NEW ZEALAND GEOLOGICAL SURVEY

DSIR
DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH, NEW ZEALAND

WATER SUPPLY REVIEW;

KINGDOM OF TONGA.

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New Zealand Geological Survey,

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INTRODUCTION

This report covers a 29 day hydrogeological assignment to the Kingdom of Tonga. The work was commissioned by NZ Ministry of Foreign Affairs following a request from Central Planning Department, Tonga, to assist in various aspects of water resource evaluation primarily on Tongatapu, and in the Ha'apai and Vava'u Groups.

Because of the critical situation relating to water source, water reticulation, and health hazards on 'Eua (not included in the original Terms of Reference), a special request was made by the Acting Manager, Tonga Water Board to visit the island. This was agreed upon, and the results of the 'Eua visit are included in this report.

BRIEF HISTORY

The Tonga Water Board was set up in the early 1960's (in the following pages exact dates are approximate only because there is very little historical data available) as a division within the Ministry of Health. It is under the direct supervision and administrative control of the Engineer/Manager who is responsible to the Minister of Health and a Water Board Committee. The first Engineer/Manager, Manuel Ramos, was succeeded in 1980 by Filipe Koloi, BE (Civil) NZ, who until the latter part of the writer's visit had been in New Zealand on 6 months leave.

The Tonga Water Board is responsible for water supply, primarily for Nuku'alofa on Tongatapu, 'Eua Island, Pangai-Hihifo (Ha'apai Group) and Neiafu (Vava'u Group) and for a few villages throughout the Kingdom. It also acts in an advisory capacity to the Public Health Division of Ministry of Health who have responsibility for implementation and operation of most rural water supply schemes. The activities of both agencies are more clearly defined in the Energy and Water section of the Fourth Five

Year Development Plan, 1980-1985, prepared by Central Planning Department, in which the emphasis is on supply, an important point to note in view of the recommendations contained in this report.

WATER BOARD CORRESPONDENCE

In addition to verbal communication during visits by overseas personnel, much information is gathered from official files and various reports. The fact that some of the correspondence on file is conducted in Tongan inevitably limits the amount of information available to outside enquirers from this source.

PREVIOUS WORK

Numerous reports prepared by overseas and local agencies have been prepared and submitted to the Board since its inception in the early 1960's. Only a few of these were on Water Board files at the time of the writer's visit, and there was virtually no reference to any of them in the Board's correspondence. Nevertheless, a reasonably complete set have been assembled from various sources locally, and from New Zealand Geological Survey files dating back to the time of the writer's first visit in 1974.

It is not intended that the present report be considered a technical review of the work of earlier consultants, each of whom have made some recommendations as regards basic data collection requirements. However, it is necessary to repeat once again that the data, particularly as regards monitoring of water levels, and metering both at source (drillholes) and at end point (household meters), are absolutely vital to preserve the Kingdom's fragile freshwater lens resource. These data, together with accurately survey datums related to mean sea level, some of which are available, are essential requirements of any hydrogeological study of a freshwater lens system conforming to the Ghyben-Herzburg concept (see below). Unfortunately there are still no records available for analysis.

Pfeiffer (1971) and Pfeiffer and Stach (1972) were among the first to report on the hydrogeology of Tongatapu. They assumed 'that fresh water with a chloride content of about 70 ppm form a lens floating over the heavier brackish and salty water deeper in the subsurface'. Thus they recognised that the Ghyben-Herzburg principle applied to Tongatapu, and by inference to the other islands of the Kingdom. From rainfall, (1800 mm/yr), permeability factor (not shown), assumed recharge to the lens of about 10%, and an assumed 20% abstraction of recharge, Pfeiffer and Stach estimated that about 25 000 m^3/day could be exploited from wells and drillholes. They also noted an increase in chloride between 1959 and 1971 in most of the 40 wells recorded. The range of increase, calculated from the data they present is 0-360% averaging 54%.

An Advisory Services Report, UNDP Project TON/72/002 (Stach, 1974) referred to 'the danger that indiscriminate exploitation of groundwater in parts of the island (Tongatapu) could upset the relationship between the freshwater lens floating on the underlying saline water', and recommended that a geoelectric survey be carried out. To this end Waterhouse (1974) reported on drilling requirements and sites, and in 1975 New Zealand Geophysics Division drillers (DSIR) undertook the drilling project (Hoffman, 1975), part of which involved pump testing (Waterhouse 1976).

In reporting on the geological aspects of the 1977 Tonga earthquake, B. R. Paterson (New Zealand Geological Survey) initiated an exchange of correspondence between his colleagues (Wilson Nov. 1977); Waterhouse (Dec. 1977) and the Tonga Water Board, relating to a reputed increase in chloride levels from drillholes on Tongatapu. There seemed to be difficulty in obtaining clarification of the situation and the writer could find no record of the correspondence during his visit. Meanwhile, Forbes (1977) had completed a geoelectric survey of Tongatapu and with these data, and that of Waterhouse (1976), Hunt (1978) presented a mathematical analysis of the groundwater resources of the island.

Muller (1978) on a Rotary International Service scheme reported on water supply problems on Tongatapu and 'Eua from a largely engineering viewpoint. He repeated the observations made by previous investigators, and suggested various modifications to existing reticulation systems, principally on 'Eua, but did not address the real issue there - water source. Muller comments on Mataki'eua that 'during this drought the chloride content has risen from 80 ppm to 90 ppm while change in water levels have been recorded'. It is not known what 'this drought' refers to, nor how or when water levels were recorded.

In summarising his Tongatapu findings, Muller stressed and underlined that 'before any major increase in irrigation or industrial use is contemplated, management of the freshwater lens must be achieved to protect this fragile and vital source'. The recommendation remains to be carried out.

A most comprehensive report on the groundwater resources of Tongatapu was prepared by Lao (1978) in which nearly every hydrogeological budgeting aspect was addressed. Lao comments 'that the lack of vital data has resulted in assumptions and transferral of data and experience that may not be completely applicable to Tongatapu'. Nevertheless, his in depth study is an excellent effort of scientific reporting, and although it is unnecessary to go into the technical details of Lao's report it is considered that as a scientific document it is wholly acceptable but as a vehicle of communication it failed to get the response it deserved. Few, if any of Lao's numerous recommendations have been carried out although he stressed, in common with earlier workers, that systematic data collection was vital.

Undoubtedly there has been additional correspondence between the Tonga Water Board and other agencies, and with aid donors in the Pacific region. Perhaps there are other reports of which the writer is unware. It is known that a joint UNTCD/ESCAP/UNESCO team (Dijon, Ahmed & Gilbrich) visited Tonga in July 1984 to report on water supply but their report is not to hand. With Australian aid, Norwegian aid, NZ aid, VASS (Voluntary Assistant Support Schemes), FSP (Foundation for the peoples of the South Pacific), Rotary International aid, and Tongan Government aid, there is a formidable input into water related activities in the Kingdom.

COMMENT ON PREVIOUS WORK

Without exception, all previous investigators have recommended the necessity for systematic data collection particularly in monitoring of water levels, and also in metering of supplies. These recommendations have yet to be implemented.

There is no monitoring, although two Leupold Stevens automatic water level recorders were acquired by the Tonga Water Board in the late 1970's. One of these was installed in a hole at Mataki'eua and records kept for about a year in the early 1980's, but the charts were not seen by the writer. One of the meters is still available, but it is unknown whether it is mechanically operational.

There is no effective metering, either mainline or end (consumer) point, although figures accurate to the last gallon are presented in the Water Board's monthly reports.

During the early part of the writer's visit the Acting Manager informed that there was no metering at Mataki'eua. This was confirmed on 6 October, when a visit to Mataki'eua revealed that of 25 drillholes, 12 were fitted with broken meters, 11 had no meters at all, and 2 (windmills) were fitted with meters that were working, but had last been read in 1982.

The monthly report for April 1984, drew attention to the 'misreadings and miscalculations by meter readers' in recording household consumption, and to buried, blockaded, or fenced meters which could not be read.

In June 1984 it was further revealed that of 3,844 meters (August report) some 150 were broken, and 1,000 replacements were on order from England.

The Acting Manager's August report, part of which is reproduced below, records consumption figures for June and July 1983-1984, and other notes.

"NUKU'ALOFA WATER SCHEME:

	Water Production (g)	Water Consumtpion (g)	Unaccounted Loss	New Inst
June 1983	22 432 032 101 963 cu m	20 542 154 93 373 cu m	9.2	25
June 1984	22 676 181 104 073 cu m	20 784 767 94 cu m	9.1	9
July 1983	20 924 629 95 112 cu m	19 179 312 87 178 cu m	9.9	19
July 1984	22 293 350 101 333 cu m	20 303 597 92 289 cu m	9.8	3

The unaccounted loss of water cannot be accurately calculated until we have a 12" meter in Mataki'eua.

The total number of installations as at 31 July 1984 is - 3,844

Water Meters and its problems:

The meter order from U.K. is still on the way from London - and should arrive next month or October 1984."

In calculating the above consumption, Unaccounted Loss is an assumed figure dating back to the time when the Tonga Water Board was first established. Judging by the running taps, leaking gate valves and pools around Nuku'alofa, the Water Board figure of 9% to 10% is in error, particularly when related to the Auckland Metropolitan area where

Unaccounted Losses from 8 well maintained individual systems range from 11% to 30% (Auckland Regional Authority, pers. comm.). The Water Consumption must also be in error if there are 150 broken meters and more that cannot be read, and as a consequence the Water Production, which is simply the addition of Loss to Consumption, is incorrect. No reliance can be placed on any of the figures as presented although various authors have quoted them in their publications (Pfeiffer 1971, Pfeiffer & Stach 1972, Waterhouse 1974, Lao 1978).

The average daily consumption is quoted as 819 393 gallons (3720 m^3) in correspondence between the Tonga Water Board and Central Planning Department (28 May 1984). Some reports from Nuku'alofa suggest that the leakage factor may be as high as 50%, thus, taking into account the broken meters, misreadings, incorrect Unaccounted Loss and unmetered water the real daily consumption may be well over one million gallon (4500 m^3). The implications arising from such usage are that the assurances given by Pfeiffer, Waterhouse, Lao et al., that a dependable water supply is assured the people of Tongatapu, is no longer valid. Indeed, for 20 years no real effort has been made to determine exactly how the freshwater lens is responding to continual pumping, and the aquifer conceivably is being progressively dewatered and getting closer and closer to introducing saline water to the reticulation system. This applies not only to Tongatapu, but also to Vava'u where there is no mainline metering and only 3 of the 6 drillholes are operational.

The Acting Manager has drawn attention to the inaccuracies in the Unaccounted Loss and informed the writer that a mainline meter was in a wharf shed at Nuku'alofa and had been there for more than 6 months.

ESTIMATES OF REVENUE AND EXPENDITURE

The annual report of the Tonga Water Board Estimates of Revenue and Expenditure for the year 1984-1985 is a review of their financial affairs. It does not include technical aspects of their activities other than forecasting maintenance expenses, capital outlays, general expenses etc. Of particular significance in this report are the references to water meters (p4) for which $10 000 has been allocated. It is the writer's understanding that this sum is for household meters, thus it appears that no provision has been made for mainline or drillhole metering.

