more effective in keeping a hole straight. Multipurpose air hammer-rotary rigs are employed for moderate depths and variable rock type. A considerable number of design variations exist such as top drive or kelly drive, hydraulic or mechanical feed, etc. and when added to all the ancillary equipment, mud pumps, compressors, mountings and transport, as well as the variations in drill tools, prospective buyers are presented with a somewhat bewildering range of possibilities.

For any one type of rig, size and weight are roughly proportional to cost and capacity, and selection of a particular rig will depend on other factors which may range from service facilities to personal experience. It would be unwise to select a rig which will be operating most of the time close to the limit of its capacity. The geological sequence at a site is rarely predictable in detail and it is well to have some extra power for emergency uses. The problem of choice becomes greater when more than one technique may be employed. The situation most frequently arises where either cable tool percussion or rotary/hammer rigs may be used. The latter are high performance rigs which are costly and complex and the entire programme of operation has to be given consideration in order to ensure cost effective use.

Selection of Drilling Rig for Pacific Island Use.

Drilling in this region is mainly concerned with domestic water supply. The requirements for civil engineering site investigations or for mineral exploration are not being discussed in the present context but if of importance, the possibility of combining operations with water supply projects in order to save costs should be looked at. In general however, the requirements are sufficiently different that for projects of any size, separate planning and equipment is to be anticipated.

The rock types most likely to be encountered include coral limestones and sandy limestones, volcanics (lavas and agglomeratic rocks), and alluvial sequences in some of the larger islands. The overburden is rarely of significant thickness and is mainly the soil profile.

Volcanic Rocks

Some differentiation must be made between the western and eastern Pacific. In the latter region and apparent most markedly in the islands of Hawaii and French Polynesia, there occur thick aquifers containing highly permeable basaltic rocks. The high permeability relates mainly to vesicular layers and to jointing and fracturing in the lavas close to the margins of flows. The thickest saturated sequences which may attain several hundred metres are usually a consequence of containment by vertical dyke systems. Abstraction is by both vertical and horizontal boreholes and a combination of deep drilling (up to 400 metres) and high yields has required drilling diameters of up to 8 inches. Flowing yields of some of the horizontal boreholes in French Polynesia attain 100 litres/sec (Guillen, Theme III).

A combination of hard rock, deep drilling in both horizontal and vertical positions, and high permeability indicate that the most suitable rig would be a combined air hammer rotary of medium to large size. The air hammer operation will give rapid penetration in the unsaturated zone or sequences of relatively low permeability; and the use of foam will extend the range of this technique. For the highly permeable sections, it becomes increasingly difficult for air circulation to cope with the fluid inflow and conversion to rotary with rock roller bits may be required.

The sequences in the Western Pacific tend to be more complex with volcanic formations, both flows and pyroclastics, alternating with volcano-sedimentary formations including reef and shelf deposits (argillite, marl and limestone). Permeabilities of the volcanic sequences tend to be low or moderate and on the whole, development of the groundwater in volcanic rocks in the Western Pacific is not advanced. Requirements will mainly be for domestic supply. Drilling depths will depend on a combination of geological and economic factors, principally relating to the costs of alternative supply sources and the scale of the demand. For low yielding boreholes (< 3 litres/sec) and in the context of domestic supply for rural communities, drilling depths are unlikely to exceed 150 m and will probably be less than 100 m. The boreholes are likely to be completed with open hole or in part with slotted casing and a diameter of 6/8 inches.

The choice of drilling rig would mainly lie between a cable tool rig of medium weight and a light-medium air hammer-rotary. Air hammer technique might suffice for all production wells in volcanic rocks of low permeability but combination rigs are not much more expensive and could also cater for high permeability aquifers or alluvial formations. The features, both advantages and disadvantages are listed below for each type. The standard criteria assumed are diameters up to 8 inch and drilling depths to 150 m.

I Medium Weight Cable Tool Rig

Fairly cheap, c. £30-£40K. Simple, reliable, easy to operate and maintain but very slow in hard rock. Rig is fairly heavy and cumbersome to transport.

II Air Hammer-Rotary

Expensive, c. £60-£80K; (essential equipment includes large compressor and mud pump). Fairly complex and therefore more difficult to operate and maintain. Drills very fast in hard rock. Relatively light and manoevrable, particularly when emphasis is on air hammer operations. Size and weight limitation constrained by rotary operation.

Limestone: Raised Reef or Shelf Limestones

Rocks of this group are medium-hard. Permeability is associated with fractures and fissures and aquifers may be high yielding. Similar borehole design to that identified for the more typical volcanic rocks would be suitable but with close attention to protection against pollution if the limestone occurs on outcrop.