Because of the totally unknown effects of pumping, abstraction rates, and water fluctuations, it is stressed that there can be no additional drawoff from the lens at Mataki'eua, or anywhere else in the Kingdom. Even the proposed extension of the mainline to Sopu, Tofoa, Anana, and Popua is cause for concern in view of the already large losses that are undoubtedly occurring in the present reticulated system. Further development of the water resources would not be justified until the basic and essential requirements are first attended to i e monitoring water levels, metering at source, repairing leaks in the reticulation system.

The net cash surplus of $39 170 for 1983-84, the Tong Water Board's $50 000 cash deposit with Bank of Tonga, and an interest income of $7 908, would go some way in attending to these essentials.

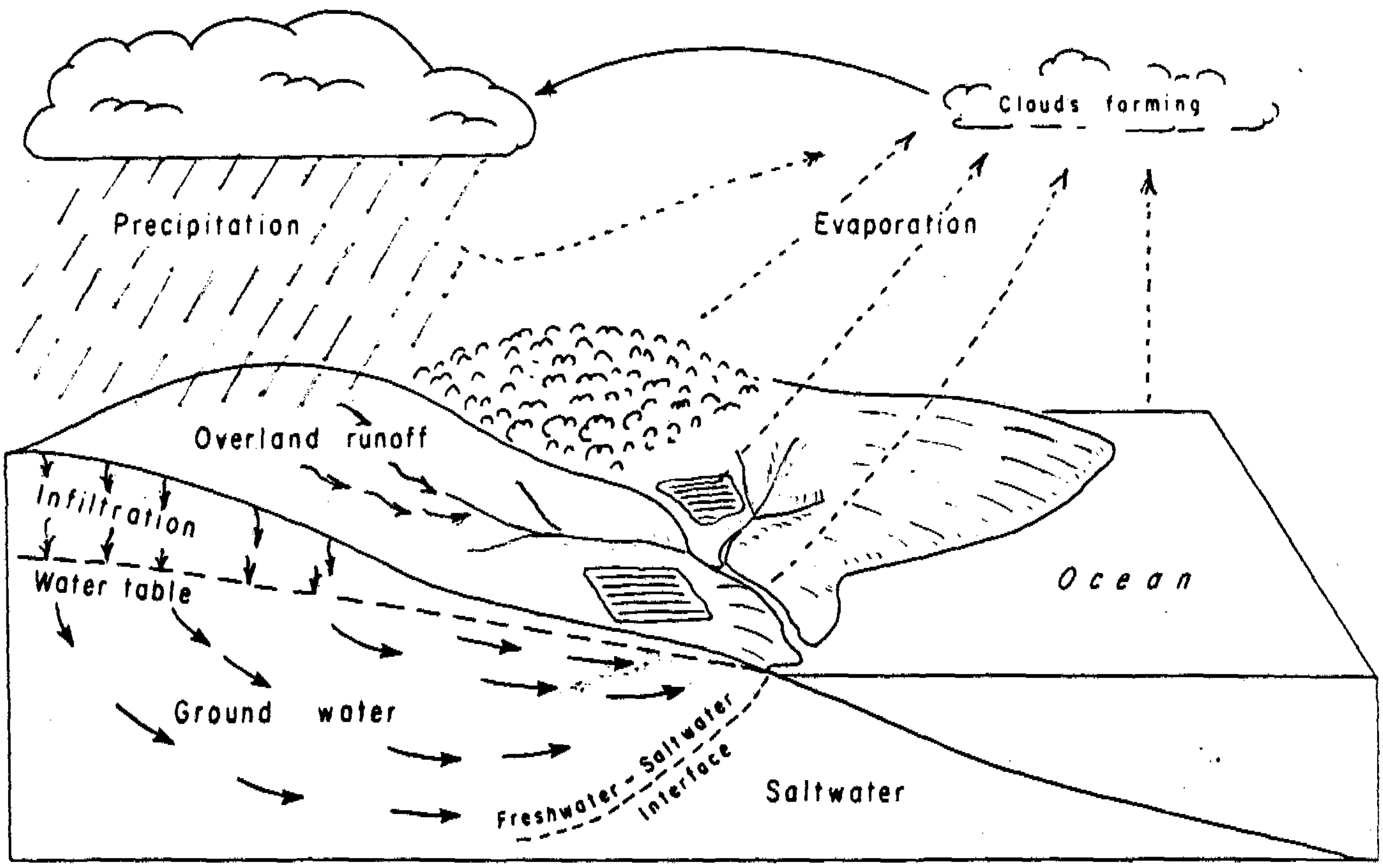
HYDROGEOLOGICAL PRINCIPLES (SMALL ISLANDS)

This is not a technical report in the sense of an in depth hydrogeological study of the Kingdom of Tonga because no data are available for analysis. Nevertheless, it is proposed to outline here the basic groundwater principles and their application to the Tongan situation, and to once more stress the absolute necessity for data collection in order to protect the fragile and valuable water resources of the Kingdom. Further deterioration of the resource could have disasterous effects for the people of Tonga and may lead to the destruction of the freshwater lens, as has happened on the island of Lifuka in the Ha'apai Group.

The principles outlined below are not an exhaustive guide to groundwater hydrology but are presented as a first step in understanding some of the more pertinent factors relating to Tonga. There are many excellent publications of a technical nature available, but for the purpose of this report it is sufficient to refer to only four for further reading. There are (for complete details see list of references):

1. Groundwater Resources Study of Tongatapu: Lao, 1978
2. Guidelines for the Investiation For and Development of Groundwater Sources: Peach, 1981
3. Basic Groundwater Hydrology: Heath, 1983
4. Water Resources of Small Islands: Proceedings of Workshop held in Suva, Fiji, 2-9 July 1984. in press

Hydrologic Cycle (Fig. 1)



The term hydrologic cycle (Fig. 1) refers to the constant movement of water above, on, and below the Earth's surface. The concept of the hydrologic cycle is central to an understanding of the occurrence of water and the development and management of water supplies.

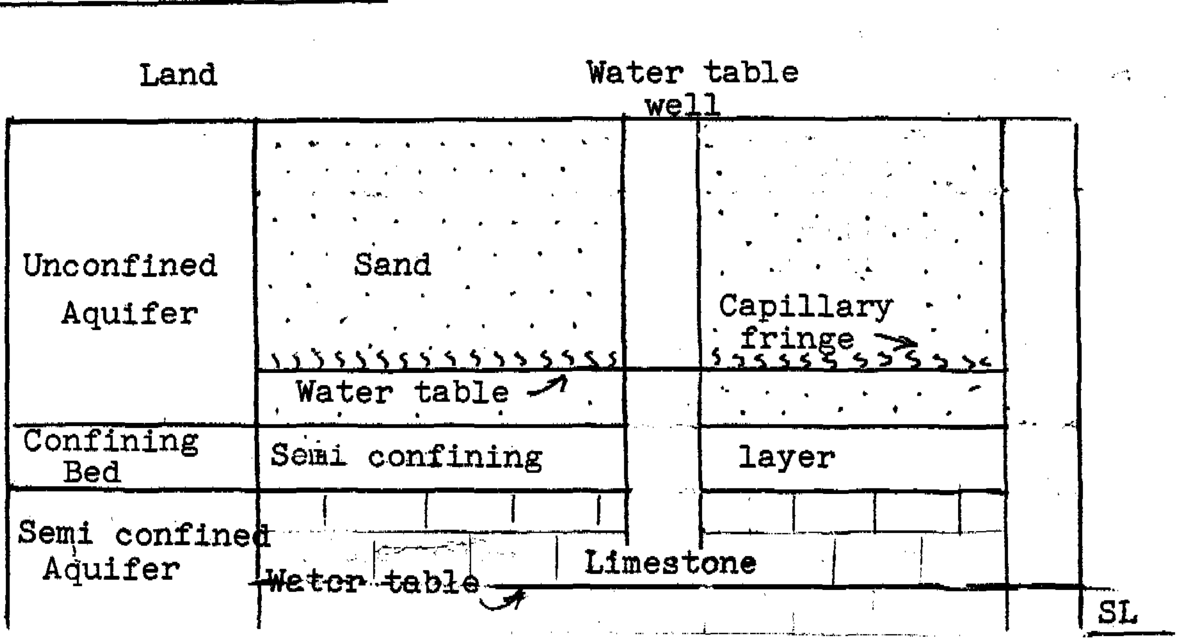
Although the hydrologic cycle has neither a beginning nor an end, it is convenient to discuss its principal features by starting with evaporation from vegetation, from exposed moist surfaces including the land surface, and from the ocean. This moisture forms clouds, which return the water to the land surface or oceans in the form of precipitation.

Precipitation occurs in several forms, but only rain is considered in this discussion. The first rain wets vegetation and other surfaces and then begins to infiltrate into the ground. Infiltration rates vary widely, depending on land use, the character and moisture content of the soil, and the intensity and duration of precipitation, from possibly as much as 25 mm/hr in mature forests on sandy soils to a few millimeters per hour in clayey and silty soils to zero in paved areas. When and if the rate of precipitation exceeds the rate of infiltration, overland flow occurs.

The first infiltration replaces soil moisture, and, thereafter, the excess percolates slowly across an intermediate zone to the zone of saturation. Water in the zone of saturation moves downward and laterally to sites of ground-water discharge such as springs on hillsides or seeps in the bottoms of streams and lakes or beneath the ocean.

Water reaching streams, both by overland flow and from ground-water discharge, moves to the sea, where it again evaporates to repeat the cycle.

<u>AQUIFER AND CONFINING BEDS</u> (Fig. 2)



From the standpoint of ground-water occurrence, all rocks that underlie the Earth's surface can be classified either as aquifers or as confining beds. An aquifer is a rock unit that will yield water in a usable quantity to a well or spring. (in geologic usage, "rock" includes unconsolidated sediments). A confining bed is a rock unit having very low hydraulic conductivity that restricts the movement of ground water either into or out of adjacent aquifers.

Ground-water occurs in aquifers under two different conditions. Where water only partly fills an aquifer as in the islands of Tonga, the upper surface of the saturated zone is free to rise and decline. The water in such aquifers is said to be unconfined, and the aquifers are referred to as unconfined aquifers. Unconfined aquifers are also widely referred to as water-table aquifers.

Wells open to unconfined aquifers are referred to as water-table wells. The water level in these wells indicates the position of the water table in the surrounding aquifer.

In the illustration above (Fig. 2) the uppermost water table is representative of the aquifer conditions in atoll islands i e the Ha'apai group, while the lower water table represents the situation on Tongatapu, Vava'u, and probably on 'Eua. It can be seen that the lower water table is close to sea level, and if its surface were lowered to sea level, salt water contamination would occur. Over pumping would exhaust the fresh water, as it has on Lifuka, and it is quite obvious that monitoring water levels and relating them to sea level and yield are absolute necessities to prevent salt water intrusion (see below), the effects of which may take months or years to eliminate.

SALT WATER ENCROACHMENT (Fig. 3)

In limestone islands or atolls fresh ground water derived from precipitation on the land comes in contact with and discharges into the sea or into estuaries containing brackish water. The relation between the freshwater and seawater, or brackish water, is controlled primarily by the differences in their densities.

The density of a substance is its mass per unit volume; thus, the density of water is affected by the amount of minerals, such as common salt (NaCl), that the water contains in solution. In metric units, the density of freshwater is about 1 gm cm^{-3}, and the density of seawater is about 1.025 gm cm^{-3}. Thus freshwater, being less dense than seawater, tends to override or float on seawater.

On islands, such as Tongatapu, precipitation forms a freshwater lens that "floats" on the underlying saltwater (Fig. 3).(1) The higher the water table stands above sea level, the thicker the freshwater lens. This relation between the height of the water table and the thickness of the freshwater lens was discovered, independently, by a Dutchman, Badon Ghyben, and a German, B. Herzberg, and is referred to as the Ghyben-Herzberg relationship. The relation, expressed as an equation, is

$$h_s = \frac{pf}{p_s - p_f} h_f \qquad 1$$

where h_s is the depth of freshwater below sea level, p_f is the density of freshwater, P_s is the density of seawater, and h_f is the height of the water table above sea level.

On the basis of equation 1 and the differences between the densities of freshwater and seawater, the freshwater zone should extend to a depth below sea level (h_s) equal to 40 times the height of the water table above sea level (h_f). The Ghyben-Herzburg relation applies strictly, however, only to a homogenous and isotropic aquifer in which the freshwater is static and is in contact with a tideless sea or body of brackish water.

Tides cause saltwater to alternately invade and retreat from the freshwater zone, the result being a zone of diffusion across which the salinity changes from that of freshwater to that of seawater (1). A part of the seawater that invades the freshwater zone is entrained in the freshwater and is flushed back to the sea by the freshwater as it moves to the sea.

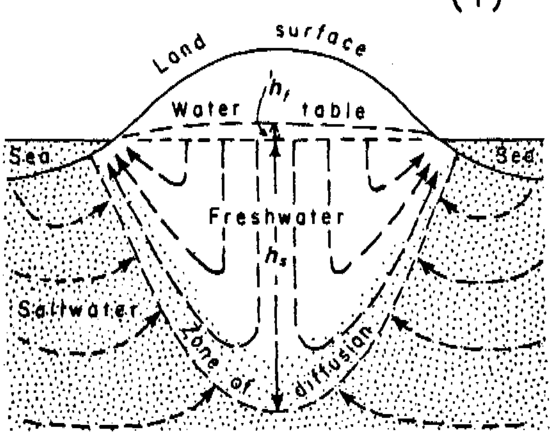
Because both the seawater and the freshwater are in motion (not static), the thickness of the freshwater zone in a homogenous and isotropic aquifer is greater than that predicted by the Ghyben-Herzberg equation. On the other hand, in a stratified aquifer (and nearly all aquifers are stratified), the thickness of the freshwater lens is less than that predicted because of the head loss incurred as the freshwater moves across the least permeable beds.

When freshwater heads are lowered by withdrawals through wells, the freshwater-saltwater contact migrates toward the point of withdrawals until a new balance is established (2). The movement of saltwater into zones previously occupied by freshwater is referred to as saltwater encroachment.

Fig 3 Salt water fresh water relationship (Ghyben-Herzburg)

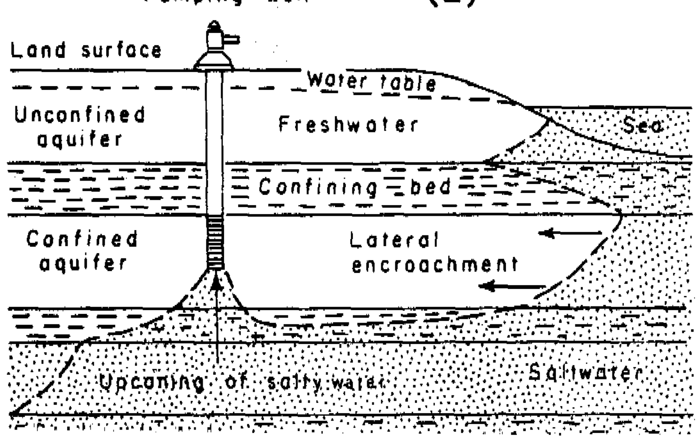
Freshwater lens floating on saltwater

(1)



Two aspects of saltwater encroachment

(2)



GROUNDWATER AND PUBLIC HEALTH

Water that soaks into the ground and ultimately completely fills the interstices, pore spaces, voids, and cavities in the rocks below i e in this case coral limestone, is called groundwater. This zone of water saturation is subject to seasonal fluctuations and the upper surface, or water table, may be close to the ground surface during rainy seasons and somewhat lower during periods of drought. In the islands of the Kingdom the water table is also influenced by tidal fluctuations, barometric pressure differences, and possibly by leakage from water pipes in reticulated areas.

The potential pollution of groundwater refers to any deterioration in the quality of the water resulting from the activities of man. This definition includes saltwater encroachment into freshwater-bearing aquifers resulting from the artificial lowering of ground-water heads. Most pollution of ground water results from the disposal of wastes on the land surface, in shallow excavations including septic tanks, or through deep wells; the use of fertilizers and other agricultural chemicals; leaks in sewers, storage tanks, and pipelines; and animal feedlots. The magnitude of any pollution problems depends on the size of the area affected and the amount of the pollutant involved, the solubility, toxicity, and density of the pollutant, the mineral composition and hydraulic characteristics of the soils and rocks through which the pollutant moves, and the effect or potential effect on ground-water use.

Affected areas range in size from point sources, such as septic tanks, to large urban areas having leaky sewer systems and municipal and industrial waste-disposal sites. Nearly all substances are soluble to some extent in water, and many chemical wastes are highly toxic even in minute concentrations.

The hydraulic characteristics of the soils and rocks determine the path taken by and the rate of movement of pollutants. Substances dissolved in water move with the water except to the extent that they are tied up or delayed by adsorption. Thus, the movement of pollutants tends to be through the most permeable zones; the farther their point of origin from a ground-water withdrawal area, the deeper they penetrate into the ground-water system and the larger the area ultimately affected.

The factors related to the movement of pollutants discussed in the preceding paragraphs must be carefully considered in the selection of waste-disposal sites, animal feedlots, and sites for other operations that may cause ground-water pollution. With these factors in mind, it is obvious that significant ground-water pollution can be avoided only if waste-disposal sites are selected in such a way that:

1. Significant thicknesses of unsaturated material containing clay and (or) organic material are present.
2. Areas are as close as possible to places of natural ground-water discharge.
3. Overland runoff is excluded, and surface infiltration is held to the minimum possible amount.

Withdrawals of water from a well cause water to converge on the well from different directions. If this convergence involves water containing a large concentration of any substance, the concentration of that substance will, after some period of time, begin to increase.

The most commonly observed increases in concentration involve NaCl (sodium chloride or common salt) and NO_3 (nitrate), but, if the well is near a sanitary landfill or other waste-disposal site, the increase may involve almost any substance commonly used by man.

Nitrate is an important constituent in fertilisers and is present in relatively large concentrations in human and animal wastes. Therefore, nitrate concentrations in excess of a few milligrams per litre almost invariably indicate that water is arriving at the well from shallow aquifers that are polluted by septic tanks or animal feedlots or that are contaminated by excess nitrates used in farming operations.

Sodium chloride is the principal constituent of seawater and is also present in significant concentrations in human and animal wastes and in some industrial wastes. An increase in the chloride content in well water most commonly indicates upward movement of water from an underlying zone of salty water.

Although increases in chloride and nitrate content are probably the most common changes in chemical quality that occur in ground water, changes may involve almost any substance soluble in water. Thus, it is important to be aware of the accidental or intentional release of potential pollutants within the area of influence of all supply wells. Substances that are of particular concern in this regard include herbicides, pesticides and other complex organics, petroleum products, and those substances that contain trace concentrations of metals.

Changes in the quality of water produced by a well, likely causes of the change, and suggested corrective action are listed in Table 1.

ANALYSIS OF CHANGES IN WATER QUALITY

Change in quality	Cause of the change	Corrective action
Biological ---------	Movement of polluted water from the surface or near-surface layers through the annular space.	Seal annular space with cement grout or other impermeable material and mound dirt around the well to deflect surface runoff.
Chemical ---------	Movement of polluted water into the well from the land surface or from shallow aquifers.	Seal the annular space. If sealing does not eliminate pollution, extend the casing to a deeper level (by telescoping and grouting a smaller diameter casing inside the original casing).
	Upward movement of water from zones of salty water.	Reduce the pumping rate and (or) seal the lower part of the well.
Physical ----------	Migration of rock particles into the well through the screen or from water-bearing fractures penetrated by open-hole wells.	Remove pump and redevelop the well
	Collapse of the well screen or rupture of the well casing.	Remove screen, if possible, and install new screen. Install smaller diameter casing inside the original casing.

Table 1: Changes in water quality from biological, chemical or physical causes. (after Heath, 1983)

WATER RESOURCES

Tongatapu (Fig. 4)

The water resources of Tongatapu have been estimated by earlier workers (Pfeiffer and Stach, 1972; Hunt, 1978; Lao, 1978) from assumed or incorrect data. It is therefore unrealistic to attempt a further water resource assessment on such grounds and none is given here. The terms of reference of the assignment 'to design and establish a water monitoring system in order to ensure that water resource development on Tongatapu and Vava'u will not impair water quality with regard to salinity' is in effect restating the requirements of 20 years standing. There are open drillholes both on Tongatapu and Vava'u suitable for monitoring, and there are two, or were, automatic water level recorders available for this purpose.

In addition to the 33 holes in the Mataki'eua-Tongamai water reserve area, there are a further 91 drillholes and wells in villages around Tongatapu. There is no monitoring of water levels, nor metering at source or at consumer end in the villages. In common with all other supplies in the Kingdom, there is no treatment of water before use unless it becomes unfit for human consumption (see report on 'Eua below).

Until some action is taken, and seen to be taken, no further development of the water resources on Tongatapu is recommended.

Ha'apai (Fig. 5)

The Ha'apai Group about 150 km NE of Tongatapu, comprises some 43 islands, 16 of which are permanently inhabited. Two of the largest islands, Foa (pop 1703) and Lifuka (pop 2938) are connected by a causeway and were visited while en route to Vava'u.

Both are 'atoll' type islands about 13 km^2 and 11 km^2 respectively with dug wells each rising to roughly 15 m asl.