The same rigs could operate as before but cable tool percussion would have additional advantages in that the rock is not unduly hard and the method avoids problems of lost circulation. Unless the latter problem constituted a major constraint, final selection is likely to be influenced by other factors in the drilling programme, notably the number of holes to be drilled and the urgency of time.

Recent Coral Reef Sequence on Low Islands

The recent coral limestones are relatively soft but become harder when cemented and the sequence may include calcareous sands and marls. The limestones are of variable permeability from low to high but the aquifers are relatively thin being constrained by the available static head which can only be a few metres at most on low islands. The fresh water of potable quality generally does not exceed 20 times the static head above sea level. The depth of boreholes is kept as low as possible in order to minimize the upward coning of saline water and typically may be less than 20 metres. Boreholes may be required for production or for exploration and monitoring purposes. Other techniques of groundwater development such as dugwells or galleries are often more efficient for freshwater lens situations.

Cable tool rigs are likely to be adequate and convenient for most purposes. They avoid the problem of lost circulation and make it easier to interpret lithological and water quality changes during drilling. Core sampling is often dersirable and this can be accomplished by a rotary attachment.

Alluvial Formations

Alluvial sequences occur on larger islands such as Efate in Vanuatu. They are soft and variably productive. Larger hole sizes than the production casing/screen may be needed in order to accomodate a gravel pack. Considerable care is needed to obtain the correct selection of screen openings and pack design and must take account of such factors as aquifer grain size variations, chemistry of water, proposed pumping rate etc.

Most of the alluvial sequences occur at low elevations and hole depths are not likely to be great. Cable tool rigs may be adequate and indeed are able to drill larger hole sizes more easily than an equivalent size of rotary rig. Problems can occur with running sands or boulder beds.

Conclusions.

In deciding on the purchase of a rig or the formulation of a drilling contract, these technological issues discussed above will need to be taken into account. But other considerations will also apply. Most of the island countries of the Pacific region are not so well endowed that they can afford the purchase of a range of drilling equipment to meet all eventualities. Versatility may therefore be a major asset. Perhaps the most important issue is ensuring that the equipment is the most cost effective and compatible with the future programmes and target objectives. Larger scale programmes and shorter time scales may allow stockpiling of materials, provision of field workshops and mechanical backup including personnel, and the use of high performance equipment. Transportation costs which can be a major factor may thereby be reduced. Cable tool rigs have many advantages but they are slow and relatively cumbersome. Transportation of such rigs to widely dispersed islands to drill the occasional hole will not achieve much and the transportation costs will be a significant component of the total budget. The disadvantages will be enhanced if the rocks are very hard, such as volcanic lavas. On the other hand, penetration rates in softer recent reef limestones will be reasonably fast and for low limestone islands, this cheaper option in drilling equipment is likely to be more appropriate.

Combination rigs have been referred to earlier, the most typical being cable tool rigs with rotary attachment and rotary-percussion (down the hole hammer). There is scope for further inprovement of combination facilities, notably perhaps in better combinations of rotary and cable tool (the typical rotary attachments to standard cable tool seem of limited value) and of cable tool with rotary-percussion. The advantages of cable tool operations in lithological sampling, drilling lost circulation zones, some well development processes and general reliability in use would be significantly enhanced in combination with the faster rotary or rotary percussion facilities. There are few technical problems in combining rotary and air hammer percussion. The hammer is substituted for the rotary drilling bit and air has to be the main flushing medium. More consideration is required for the addition of cable tool - the need for a suitable winch for manipulating heavy weights (drill string) and ensuring adequate space on the platform for easy and efficient operation. An additional cost for a cable tool facility might be of the order of 5-10% above that of the basic rotary or rotary-DTH rig.

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SHORT GENERAL DISCUSSION AFTER THEME V

Training was the main point raised. It was generally felt that there were no problems with graduate and post-graduate training as adequate courses were available at local and foreign universities. Concern was expressed about students who studied overseas but failed to return to their own country. It was agreed that the Workshop could not solve this type of problem.

The main need for training was identified as technician training. Four approaches were suggested:

(i) Single instructor visits to provide on-job training
(ii) Visits by groups of instructors
(iii) Regional centres with the technician visiting for course
(iv) Overseas (out of region) training

The first three were considered as suitable but not the last.

The UNESCO delegate offered to pursue the question with his organisation and it was suggested that regional courses could be run at USP and UPNG.