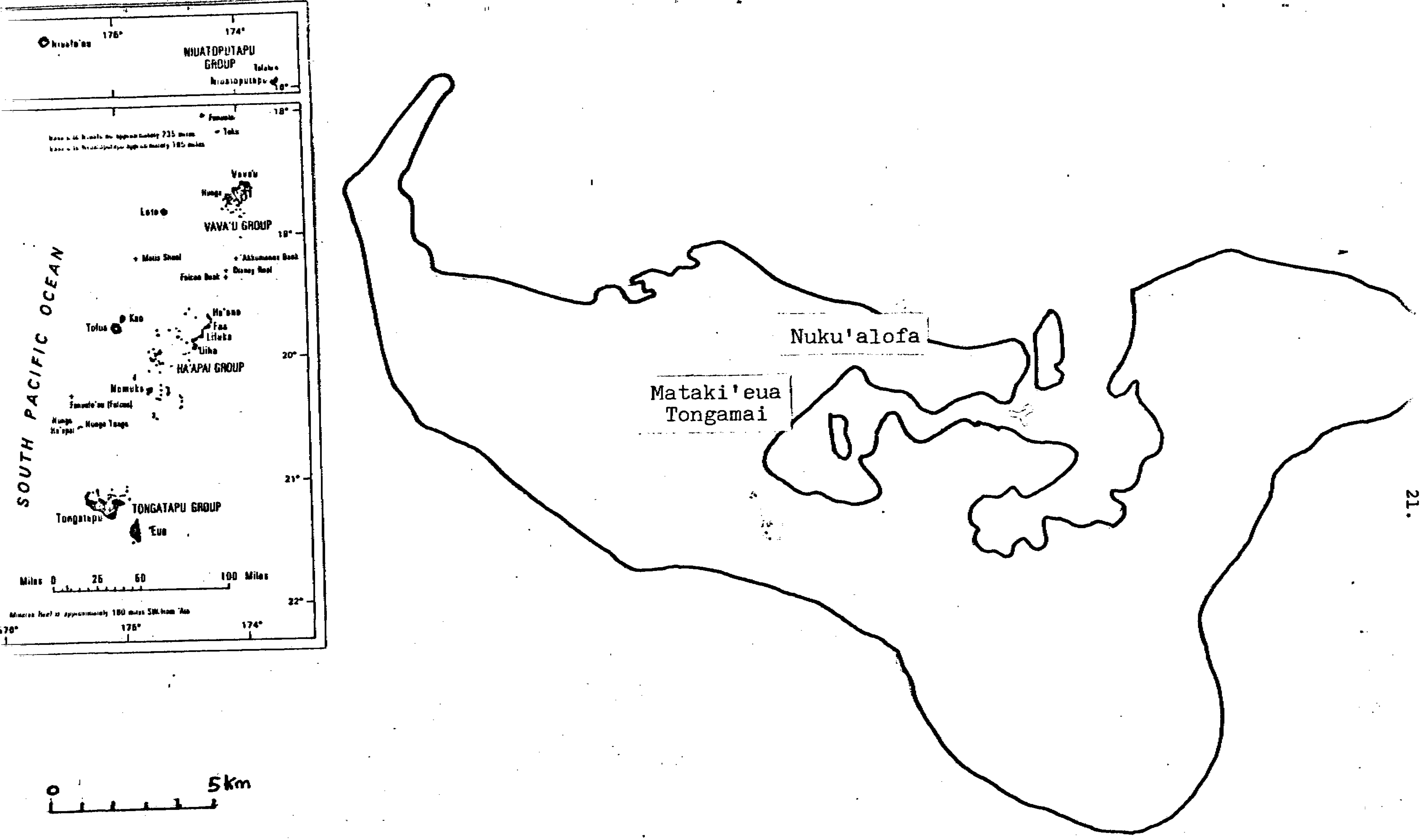


Fig 4 Distribution of islands of Tonga Group (inset) and Tongatapu Island

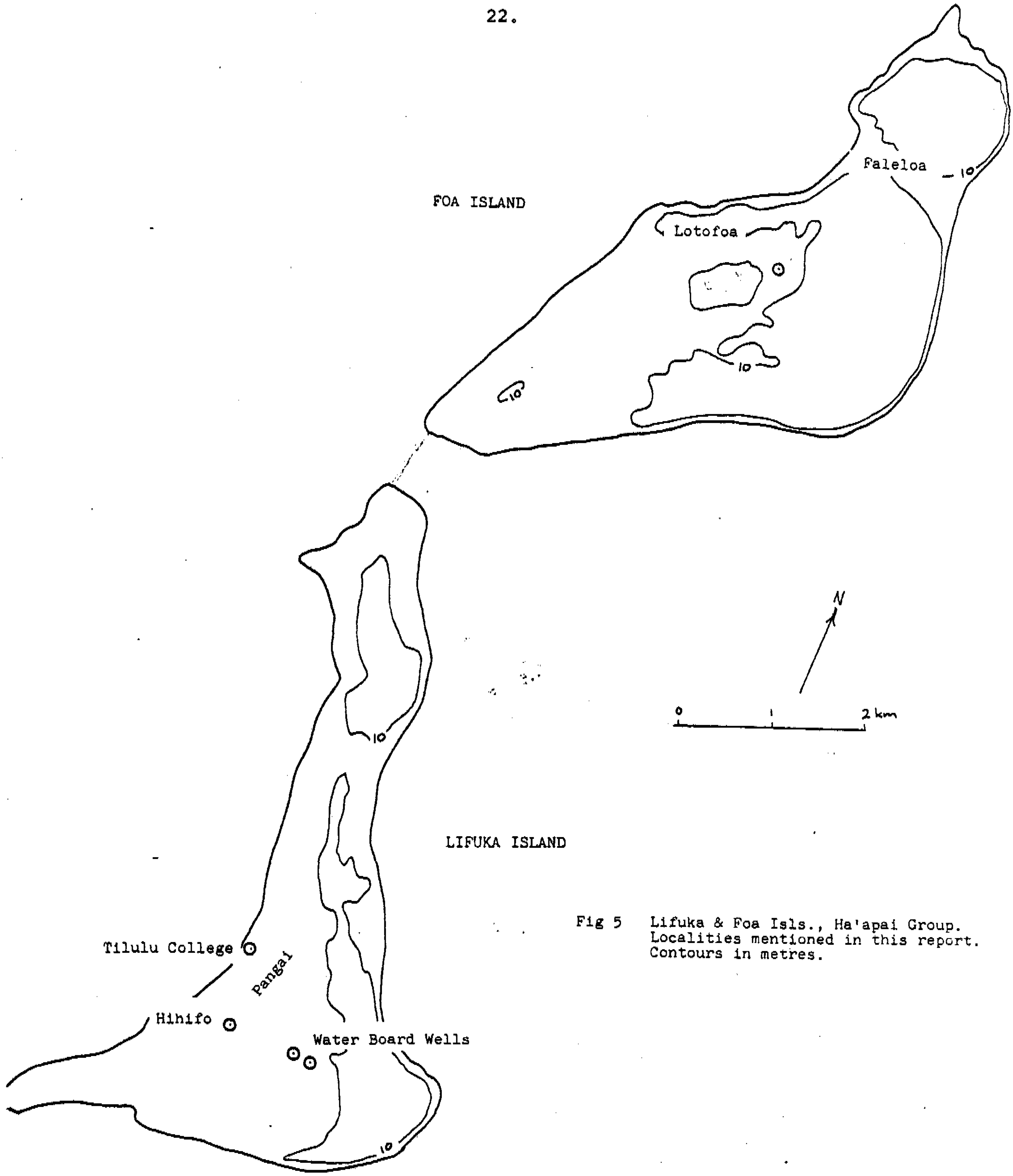


Fig 5 Lifuka & Foa Isls., Ha'apai Group. Localities mentioned in this report. Contours in metres.

A reticulated water supply on Lifuka is administered and maintained by the Tonga Water Board. The water source is from 2 wells dug in 1970-71 to about 8 m depth in sand (0-4 m) and coral limestone roughly in the centre of the southern end of the island. Well collar heights (asl), pump intake setting, pumping rate, water level, and water level fluctuation due to tidal influence are all unknown.

The Acting Manger (Proposed Hydrogeological Survey in Lifuka, undated) estimates for the month of July, 1984, water consumption in the Pangai-Hihifo area was 2600 m^3, or 84 m^3/d. He also noted that after 4-5 minutes pumping from the Tonga Water Board wells in the centre of the island they yield sea water, a condition that has been known for years since commissioning of the holes in the early 1970's.

During a further visit (Report on Acting Manager's Emergency Visit to Ha'apai and New Proposal for Lifuka Water Supply Scheme, undated), two water samples revealed an increase from 800 ppm to 950 ppm NaCl (sodium chloride) over a two hour period. It is further reported that village tap water on average contains 1000 ppm NaCl, a figure clearly in excess of the World Health Organisation maximum permissible limit of 600 ppm. The uncontrolled abstraction from the two Water Board wells on Lifuka has resulted in the freshwater lens being pumped to destruction and the rising freshwater/saltwater interface, or brackish zone, is being pumped into the reticulation system. As on other islands, it is untreated.

Two villages Lotofoa and Faleloa on Foa Island have a reticulated water supply from dug wells administered by village committees. Both supplies are of acceptable quality because of the much more limited drawoff from the Foa lens than that being abstracted at Lifuka. There are also the possibilities that the lens on Foa is marginally thicker because of the bigger size of the island, and the pump intake is not immersed to below mean sea level.

It has been suggested that Foa water might be piped to Lifuka but it must be pointed out that no plans to do so should be undertaken until a quantity assessment is made. The hydrogeological aspects of both islands are identical and overpumping of the Foa lens will also result in salt water intrusion into the drillhole. This is confirmed by the Acting Manager in his Report on Emergency Visit to Ha'apai (Agenda 6.2 undated) in which he records from the Faleloa well salinities of 100 ppm at 0900 hrs, 140 ppm at 1200 hrs, 180 ppm at 1500 hrs, and 210 ppm at 2300 hrs; and from Lotofoa 250 ppm at 0930 hrs, 290 ppm at 1300 hrs, and 300 ppm at 2330 hrs. The yield from each well was given as 4.5 m^3/hr (1000 galls).

'Traditional' Wells

Hand dug shallow wells have been a traditional source of water in Tonga for many hundreds of years. Their success is due to their penetrating only a short way into the fresh water lens, and to small drawoff by bucket for individual household purposes. If they were pumped by wind driven, diesel, or electric means they too would turn salty.

A small hand operated lever pump has been developed by a resident, Conrad Rosemont, and fitted to a few wells at Pangai. They are made from PVC pipe and incorporate two simple non return rubber valves and various inexpensive items obtainable in Tonga. According to Mr. Rosemont they are capable of delivering about 40 l/min by hand, or lever operation.

Pump Test

A Constant Discharge pump test was conducted in a well containing 1.3 m of water 400 m inland of the coast at Hihifo (Fig. 6). The hole was dewatered in 60 mins but the erratic discharge rate makes this first part of the test unsuitable for analysis. The recovery (residual draw-down) reached the original standing water level in a further 60 mins, and these data indicate a relatively high transmissivity of 50 m^2/d. Judging by the inrush of water from all sides of the dewatered hole, the coral limestone is open textured and permeable, and these lithological characteristics are likely to extend throughout most of the islands in the eastern part of the Ha'apai Group.

In common with all other holes and wells on Lifuka and Foa, if the water level were maintained in a depressed state i e lowered to sea level or below, it would turn salty.

Rainwater Tanks

An active programme of building roof catchment tanks is underway in the Group. A number of aid agencies have contributed funds for the construction of tanks of various design and capacity. The Foundation for the Peoples of the South Pacific (FSP), in conjunction with the Ministry of Works have been largely responsible for tank building activity and for repair work. Not all of the various type of tank nor the design have proved satisfactory. Galvanised tanks, because of their exposure to salt spray, and with no protective painting, rust away relatively quickly, and the recently introduced WHO 'Videnov' square ferro cement tank, is for technical reasons considered unsound (pers. comm. Connell Eddie Riedel & Byrne, Consulting Engineers). Nevertheless, tanks are an important and relatively cheap means of storing water

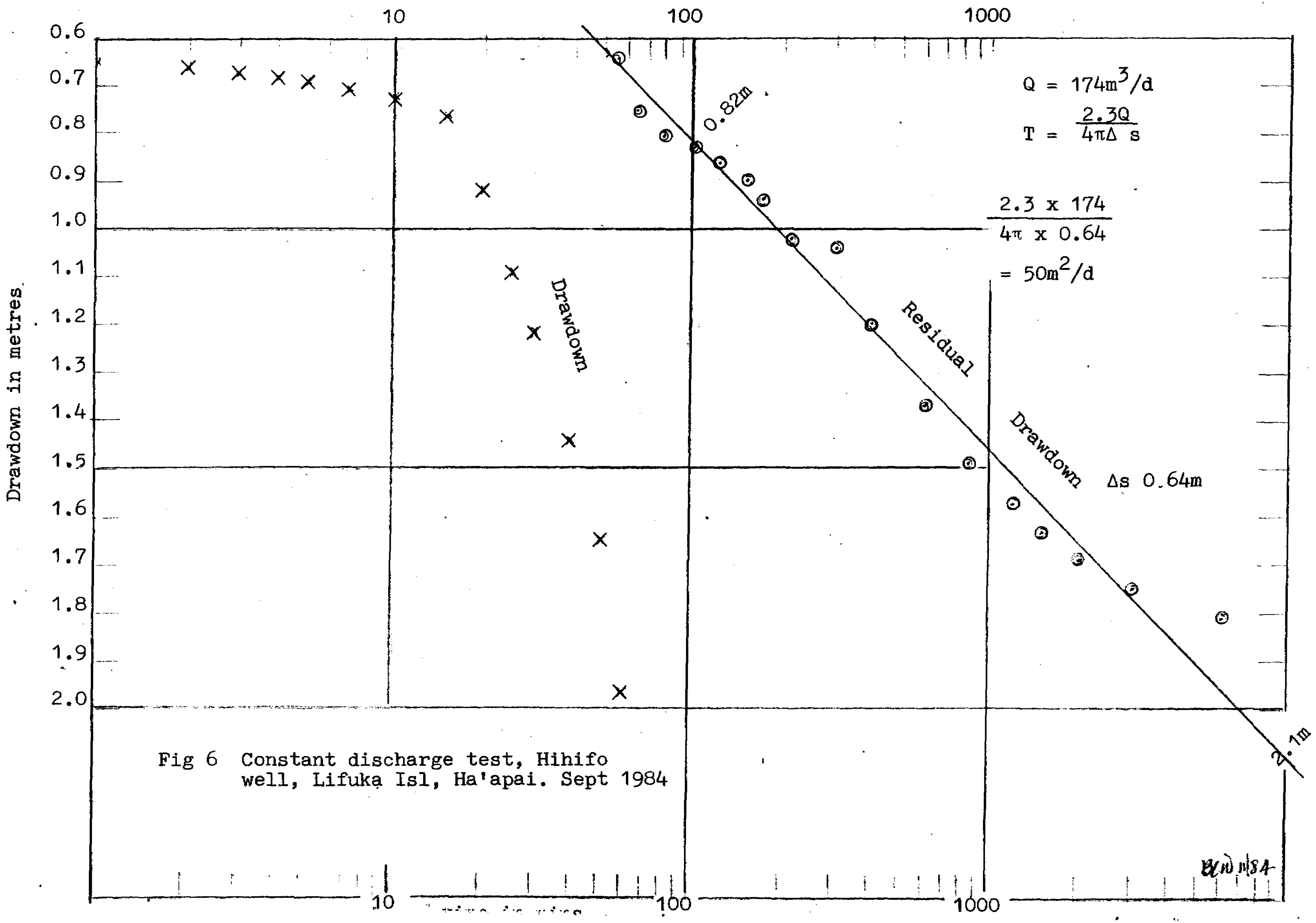


Fig 6 Constant discharge test, Hihifo well, Lifuka Isl, Ha'apai. Sept 1984

and their continued use is to be encouraged particularly in view of the fact that the alternative, groundwater, is as yet by no means a proven source.

Health Hazards

The use of 'traditional' wells as a community water source on low atoll type islands such as Lifuka, Foa, etc. and their location to nearby dwellings must be viewed with some concern because of the potential health risks.

The Acting Manger (Dr. Puloka, pers. comm.) informs that the incidence of typhoid on Lifuka particularly, and in Tonga generally is very high by world standards. He has, through his many years of study of infectious diseases, related health to hygiene, hygiene to water supply, and water supply to water source and has considered the implications of an inadequate clean water supply for the Kingdom.

There are alarming incidences of potential health hazards on Lifuka, and perhaps elsewhere in Tonga, that need immediate attention as regards possible pollution of public wells by both human and animal activities. The pump test at Hihifo clearly indicated the permeable nature of the limestone both from the mathematical analysis, and visual observations of water cascading into the dewatered hole. At Tilulu College a public well (Fig. 7) from which water is pumped for community purposes is sited 11 m on the downstream side of a pit latrine. At Pangai in a sunken depression, the site of a collapsed traditional well now used as a rubbish dump, a pig and her litter were observed rooting around and defecating in the refuse. Each of these by itself is cause for concern; collectively they are even more so. The U.S. Public Health Service

Fig 7 Tilulu College public well and hand pump, Pangai, Lifuka Island, Ha'apai Group. The well is sited 11m from an open pit toilet at rear of house. Groundwater moves from left to right in open textured coral below a veneer of coral sand. A pump test (Fig 6) at Hihifo (Fig 5) indicates high transmissivity at $50m^2/d$. Lifuka is noted for its high incidence of typhoid.

states that there is no safe distance over which polluted water can travel in fractured or fissured rocks. The limestone base of the Tonga island is known to be highly permeable and as such it could transmit polluted water great distances.

Vava'u (Fig. 8)

The hydrogeological conditions on Vava'u are similar to those on Tongatapu in that a freshwater lens is contained within permeable coral limestone close to sea level. The main town, Neiafu, is supplied from six dug wells and drillholes (1, 2, 3 and 4, 5, 6 respectively) in a water reserve area about 1 km north of the town. Five of the holes are on the eastern side of the road (1-5), with a further 2 (6-7), only one of which is equipped with a pump (6), on the opposite side. At the time of the visit (20 Sept.) three of the six pumps were broken and one at least had been out of operation for 12 months.

Drillholes

Drillhole data are summarised in Table 2 form the records in Ministry of Lands, Survey and Natural Resources, and New Zealand High Commission, Nuku'alofa, and from New Zealand Geological Survey, and Geophysics Division, DSIR.

The exact locality of Neiafu Nos. 1 and 2 (Table 2) and height above sea level is unknown. Survey heights obtained from Ministry of Lands, Survey, and Natural Resources Nuku'alofa show the road to rise from 26 m to 28.7 m over a distance of about 200 m of Board property. The water level is lowered to 27.66 m on pumping thus it can be seen that there is at best less than a metre of freshwater to draw upon in the wellfield. With only three of the six holes operational and long hours

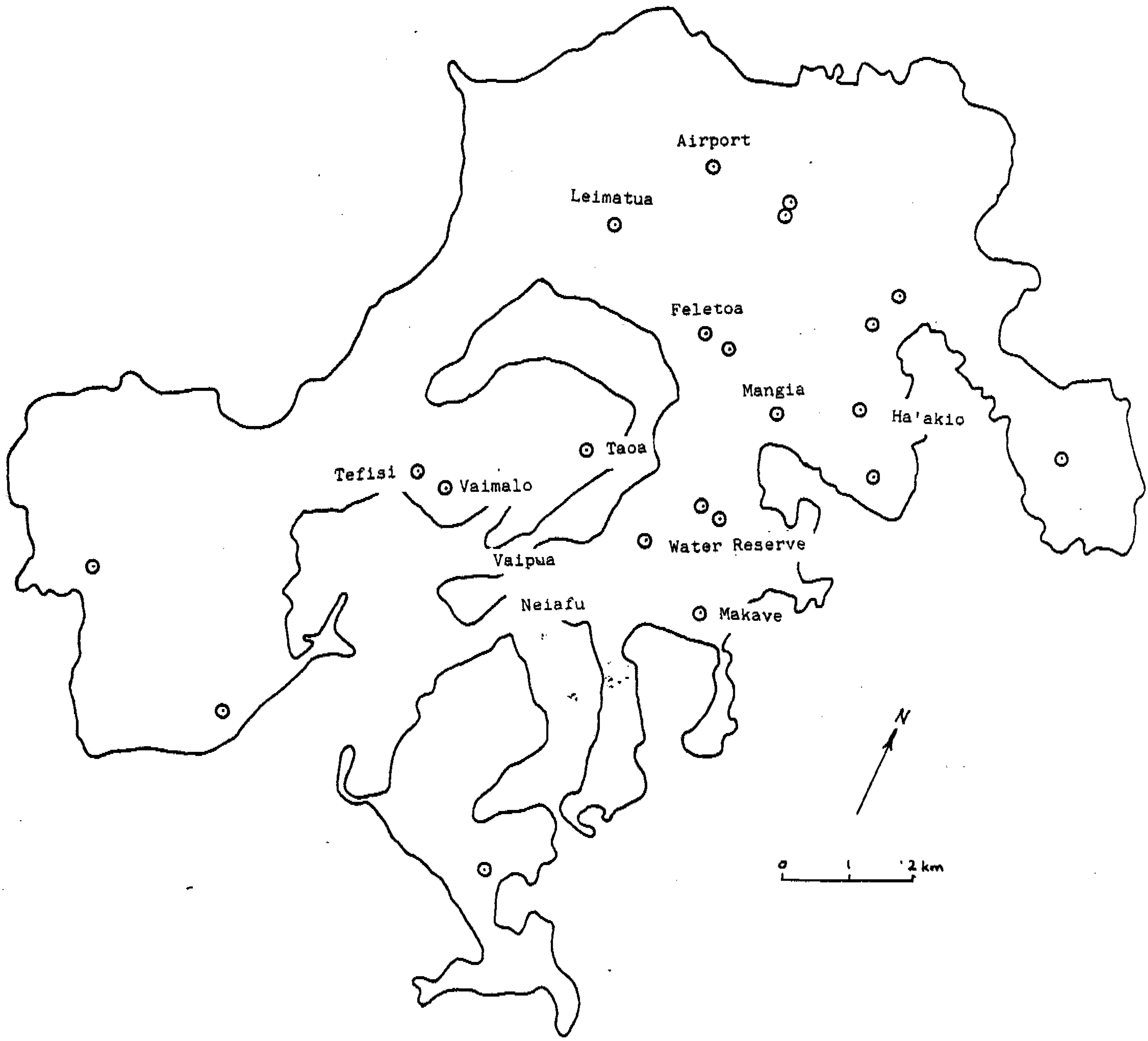


Fig 8   Vava'u Island with drillholes mentioned in this report

Drillhole	Number	Ground level (m)	Depth of hole (m)	RL	Depth to coral (m)	RL	Depth to water (m)	RL	Depth to water after pumping (m)	RL	Drawdown (m)	Test Period (hrs)	Remarks
Neiafu No 1	1	-	30.5	-	5.49	-	25.91	-	27.68	-	1.77	2	
Neiafu No 2	2	-	29.44	-	4.57	-	26.82	-	27.68	-	0.86	2	
Makave No 1	3	-	19.38	-	5.36	-	15.60	-	15.86	-	0.26	4	Increasing saltiness over 4 hr period
Makave No 2	4	25.0	19.20	5.8	3.96	21.04	18.06	6.94	18.60	6.40	0.54	4	
Vaimalo	5	48.0	49.83	-1.83	10.06	37.94	48.46	-0.46	49.07	-1.07	0.61	3	
Tefisi	6	47.33	49.81	-2.48	2.74	44.59	48.77	-1.44	49.20	-1.87	0.43	5	
Taoa	7	61.36	63.85	-2.49	-	-	61.72	-0.36	62.33	-0.99	0.61	4	
Mangia	8	30.25	32.61	-2.36	0.14	21.11	31.24	-0.99	31.55	-1.30	0.31	2	
Ha'akio	9	46.24	51.36	-5.12	-	-	45.41	-0.83	49.07	-2.83	3.66	4	
Feletoa	10	-	63.09	-	7.31	-	60.35	-	61.11	-	0.76	4	
MOW Neiafu	11	-	20.73	-	-	-	18.72	-	19.20	-	0.48	4	

Table 2 Summary of drillhole data, Vava'u, from Lands & Survey, Neiafu

of pumping, the water level may be much closer to sea level than the above indicates.

Village Supplies

There are some 18 holes and wells supplying the villages on Vava'u, and 7 of these are recorded in a 1981 Drilling Programme Report (Claridge, 1981). Testing was carried out over a 2 hr to 5 hr period, and if the water did not contain salt, at the end of the test, it was considered suitable for village use. Some holes were resited after turning salty (Makave No. 1). The driller considers that 2 holes, one at the airport and at Leimatua, were not drilled deep enough, and concludes 'that without proper measurement ..... drilling is just done by chance'. However, a visit to Leimatua revealed a pig wallow at the base of 2 x 22 m^3 (5000 gall.) raised tanks. The pump had been left running too long and the tank had overflowed so there was at least some water in the Leimatua hole.

Nevertheless, village water supplies are reputedly good and provided drawoff is kept small and pump immersion is limited to less than 20 cm (a guess) good water should be assured the villagers for some time. It is again stressed that leaks in storage tanks could account for considerable loss.

Makave No. 1 (3 in Table 2) showed an increase in chloride during the 4 hr test period and was abandoned. Makave No. 2 (4) is apparently yielding good water but the ground level (obtained from a plan prepared by E. Ramos, Tonga Water Board) must be viewed with suspicion because of the anomalous reduced levels calculated from drillhole data. Table 2 shows the standing water level to be 6.94 m asl, but in view of the depressed levels indicated in holes 5-9, this seems most unlikely unless there is a groundwater mound underlying Makave village. At this stage there is no reason to suspect that any such mound exists, and the ground level at Makave No. 2 should be checked.

In the remainder of the surveyed holes (5-9) a significant item to note is that water levels are all minus, or below sea level. The reduced levels given in Table 2 depend upon the accuracy of the original figure given for the ground level which should be related to mean sea level datum. If this figure is incorrect, then all subsequent calculations will be in error. The original standing water level can only be below mean sea level if there is a pronounced tidal influence or barometric influence on the water table, and it seems too much of a coincidence that this would occur in every case during the drilling of the holes over a period of some months. If nothing more, the anomalous results shown in Table 2 highlights the absolute necessity of accuracy in surveying, and logging, and in the installation of water level monitoring instruments.

Monitoring, metering, leaks

There is no main line metering on Vava'u and no monitoring of water levels although one hole, referred to as number 7 in Water Board files, is not equipped with a pump and could be fitted with an automatic water level recorder. There are also obvious leaks in the storage tank at the hospital where the base of the tank has rotted away. A verdant growth of green algae around the rust holes indicates that the leak has been there for some considerable time. More than likely there are additional leaks in the reticulation sytem not observed during the visit, thus as elsewhere in the Kingdom the aquifer is being pumped without knowing what the cumulative effects on the fragile freshwater lens are.

The annual consumption of 15 700 m^3, calculated from the August 1984 consumption, is a minimum figure and is probably much higher than quoted.

A rough guide to water consumption is shown in Fig. 9. The plot is based upon the number of installations given in Water Board files on Vava'u and an August 1984 consumption rate of 13 353.4 m^3 (720 l/day/metre), extrapolated back to 1972.

It can be assumed that the steady increase in consumers will result in an every increasing demand on the resource, and since the values shown in Fig. 9 do not take into account real losses through leaks etc., the ability of the lens to maintain this increasing drawoff must be viewed with concern.

Pollution Potential

In a quarry at Vaipua 1.5 km NW of Neiafu, up to 2 m of brown ash clay overlies grey coral limestone, and white open textured jointed limestone. This sequence is expected to persist over much of the island, although it was not recorded as such in the drillers logs of Neiafu 1 and 2 drillholes.

During the visit to the water reserve, horses, pigs and chickens were roaming freely over the area, and areas were planted in gardens. On the road frontage a house of relatively large dimension and outbuildings (Fig. 10) extended to within 50 m in one direction, and 75 m in another of 2 drillholes, one of which was pumping. On the opposite side of the road a church and property of the Latter Day Saints was within 10 m of another pumping hole.

The only apparent barrier to surface water soaking vertically to the underlying aquifer seems to be the impermeable surface clay observed in Vaipua quarry. If this were punctured, as might happen during the digging of house foundations, post holes, septic tanks, or pit latrines,

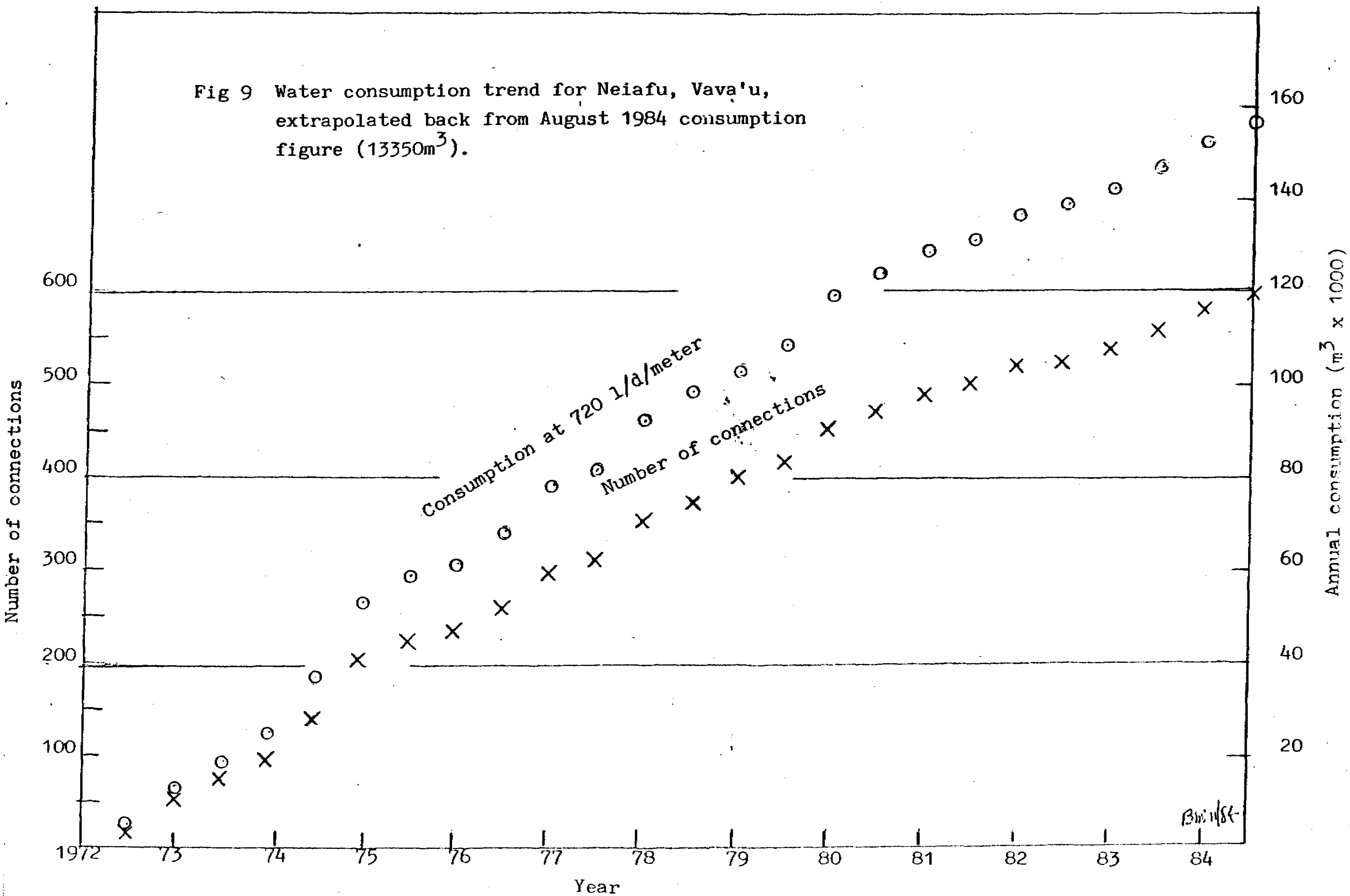


Fig 9 Water consumption trend for Neiafu, Vava'u, extrapolated back from August 1984 consumption figure (13350m^3).

Fig 10   Neiafu town water reserve area, Vava'u. Drillhole No 5 in left foreground with Tongan house and outbuildings beyond large tree. Main road and Mormon church in distance.

surface water would have immediate access to the aquifer. The coral limestone is known to be highly permeable because of the high yields obtained from drillholes both on Vava'u and Tongatapu, and from pump test results from Ha'apai, and as already pointed out, there is no safe distance over which polluted water can travel before becoming purified. A later visit revealed that the animals had been removed, and an assurance was given that the whole area was to be tidied up and that any surface activities were to be prohibited.

'Eua (Fig. 11)

'Eua island stands alone about 20 km SE of Tongatapu. The geology is more complex than other islands in the Kingdom and a long history of tectonic disturbances (earthquake) have been recorded from within or nearby.

The older rocks comprise a suite of igneous lava, agglomerate, conglomerate and tuff intruded by andesitic dykes. They are overlain by a succession of foraminiferal and algal limestone with interbedded volcaniclastics and coral reef limestones of Eocene to Quaternary age. In the east the coastline extends in an unbroken line roughly north and south for some 19 km and rises in a series of spectacular bluffs to a maximum of 300 m asl. The topography is reflected in the regional dip to the NW in which direction the limestone sequence youngs, and the surface slopes gently to the inhabited east coast.

In limestone areas the surface is rugged, particularly in the interior. Depressions, sinkholes, caves, and underground drainage patterns are typical of karstic topography, much of which is obscured by a verdant cover of second growth bush.

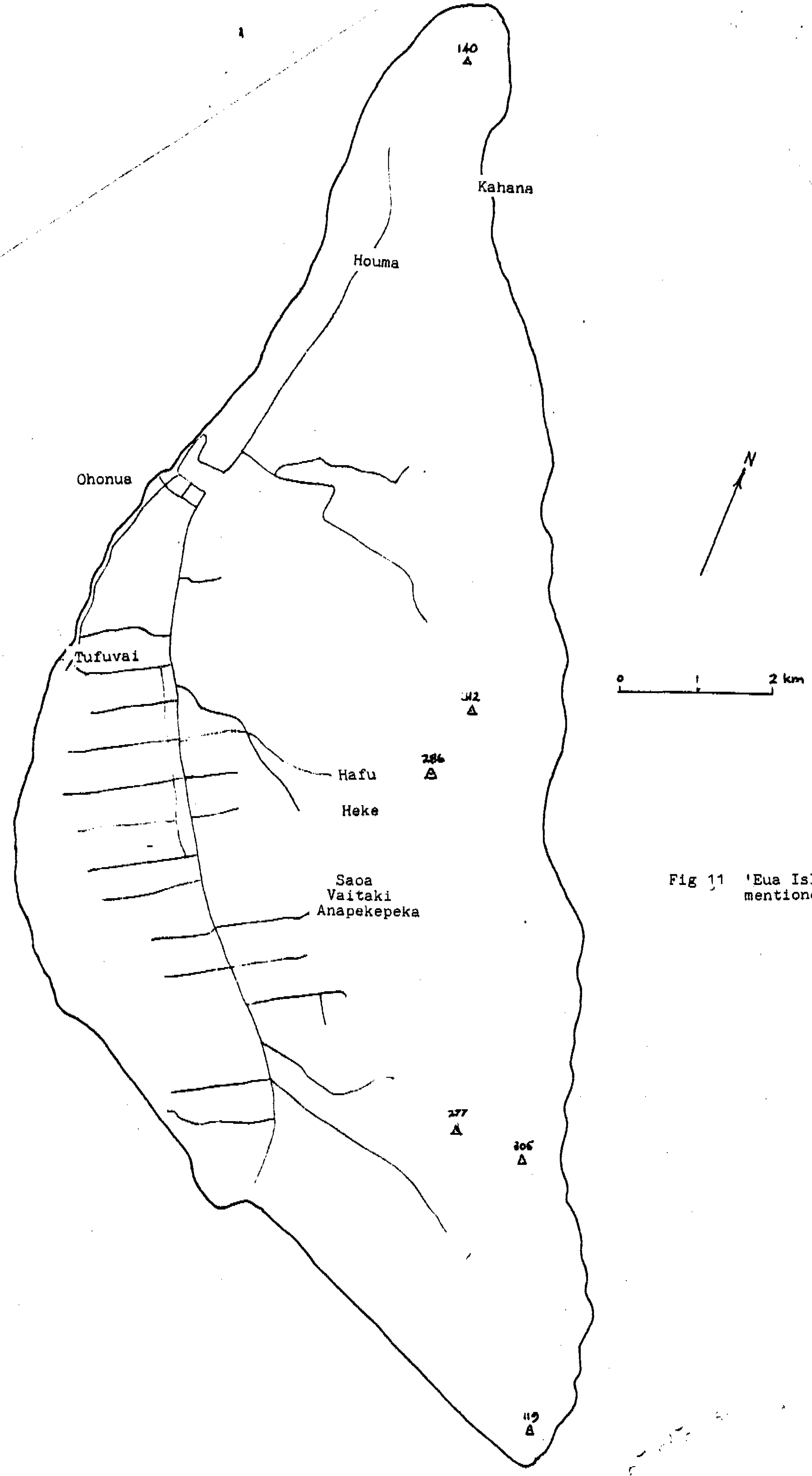


Fig 11 'Eua Isl, showing localities mentioned in this report

Water Supplies

The water supply of 'Eua has been a matter of contention for many years. There are no drillholes and the inhabitants have relied upon either roof catchment tanks, stream intake reticulated water, or from a traditional well near the coast at Tufuvai. None have proved entirely satisfactory in either quantity or quality and many attempts are being made to improve the water supply facilities.

It is a popular misconception that the inland streams are capable of yielding a permanent supply of good quality water, and crude, largely ineffective water intake systems have been erected on this premise (Fig. 12). Of the five or more intakes that were constructed, two have been abandoned (Hafu, Heke) and the remaining three (Saoa, Vaitaki, Anapekapeka) are unsatisfactory. A further source at Kahana Spring (Fig. 13) 1.8 km NE of Houma, has diminished since 1977 from about 1100 l/hr (Dr. Puloka, pers. comm.) to 270 l/hr in 1978 (Muller, 1978), to a trickle in September 1984.

A succession of both local and overseas engineers have recommended alternative areas for development of further stream intakes, or modifications to existing facilities. None have been successful long term, and in the writers' opinion no further attempts should be made to utilise such unreliable sources as streams or springs on 'Eua.

Factors Governing Quantity

Rainfall is the source of all water on 'Eua. When it reaches the ground surface, rainwater drains rapidly to lower levels through surface and subsurface drainage channels in the limestones and ultimately discharges at the coast. The intricate drainage pattern within the limestones cannot

Fig 12 Saoa intake, 'Eua . In a dry spell stream level would fall to below the intake pipe.

Fig 13 Kahana Spring, source of water for Houma village,

be determined by a cursory examination of the ground surface, and may bear no resemblance to the surface topography whatsoever.

The limestones cover most of the island, and they can be likened to a honeycomb through which water will move rapidly both vertically and laterally, and in the process will dissolve the limestone away. As the solution cavities and caves become enlarged by both dissolution, and interconnection of subsurface patterns, the process of enlargement is hastened, and when the caves near the surface the weakened roof collapses to form sinks and gullies. At the same time the ground surface is continually modified by erosion, the results of which are in clear evidence in the 'mountainous' interior of 'Eua. Most purely hydrological studies, as opposed to hydrogeological studies are to a large extent influenced by surface catchment area. In the case of a karst topography, the subsurface catchment may be appreciably larger than that indicated by surface topographic expression, a point that should be noted in the event that it is contemplated establishing a Water Reserve area.

Because the intakes are established in the interior, only the rain that falls in the area between the intake and the watershed between east and west coast will be captured. In this area runoff will be rapid since it is in the high part of the island where gradients are high. The intakes intercept water flowing westwards only as long as the streams are maintained by the head of water at higher levels, thus it can be seen that as soon as the head is depleted, the streams will dry up to progressively lower and lower levels. In times of heavy rain the streams flood from runoff from the steep gradients above them, and are often blocked by fallen rock, trees, and debris washed off the hillsides.

Conversely, in times of drought they dry up because the head of water drains away to lower levels.

It is also reported that the depletion of forests through milling over the past 40 years has resulted in more rapid surface runoff, the effects of which increase erosion and wash clay and silt into streams and valleys.

The cumulative results of these processes is an unreliable water supply from surface sources and established or newly constructed intakes may fail from blockage in the intake area or reticulation pipes, or dry up during droughts.

Water Tanks

The Saoa water intake (Fig. 12) is an example of a poorly designed system. It can be seen from the photo that stream level would not fall far before reaching in the intake. Muller (1978) reported that a small weir he inspected had dried up and a second constructed downstream showed little increase in yield. By tracing the creek downstream he found a suitable site but in the writer's opinion the hydrologic conditions do not justify any further attempts at obtaining water from the Saoa.

The Vaitaki intake (Fig. 14) was not visible because it is sited in a cave the entrance to which is blocked off. A 150 mm (6 in.) pipeline leading from the entrance is covered by rocks blasted from a limestone face above, before entering another cave and emerging further downstream. It was not known when the intake had been last inspected nor what effect the falling limestone rock had had on the pipeline, factors which should be cause for concern. Magno (1982) reported that debris, muds, and silts were built up at the Vaitaki intake, and that holes and openings above the Vaitaki allowed surface runoff carrying silt and debris to enter.

Fig 14 Vaitake intake, in cave the entrance of which is blocked off by coral blocks.

Fig 15 Windmill damaged by hurricane Isaac, 1982.

Such build up of material in the cave would be a continuing process and would not be flushed out because the entrance is now blocked.

The Anapekapeka had been constructed as a temporary measure to alleviate the water shortage but at the time of the visit (29 Sept.) the 75 mm (3 in) pipe was broken and the water was running to waste. A brief visit to Kahana spring where water was dribbling from the contact of volcaniclastics and limestone in a cave (Fig. 13) was made on 30 Sept. The supply has been gradually diminishing and there is no indication that the yield will improve. An earthquake is reputed to have affected the flow, but it might also be because of a change in the drainage pattern through dissolving of the limestone, or from being a perched aquifer that has gradually been dewatered.

Muller (1978) reported that Kahana (unnamed but his description fits) could not be considered as a source for Houma water supply. Nevertheless a pump and reservoir have been built at the spring site, and a further reservoir is constructed about mid way between Houma and the coast. It is important to note that even at the time of Muller's visit, the spring was measured at 270 l/hr (60 gph), an insignificant amount for the 41 homes it was to supply.

Pollution of 'Eua Water Supply

Much of the interior of the island is farmed with stock free ranging throughout. Some three or four wire fences with local untreated posts and stakes are erected to protect apis (gardens) from horses and cattle but none could be considered stock proof.

Streams, pools, sinks, or high level lakes provide drinking water for stock purposes, and because of the rugged karstic nature of the ground surface and consequent hazards for wandering stock, the chances of animals becoming injured, entering caves, or becoming trapped in sinkholes is relatively high.

At least two cows have died in sinkholes supplying water to the villages, the most recent occurring during the writer's visit to Tonga. At such times the water is condemned for human consumption and at the time of the writer's visit the cow had lain in the sinkhole draining to the Vaitaki intake for three weeks before being discovered and the water was still highly polluted.

The Senior Medical Officer, Public Health (Dr. S. T. Puloka) has repeatedly drawn attention to pollution risks on 'Eua. As long as surface or cave water is used, these risks will remain, and it will only be a matter of time before more animals die in sinks. Dr. Puloka lists four main sources of pollution (Report of Visit of a Team to 'Eua, October 1984). They are:

1. Micro organisms from animals, humans and birds
2. Poisonous chemicals such as insecticides etc.
3. Mud
4. Rubbish

In discussing (1) it has been suggested that fencing off water reserve catchments would protect the source. Local fencing is quite inadequate to prevent thirsty animals from reaching water, and the cost of erecting a seven wire post and batten animal proof boundary fence at current prices of $NZ2,700 per kilometre (NZ Min. of Agriculture and Fisheries, pers. comm.) plus labour and cartage, would be prohibitive. Because of the nature of the subsurface catchment the area to be protected could be very large and would undoubtedly affect many garden areas. The loss of productive garden areas, together with sheer physical difficulties of erecting boundary fences over karst topography, the costs, and the totally unreliable nature of the water source, suggests the only way of overcoming pollution from micro organisms etc., is to abandon the existing surface sources altogether. In doing so, 2, 3 and 4 would disappear.

THE ROLE OF GEOLOGISTS/HYDROGEOLOGISTS IN RESOURCE ASSESSMENT

Water is a mineral and all minerals are traditionally studied, classified and assessed by geologists. When water is influenced by the geology, or when it occurs subsurface as groundwater, it is studied by both geologists and hydrogeologists, both of whom have the same basic training. In Tongà the geology is relatively well known from earlier work and from the recent activities in mapping and drilling in the search for oil, the results of which are about to be formally published as an American Association of Petroleum Geologists Memoir 'Tonga Ridge Resource Study and Tripartite Cruise Report' (D. Tappin, Pers. Comm.). The hydrogeological principles, as they apply to Tonga are also known or concluded from field observations, but data suitable for analysis are not available i e water level fluctuation in drillholes and wells, yields, stream flows etc., thus a detailed hydrogeological assessment of the water resources of the Kingdom is not possible.

In Tonga there exists within the Department of Lands, Survey, and Natural Resources, a geological unit under the control of the Government Geologist. The unit is responsible for all natural (mineral) resources, and therefore, technically, it is also responsible for water affected by the geological environment, and for groundwater including the freshwater lens contained within the rocks near sea level. Thus the basis for a

Kingdom wide hydrogeological survey is already established i e a resident geologist and his staff who know the geology and have available geological maps. As the two disciplines of geology and hydrogeology are intimately related, it is recommended that the Tongan Government Geologist should be the first point of contact in any future water resource investigation and that he be consulted in all matters pertaining to hydrogeological assessments.

It is important to recognise the part a local resident geologist can play in relating the geological aspect of his day to day work to the problems in water supply. Rock outcrops, their lithology, structural disposition, thickness, age etc., together with drill and well logs represent the fundamental basis for a successful water resource study. The availability of these data, before the arrival of any hydrogeologist would save much time, expense, and effort in selecting appropriate areas for further study, and/or sites for drilling. The geologist and his staff would be invaluable in assisting in the stratigraphic logging and interpretation of results, and any other activities as are mutually agreed upon i e routine monitoring of water levels, plotting data on maps and for filing, and in the preparation of reports. It is also important to note that the Government Geologist is on a two year contract from the United Kingdom and his Tongan counterpart would probably become responsible for water resource work at the expiry of the contract period. For this reason, the foundation for geological involvement should be laid now so as the counterpart can learn the techniques and methods employed in groundwater work.

DRILLING

The groundwater resources assessment of the Kingdom will require the use of a drilling rig. This tool is as much a part of the hydrogeologists equipment as is a geological hammer to the field geologist and as such it should be capable of performing specific functions.

A discussion with the Australian High Commission, Mr. Brian Smith, revealed that the Australian Government might donate a rig to Tonga under their aid scheme. Undoubtedly it would be useful for other work such as foundation drilling and quarrying, but for water supply investigations the specifications should be that it is capable of drilling a 100 mm diam. (4 in) hole to a depth of up to 100 m. This depth is the extreme limit likely to be encountered but most holes will be much shallower. A range of bit sizes would also be useful because it is thought unnecessary to drill a 100 mm hole unless it is to contain a deepwell pump. Purely exploration holes can be up to 50 mm diameter.

Since the drill rig would be a vital item of equipment for geological/ hydrogeological studies, it would be preferable for it to be under the administrative control of the Government Geologist, with the Ministry of Works being responsible for maintenance, storage, and providing drill crew(s). A training period will be necessary but presumably the Australians would arrange for one of their people to undertake the programme.

OTHER TRAINING

Basic skills are required to maintain even simple systems of water supply and reticulation. The acceptance by the Tongan authorities of largely European methods of technology, implies a readiness to also accept the responsibility for maintaining those facilities in working order.

There are at least 150 broken water meters in a shed at the Tonga Water Board. Some are damaged beyond repair, but if stripped down, the parts could be reassembled. A store of reconditioned water meters would make a valuable addition to the 1000 replacements now on order from England.

Leaks and blockages abound in pipes throughout the Kingdom and some have been leaking for months and possibly years. In some instances the initial workmanship in installation was poor (Dr. Pulok pers. comm.) and pipes were glued together while still containing mud and clay.
A suggestion by the Australian High Commissioner, and with which the writer agrees, is that basic elementary training in the various trades, including plumbing, should be conducted in Tonga for Tongans. The practice of sending a selected few to courses overseas has proved only moderately successful and in any event such courses would be pitched at a higher than necessary level for the majority of Tongan workers. According to the High Commissioner a building in which to conduct trade training practices could be made available, and it would seem an opportunte time to initiate a move to get training under way.

Elementary skills learned by many are of far greater value to the community as a whole than higher skills learned by a few. Simple plumbing techniques and repair would benefit the village communities in their various water supply schemes, including the repair of tanks, taps, valves, gutters, downpipes etc. all of which are essential elements of a successful water supply.

Ultimately the skills could be passed on and even relatively difficult jobs such as re-erecting windmills and other facilities damaged by earthquakes or hurricanes could be attempted, rather than do nothing as is apparent from the windmill (Fig. 15) damaged by hurricane Isaac in 1982.

RECOMMENDATIONS

General

The ability of the Kingdom's groundwater source, i e the fresh water lens, to continue to yield good water depends on how the system is responding to current drawoff. There is no magical way in which this can be determined and until the recommendations made previously, and repeated here are carried out, there can be no further development of groundwater on any of the islands in the Kingdom.

The indiscriminate abstraction from the lens has led to its destruction in the vicinity of the wells on Lifuka, and there is no way of telling whether this stage is approaching on Tongatapu and Vava'u. Immediate steps must be taken to ensure that the valuable and vital water resource of Tonga is protected. If it becomes exhausted through overpumping, the damage may take months or years to remedy, and the consequences for the Kingdom would be disastrous. The following recommendations are the minimum requirements that need immediate attention.

Tongatapu

(1) Install water meters in delivery lines from each well or drillhole and in the main lines from Mataki'eua.

(2) Check or establish survey heights, relative to sea level, of ground level at each well or drillhole on Tongatapu, and monitor water levels on a routine basis.

(3) Install automatic water level recorder in one of the unused holes at Mataki'eua, and keep the record charts.

(4) Undertake no further drilling, for abstraction purposes, no increased drawoff, and no extension of present facilities until 1-3 are done and the records kept for at least a year.

(5) In all matters pertaining to groundwater, consult the Tongan Government Geologist.

Ha'apai

(1) The freshwater lens in the vicinity of the Tonga Water Board wells has been overpumped and is yielding salt water. Any future study of the potential yield from the fresh water lens on Lifuka should be carried out at least 500 m distant from the Water Board wells. The study will require accurate surveying of test drill sites (related to mean sea level) drilling to sea level, pump testing and analysis of results, and analysing water samples for salt contamination. Geologist and hydrologist to plan and undertake study.

(2) Discourage use of 'traditional' wells because of their potential health hazard.

(3) Continue to construct and encourage use of rain water tanks as a supplementary source in the event that the fresh water lens is satisfactory.

(4) If the lens on Lifuka is not capable of yielding the required amount for the Pangai-Hihifo area, abandon any further thought of lens development. The lens will only yield a limited amount of water, therefore actual demand must be regulated to the yield.

There may be enough from the one source to satisfy individual village requirements but not enough for all villages collectively.

(5) If there is insufficient water for community purposes on Lifuka there will also be insufficient on Foa. The reason Foa is good now is because less water is being pumped from the lens.

Vava'u

(1) The same recommendations apply as for Tongatapu. Monitoring of the water levels in the Water Reserve, metering of the supply, and repairing leaks should be carried out immediately. The continued abstraction of water from Vava'u, without knowing what effect it is having on the lens could result in pumping salt water, as has happened on Lifuka.

(2) No further development or pumping from the Water Reserve area should be undertaken until (1) is carried out and the results analysed.

(3) The close proximity of the well field to built up areas increases the risks of pollution. It may be necessary to start to look now for alternative areas in which to establish a future well field.

'Eua

(1) Continue with use of reticulated supply meantime but abandon all further development or modification to stream intake systems on 'Eua. They are unreliable in permanency of yield, and a health hazard because of pollution from animal, human, and farm sources.

(2) Adequate geological maps of 'Eua are available from which to select potential sites for hydrogeological test drillholes. Consult Tonga Government Geologist before commencing programme.

(3) In terms of supply and health hazards 'Eua is number 1 priority in the Kingdom. An alternative to the present system is necessary but it may take 12 months or so to organise and implement. Clean out dirty pipes and intakes as remedial measure only until a better supply is found.

Other

(1) The Government Geologist in collaboration with a hydrogeologist, should be made responsible for all groundwater resource evaluation in the Kingdom.

(2) The Tonga Water Board should be responsible for matters relating to supply and reticulation of water, as outlined in the 4th 5 year Development Plan, 1980-85 (Central Planning Department).

(3) Provision should be made in the Water Board budget for the purchase of water meters and monitoring equipment. This could be met from Board funds and it should not be necessary to rely on aid agencies for the procurement of essential pieces of equipment or instruments.

(4) Basic training in maintenance procedures and repair of items such as water meters, leaking valves, leaking pipes, and any elementary plumbing should be undertaken in Tonga.

(5) The attention of the authorities is drawn to the recommendations contained in reports prepared by earlier advisers.

(7) A drilling rig is vital in any hydrogeological investigation and should be an integral part of the geological/hydrogeological equipment. As such it should be under the administrative control of the Tonga Government Geologist, and maintained, operated, and stored by Ministry of Works.

(8) There appears to be no technical accountability, and there is no works supervision by aid donor countries after project approval is given, a factor already commented on by Muller (1978). It would be in the Tongan and donor's interest to inspect programmes before and during construction on a routine basis.

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